Vague D
Campagne d'évaluation 2017 – 2018

Unité de recherche

Dossier d'autoévaluation

Informations générales

Nom de l'unité :	**Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique et Atmosphères**
Acronyme :	**LERMA**
Champ de recherche de rattachement :	
	Primary: Sciences de la terre et de l'univers
	Secondary: Physique, Sciences et technologies de l'information et de la communication
Nom du directeur pour le contrat en cours :	**Dariusz C. Lis**
Nom du directeur pour le contrat à venir :	**To be selected in 2018**

Type de demande :

Renouvellement à l'identique ☒ Restructuration ☐ Création ex nihilo ☐

Établissements et organismes de rattachement :

Liste des établissements et organismes tutelles de l'unité de recherche **pour le contrat en cours** et **pour le prochain contrat** (tutelles).

Contrat en cours :	Prochain contrat :
- Observatoire de Paris	- Observatoire de Paris
- CNRS	- CNRS
- Université Pierre et Marie Curie - Paris 6	- Université Pierre et Marie Curie - Paris 6
- École normale supérieure	- École normale supérieure
- Université de Cergy-Pontoise	- Université de Cergy-Pontoise
-	- Université Paris Diderot - Paris 7

Choix de l'évaluation interdisciplinaire de l'unité de recherche ou de l'équipe interne :

Oui ☐ Non ☒

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DOSSIER D'AUTOÉVALUATION

Executive Summary

LERMA is a modern research laboratory with demonstrated scientific and technical leadership in key areas of astrophysics, physics, and Earth science. The unique strength of the laboratory is its multidisciplinary approach, combining expertise in observations, theory, numerical simulations, laboratory experiments, and instrumentation. This enables scientific leadership of ambitious observational programs using state-of-the-art space and ground-based astronomical facilities across the electromagnetic spectrum (*Herschel*, *Planck*, IRAM, ALMA, SOFIA, VLT, CFHT), as well as physics facilities (SOLEIL, Orion, PALS). The observations carried out with these facilities, in turn, stimulate new laboratory, theoretical, and instrumentation activities.

The laboratory has a consolidated yearly budget of about 2 M€ and a total staff of 60 permanent researchers, 34 permanent engineers and technicians, and 63 contractual personnel. The LERMA staff is hosted by the Paris Observatory, UPMC, ENS, and UCP. The laboratory is organized into 4 thematic poles, which all carry out cutting-edge research in their respective fields:

- The *Galaxies and cosmology* pole studies baryonic processes in galaxy formation; star formation efficiency, history, and stellar populations; fueling and feedback of black holes; epoch of reionization; large-scale structure of the Universe, nature of dark matter and dark energy, and inflation models.
- The *Interstellar medium and plasmas* pole investigates the complex physical and chemical processes, as well as dynamics of the various phases of star formation and stellar plasmas, through observations, numerical simulations, and laboratory experiments, to derive a reliable understanding of the effects of the magnetic field, radiation, and non-equilibrium chemistry.
- The *Molecules in the universe* pole carries out a broad range of laboratory activities, deeply linked to astrophysics and Earth and planetary science, including both numerical simulations and low-temperature molecular physics experiments, and ultra-high-resolution molecular spectroscopy.
- The *Instrumentation and remote sensing* pole designs and fabricates state-of-the-art superconductive and Schottky devices for terahertz heterodyne spectroscopy, with applications to astrophysics and Earth's observations; it develops innovative methods for quantifying key variables of the Earth's water and energy cycle using satellite observations.

Scientific activities of the laboratory are supported by the administrative and IT support teams, organized in the *Support* pole.

LERMA is closely involved, on both scientific and technical levels, in preparation of the new large space and ground-based projects of the future (JWST, *Euclid*, JUICE, NenuFAR, SKA, OST, MetOp-SG, SWOT) and is very well positioned to take full advantage of the observational opportunities provided by these facilities, when they become operational. The laboratory plays a leadership role in a number of observation services (ANO). LERMA computer codes are considered as a worldwide reference in their respective fields and major computer simulations draw on computational resources from the regional (MésoPSL) to the national (GENCI) centers. With the increase of the observing data volumes, LERMA is developing new expertise in *Big Data* techniques, such as machine learning, with application to both astrophysics and Earth remote sensing.

In addition to research, education and public outreach are important activities of the laboratory. The strong university links (UPMC, ENS, UCP, UPD) provide access to high-quality students, complementary resources, and reinforcement in the form of new faculty and technical positions. Nevertheless, recruitment of young researchers and engineers, to replace the multiple foreseen retirements, remains a big challenge for the future.

This document is organized as follows: Section 1 provides a general presentation of the laboratory, Section 2 describes selected research highlights and LERMA instrumental platforms, Section 3 describes the organization of the laboratory, Section 4 is the SWOT analysis, and Section 5 describes the position of the laboratory at national and international levels, observation services, as well as education and outreach activities. The general presentation of the laboratory is then followed by detailed presentations of the 4 scientific poles in Sections 6–9.

1. Presentation of the laboratory

Introduction

The *Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique et Atmosphères*, LERMA, is deeply rooted in the early development of French radioastronomy, as well as atomic and molecular physics. Created in 2002 through a merger of two scientific departments of the Paris Observatory, the *Département de Radioastronomie Millimétrique* and the *Département Atomes et Molécules en Astrophysique*, LERMA has been fundamentally dedicated to molecular astrophysics and the development and exploitation of powerful space and ground-based facilities for spectroscopy and spectro-polarimetric imaging. The laboratory was further enlarged in 2014 through a merger with the *Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique*. LPMAA was a fundamental physics laboratory at UPMC dedicated to modern molecular physics, with applications to astrophysics, atmospheric physics and environment, which stemmed from the *Laboratoire de Chimie Physique de la Faculté des Sciences de Paris*, where molecular lasers were first developed, along with high-resolution spectrometry. Another active research team with profound expertise in fundamental molecular physics and astrochemistry also arrived at the same time from the *Laboratoire Univers et Théories*. Finally, a new cosmology team from the *Université Paris Diderot*, hosted by the Paris Observatory, joined LERMA in 2017.

All these historical developments have led to a great diversity of activities and a vast network of collaborations and partnerships in France and abroad. Today, a broad range of research topics is investigated, from astrophysics to Earth science, with emphasis on dynamical and astrochemical aspects of galaxy, star, and planetary system formation. These investigations have now expanded far beyond radio observations, into other parts of the electromagnetic spectrum. In addition, LERMA has developed unique expertise in modeling, numerical simulations, and laboratory astrophysics. The laboratory also builds state-of-the-art heterodyne radiometers at millimeter to far-infrared wavelengths, with applications to astrophysics and Earth remote sensing.

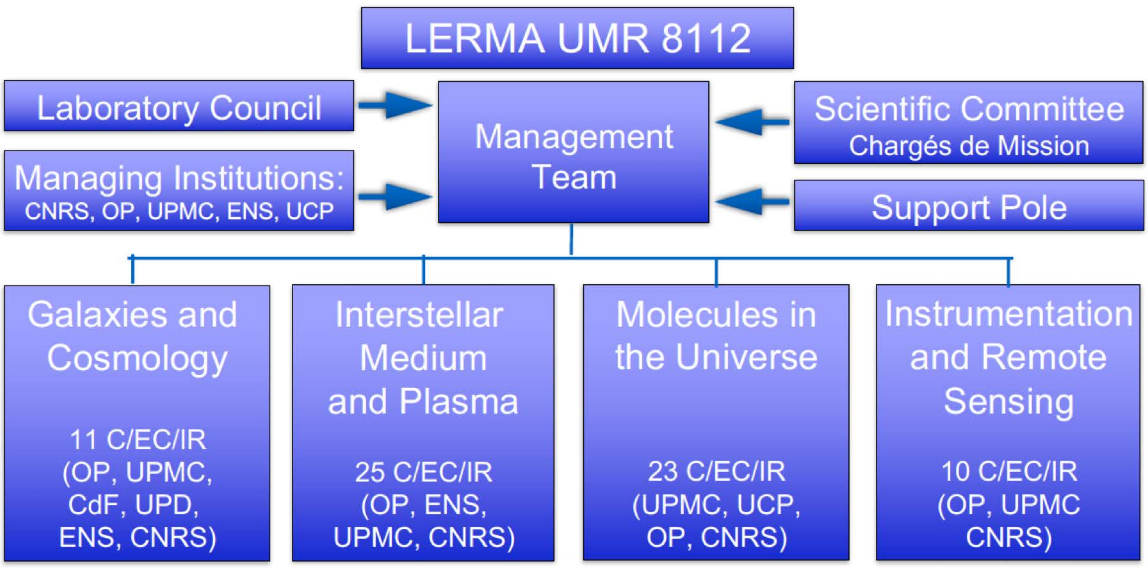


Figure 1: *Simplified LERMA organizational chart. The number of permanent researchers and research engineers is listed for each pole. Repartition of the staff per employer is shown in Fig 2.*

A heritage from these historical developments is the implantation of the laboratory within 5 academic institutions in Paris: *Observatoire de Paris* (OP), *École normale supérieure* (ENS), *Université Pierre et Marie Curie* (UPMC; soon to become *Sorbonne Université*) and *Université Paris Diderot* (UPD), both heirs of the original *Sorbonne*, as well as *Université de Cergy-Pontoise* (UCP). The resulting geographic dispersion of the research teams throughout the Paris area (Fig. 1) clearly influences the laboratory life. However, the scientific advantages much outweigh the organizational drawbacks. In this context, the move of one of the UPMC teams from Ivry to the main Jussieu campus in 2014 was a positive development, enabling much closer interactions with other UPMC laboratories.

Staff and resources

As of June 30, 2017, LERMA has a total staff of 157, including 60 permanent researchers (including 12 emeriti), 34 permanent engineers and technicians, 40 PhD students, and 8 postdocs. Most of the staff is hosted at the 2 sites of the Paris Observatory, 44% at Denfert-Rochereau, and 13% in Meudon. Following the arrival of LPMAA in 2014, Jussieu is now the second largest LERMA site, with 24% of the staff. The remaining staff is hosted at ENS (10%) and Cergy-Pontoise (8%). Two permanent staff members have long-term assignments at IRAM in Grenoble and C2N (formerly LPN) in Marcoussis.

The number of permanent staff has remained stable since the beginning of the current contract, as the laboratory has been able to keep up with retirements and other departures of permanent researchers and engineers, both through new recruitments and accretion of new teams. Projecting into the future,

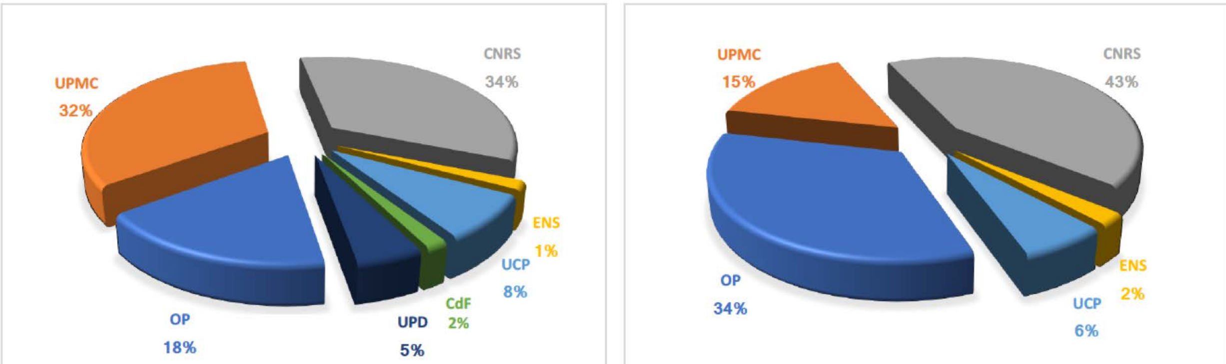


Figure 2: *LERMA staff (permanent and contracts, excluding students and postdocs) per employer as of June 30, 2017. (Left) Researchers (62). (Right) ITA personnel (47).*

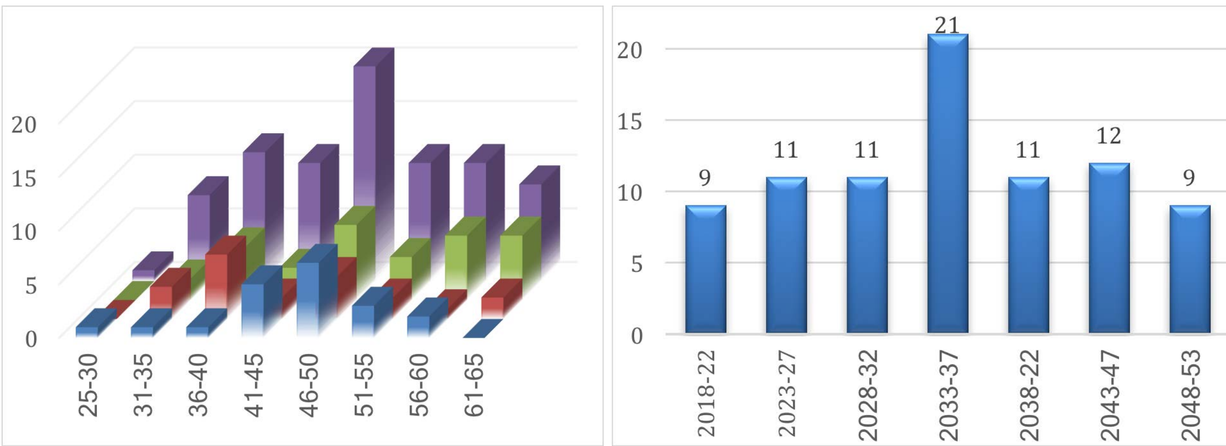
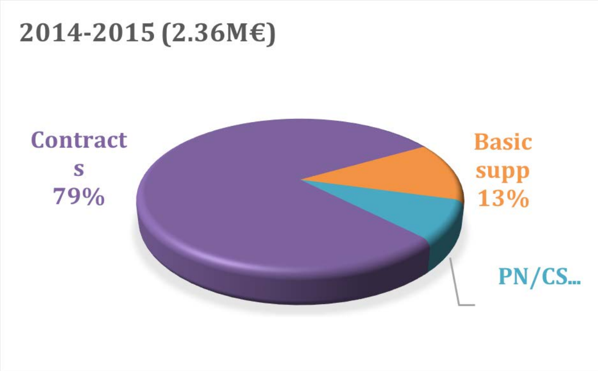


Figure 3: *(Left) LERMA age pyramid for permanent researchers and ITA staff (blue: Paris Observatory, red: UPMC, green: CNRS, plum: total). (Right) Expected number of future retirements.*



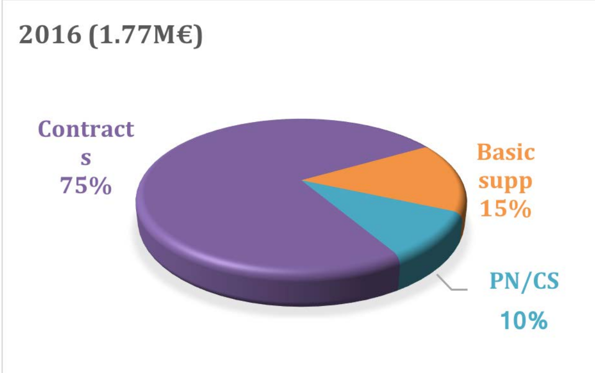


Figure 4: *LERMA consolidated budget for the 2014 – 2016 period. The budget is divided into external contracts (plum), basic support (orange), and National Programs/Scientific Councils (blue).*

a large number of CNRS researchers are approaching their retirement age (Fig. 3). On average, 2 retirements per year are expected into 2050s, with a peak of 4 retirements per year in the period 2033–2037. In the immediate future (2018–2022), LERMA will be faced with retirements of 5 senior researchers. Replacing them with new recruitments will clearly be a challenge in the current environment. We note that since the beginning of the current contract, the laboratory has averaged one new recruitment of a researcher per year (1 CNAP, 1 CNRS, 1 MdC UPMC, 1 Prof. ENS). The future of the *Galaxies and cosmology* pole was identified as a threat in the previous AERES report. This has now been addressed with the arrival in 2017 of 2 UPD faculty and the recent recruitment of one ENS professor. Many of the near-term retirements will affect the *Interstellar medium and plasmas* pole. In spite of 2 recent recruitments in 2014 and 2016, this pole faces additional challenges in the future, in particular for the experimental plasma activities. The molecular physics activities are in urgent need of engineering support to maintain the multiple experimental platforms, as well as reinforcement of its theory component in support of experiments, following recent and sudden departures of key leaders. In addition, a replacement of a key research engineer working on Schottky and superconductive devices (CNRS, FSEP departure in September 2016) has been communicated to INSU and the Paris Observatory as critical for maintaining the current activities of the *Instrumentation and remote sensing* pole.

The consolidated budget of the laboratory was 1.8M€ in 2016, as compared to 2.4M€ in 2014–2015 (Fig. 4). External contracts (ERC, ANR, ESA, CNES…) constitute 75–80% of the budget, the "basic support" provided by the managing institutions 13–15%, with the national programs and scientific councils providing the remaining 8–10%.

The decrease of the total budget in 2016 corresponds to the end of the ERC MOMENTUM. We note, however, that three new ANR programs have been funded at the end of 2016 – 2017, and a new ERC Advanced Grant MIST was awarded in 2017. The laboratory has thus been able to remain competitive in attracting external funding in the current difficult environment for fundamental research. Funding provided by the managing institutione, the various Labex (Plas@Par, Michem, ESEP, ILP…), the Idex PSL and Sorbonne

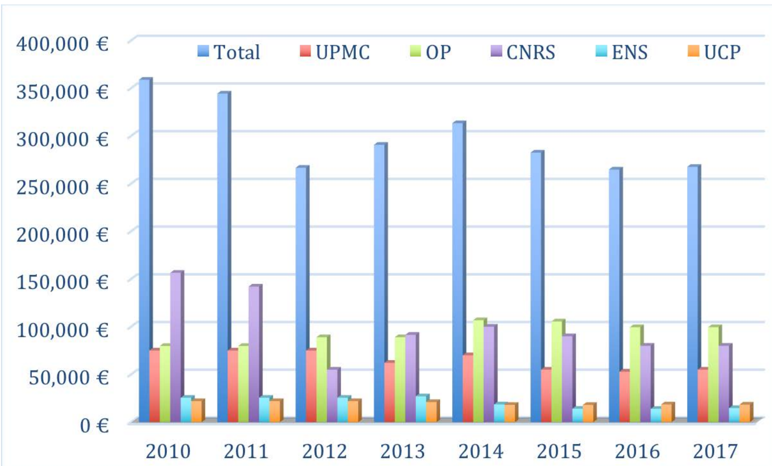


Figure 5: *Evolution of the annual basic support provided by the LERMA managing institutions during the period 2010 – 2017.*

Universités, Paris/Seine, as well as the *Île-de-France* Region (DIM-ACAV/DIM-ACAV^{+}) plays a very important role in supporting LERMA research and educational activities.

The "basic support" has decreased by 24% in 2016–2017, as compared to 2010–2011 (Fig. 5). The largest decrease has occurred for CNRS (–46%), ENS (–44%), and UPMC (–28%). The UCP contribution has remained relatively stable (–16%), while that of the Paris Observatory has increased by 25% following the enlargement of the laboratory in 2014, in particular the arrival of the ISM team from LUTh. Based on the work of the budget commission of the LERMA Laboratory council in 2014, we estimate that a global budget of 300k€ is necessary to maintain the current scientific activities. The 2016 – 2017 budget is about 11% below the required level. At the same time, the laboratory has grown considerably with the arrival of the UPD cosmology team at the beginning of 2017 and the recent arrivals at ENS.

Scientific policy

LERMA is an interdisciplinary laboratory that carries out research in key areas of modern astrophysics, physics, and Earth science (see Executive summary). To achieve scientific prominence in these fields, the laboratory has developed state-of-the-art expertise in observational techniques, modeling, computer simulations, and laboratory experiments. This combination has allowed LERMA researchers to lead ambitious observational programs using large ground-based and space facilities: *Herschel*, *Planck*, ALMA, NOEMA, VLT, CFHT… This will continue into the future with JWST, *Euclid*, JUICE, ELT, NenuFAR, SKA, MetOp-SG, and SWOT.

Through its research and instrumentation activities, LERMA has developed strong links with French and international universities and organizations, including IRAM, ESO, CNES, ESA, NASA/JPL, CEA, I2N, IPSL, etc. The LERMA VAMDC team (M.-L. Dubernet et al. 2016) has led the creation of the worldwide VAMDC e-infrastructure that inter-connects about 30 atomic and molecular databases, and of the VAMDC Consortium. The team is currently the leader of both the e-infrastructure and the consortium. New international collaborations are constantly being developed, for example in the framework of PSL (USA, China, Chile).

Partnerships and links with industry are actively sought. The current industrial partners include Alcatel/Thalés, EADS/Astrium, and RPG. Patent protection and transfer of the technologies developed for industrial application is pursued, when appropriate. A startup, Estellus, was created in 2009 as a spinoff of the R&D activities in the *Instrumentation and remote sensing* pole. The company, which provides atmospheric and environmental services and specializes in the treatment of satellite observations, was hosted by LERMA until 2016, providing in turn active scientific collaborations and funding for Ph.D. students.

As a direct contribution to the resolution of socio-economic problems in the area of Earth science and climate change, LERMA scientists play an important role in the preparation of operational meteorological satellite missions for daily weather forecasting, such as MetOp-SG. In addition, the FTS instrument in Jussieu, operating within the worldwide TCCON network, provides key measurements of the concentration of global warming gases in the atmosphere above Paris and is crucial in the validation chain of current and upcoming satellite missions such as MicroCarb and Merlin. The expertise in remote sensing at microwave to submillimeter wavelengths from multi-satellite observations is also contributing atmospheric and surface variables on global scale, used to evaluate or to feed climate models. These activities are organized within the group TASQ (*Télédétection Atmosphérique et Spectroscopie Quantitative*), part of the federation *Institute Pierre-Simon Laplace*.

Another LERMA contribution to the society at large are the close, long-term scientific collaborations with developing countries, in particular Vietnam (multiple collaborations with USTH involving members of the *Interstellar medium and plasma*s and *Instrumentation and remote sensing* poles) and Algeria (the VUV spectrograph group of the *Molecules in the universe* pole), involving regular exchanges of researchers, organization of conferences, or co-supervision of students.

LERMA scientists actively work for the benefit of the scientific community through research animation and education activities, including involvement in the French Academy of Sciences (F. Combes, chair of the Sciences of the universe section; P. Encrenaz), national programs, such as PCMI (J.-H. Fillion and J. Pety, directors), INSU (M. Gerin, déléguée scientifique and M. Perault, chargé de mission), Doctoral School ED127 (J. Le Bourlot, director), CNAP (F. Le Petit), CNU (S. Mei, vice-president of section 34), Labex Plas@Par (C. Stehlé, director). At the local level, LERMA has many elected members of the Scientific committees or Administrative/Department boards at the Paris Observatory, UPMC, and UPD. The researchers participate routinely in organization of international conferences, symposia and workshops, in particular IAU and EWASS, serve as members of peer-review panels and time allocation committees for major international astronomical facilities (e.g., IRAM, ALMA, SOFIA, ESO, HST…), or as experts for satellite mission advisory groups. More details are provided in Annex 4.

2. Research products and activities

Numerical data

The numerical data can be found in the worksheet "*5. Produits et activités de la recherche*" of the Excel spreadsheet "*Données du contrat en cours UR.xlsx*".

Selection of research products

During the review period January 1, 2012 – June 30, 2017, LERMA researchers have published 1050 refereed publications, or 190 publications per year. A selection of LERMA research products is presented in Annex 4. A full bibliography is available online:

- Pole *Galaxies and cosmology*: http://aramis.obspm.fr/~combes/pole1/pub.html
- Pole *Interstellar medium and plasmas*: https://lerma.obspm.fr/spip.php?article351
- Pole *Molecules in the universe*: https://lerma.obspm.fr/spip.php?article153
- Pole *Instrumentation and remote sensing*: https://lerma.obspm.fr/spip.php?article342

Recent significant results

In this section, we present a selection of recent scientific and technical highlights that show the broad scope of interdisciplinary activities carried out by the LERMA staff. More details are provided in Sections 6 – 9.

Planck Collaboration, including ***J.-M. Lamarre, A. Coulais,*** *2016, Planck 2015 results. XIII. Cosmological parameters.* — LERMA scientists have been closely involved in the ESA *Planck* mission, which has now released its full results on the temperature and polarization anisotropies of the cosmic microwave background (CMB) radiation. The main parameters support the Λ-CDM standard model of a flat universe, dominated by dark energy (70%) and dark matter (25%). The derived Hubble constant H_o is, however, too low compared to the astronomical measurements, and some discrepancies also exists for the amplitude of fluctuations, which might be solved by new physics. There is only a limit on the tensor-to-scalar ratio, meaning that no evidence has yet been found for the primordial gravitational waves, expected from the inflation theory.

Q. Salome, P. Salome, F. Combes, *S. Hamer, 2016, Atomic-to-molecular gas phase transition triggered by the radio jet in Centaurus A, A&A 595, A65.* — Understanding the formation of massive black holes and their influence on the surrounding medium is one of the key questions of modern astrophysics. Centaurus A, an active elliptical galaxy with radio jets, is one of the best examples of such AGN feedback in the nearby universe. The northern radio jet is impacting a neutral (HI) gas shell, coming from an earlier merger. Molecular gas was discovered and mapped with APEX close to this shell, corresponding to an ionized gas filament, where young stars are actively forming. Along the jet, the atomic HI gas is very efficiently transformed into molecular gas, explaining the positive AGN feedback, and the star formation triggering by shocks.

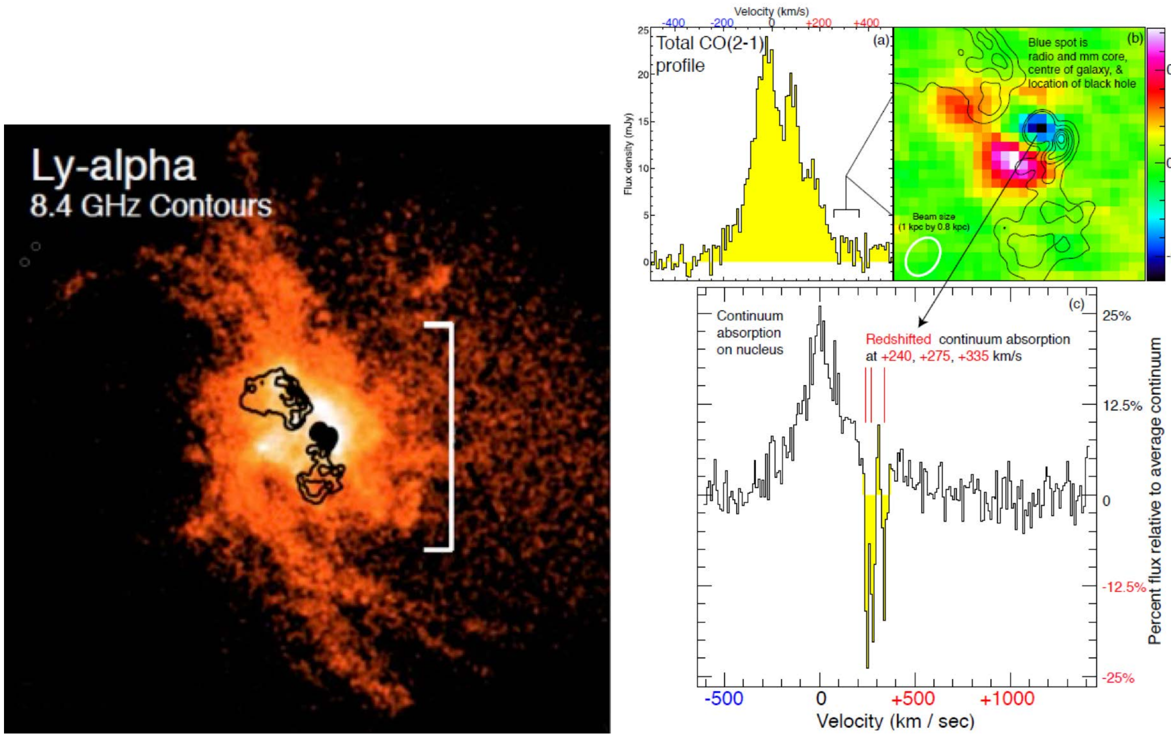


***Figure 6:** Molecular gas in the cool core cluster Abell 2597 (z=0.0821) mapped with ALMA. For the first time, molecular gas seen in absorption in front of the central AGN reveals an inflow of gas accreting onto the black hole (Tremblay et al. 2016).*

*G.R. Tremblay, J.B.R. Oonk, **F. Combes, P. Salome**, et al., 2016, Cold, clumpy accretion onto an active supermassive black hole, Nature 534, 218.* — In the center of rich clusters, hot X-ray gas can cool down in less than the Hubble time, giving rise to a cooling flow. The central AGN is moderating the flow, and radio jets can expel the gas, in an inflow/outflow cycle, which is still largely unknown, although fundamental for understanding galaxy evolution. For the first time, molecular line absorption has been detected by ALMA in front of the AGN in the center of a cool core cluster, showing only redshifted components, thus demonstrating clear gas inflow (Fig. 6).

New stochastic formalism to simulate H_2 surface chemistry. — Surface chemistry models neglect some fundamental processes, such as stochastic grain temperature fluctuations. Re-thinking how surface chemistry is commonly simulated, we have developed a new formalism based on a statistical approach to consider the impact of these stochastic processes on H_2 formation (**E. Bron** et al. 2014, 2016). With this approach, we have been able to explain the H_2 formation rate observed by ISO and *Spitzer* in bright PDRs and demonstrated that H_2 ortho/para conversion on grains is efficient. This result modifies the interpretation of observations of other molecular tracers in PDRs (such as high-J CO observed by *Herschel*), since the location of the formation of molecules depends on the H_2 formation rate. LERMA participates in the “tiger team” of the JWST ERS proposal that aims at studying PDRs. The numerical models provided will be used to interpret the observations of the international consortium.

*Planck Collaboration Int. XX (2015), led by **F. Levrier**,* has presented statistics of the polarization fraction and angle of the 353 GHz thermal Galactic dust emission observed by *Planck* in nearby regions, sampling both the diffuse interstellar medium (ISM) and dense molecular clouds (N_H column densities from 10^{20} to a few times 10^{22} cm^{-2}). The maximum polarization fraction decreases with increasing gas column density (Fig. 7), demonstrating the importance of the tangling of the magnetic field lines along the line of sight. Moreover, the polarization fraction is anti-correlated with the local dispersion of polarization angles. These observations are compared with simulations of anisotropic magnetohydrodynamical (MHD) turbulence (P. Hennebelle et al. 2008). The dispersion of polarization angles is found to be larger in the simulations than in the observations. The intrinsic dust polarization fraction may be recovered if the magnetic field is uniform and perpendicular to the line of sight, showing that the large-scale magnetic field orientation plays a major role in the quantitative analysis of polarization data.

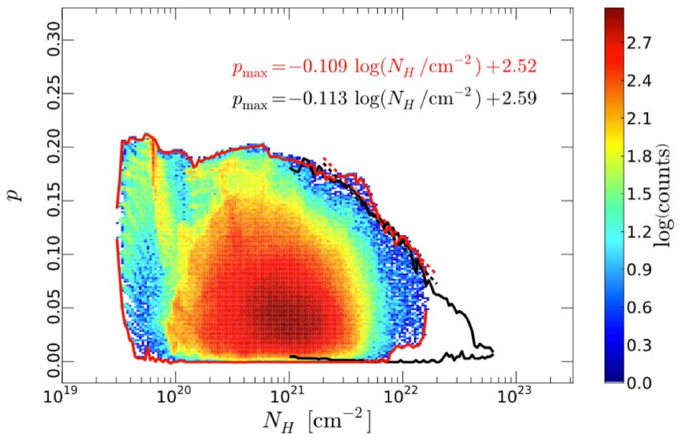


Figure 7: *Comparison between the distributions of the polarization fractions and column densities in the simulated observations (color scale, with upper and lower envelopes in solid red lines) and those of the observations (solid black lines). Dashed lines are linear fits on the distributions' upper envelopes.*

Magnetic fields in accretion-ejections phenomena in young stars (**A. Ciardi** et al.) — Magnetic fields mediate the extraction of the angular momentum from accreting matter and are central to the launching and collimation of jets. We have investigated the formation of disks and jets in the collapse of dense pre-stellar cores, showing that magnetic braking can be drastically reduced even within the ideal MHD framework. Jets and accretion flows were also investigated for the first time in scaled laboratory experiments carried out in a magnetized laser environment. The results support the scenario where the observed stationary X-rays in YSOs are produced in a re-collimation shock.

An empirical formula for quantitative chemical desorption. — In dark molecular clouds, a surprisingly high fraction of species is observed in the gas phase, even though accretion on grains should be a very efficient process. It is speculated that reactive desorption provides the necessary energy for molecules to return to the gas phase, thus possibly explaining the observations. So far, reliable data and approximations that could be used in astrochemical models were missing. Based on their experiments using the FORMOLISM setup, **M. Minissale** et al. (2016) have proposed a new empirical formula for reactive desorption on bare substances (amorphous silicates, oxidized graphite), which is in agreement with laboratory evidence and has been validated by modeling abundances of methanol, HO_2 and H_2O_2 in astrophysical environments such as ρ Oph A.

First direct measurements of photodesorption of methanol. — The molecular origin of the universe and life are tightly linked to molecular processes in grain ices and at the interface between the gas and solid phase, but the physicochemical parameters and processes that explain the observed abundances of many molecules are often unknown. In an experimental study with the SPICES instrument installed at the national synchrotron facility SOLEIL, the LERMA team has investigated in detail the process of UV

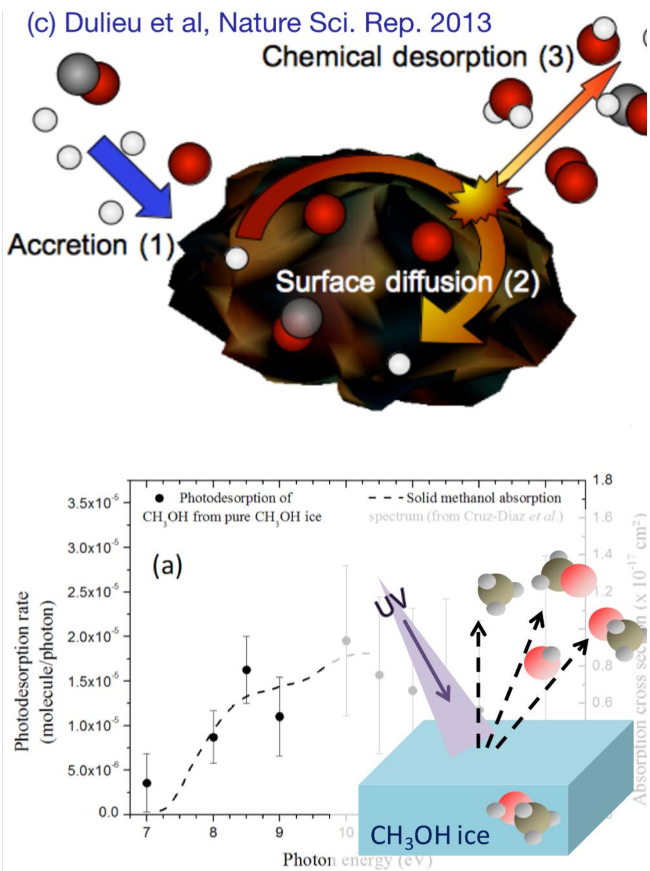


Figure 8: *(Top) Chemical desorption process. (Bottom) Direct measurements of the photodesorption of methanol.*

induced photodesorption of methanol, which is thought to be a starting point for the synthesis of more complex organics, ultimately leading to the formation of prebiotic molecules. These first direct experimental measurements of the wavelength dependent photodesorption rate of methanol ices have shown a surprisingly low (~100 times lower than usually assumed) rate of methanol desorption, but indicate that many radical fragments such as H_3CO are produced, which in turn can influence the gas-phase chemistry of complex organic molecules (**M. Bertin** et al. 2016).

New era for ground based mid-IR atmospheric remote sensing with the FTS-Paris instrument. — The Paris Fourier-Transform Spectrometer (FTS-Paris instrument) has been operated by LERMA on the Jussieu campus in the center of Paris since 2007. The high-resolution spectrometer regularly measures total column abundances and profiles of atmospheric pollutants and greenhouse gases above Paris (**Y. Te** et al. 2016) by absorption of solar radiation in the mid-IR. Constant improvement, development and automatization of the instrument have allowed to comply with the stringent requirements of the international greenhouse gas observation network TCCON (Total Column Carbon Observation Network), dedicated to the global study of the evolution of climate gases and the validation of Earth observing satellites, such as OCO-2/3, Merlin, and CarboSat. With the adherence of the FTS-Paris instrument to the network in 2014, the first French site started operation. The FTS-Paris is also the first European (and second worldwide) TCCON instrument situated in a mega-city. As such, it is predestined to study the emissions of large agglomerations and will thus play a central role in upcoming satellite mission dedicated to the study of emission of greenhouse gases.

Breakthrough developments in millimeter waves to THz electronics, for astronomy, planetary and Earth sciences. — After 10 years of efforts to develop from scratch a new process for the fabrication of millimeter to THz electronic circuits with gallium arsenide (GaAs) Schottky diodes, LERMA (**A. Maestrini, L. Gatilova** et al.) — in close partnership with the Center for Nanosciences and Nanotechnologies (C2N, Marcoucis; formerly Laboratory of Photonics and Nanostructures, LPN) — has developed the most sensitive Schottky mixer (detector) in the world in the 1080–1280 GHz band. This is a significant breakthrough that will directly benefit the Submillimeter Wave Instrument (SWI) on the planetary probe JUICE (JUpiter ICy moons Explorer), the first of the three large missions of the European Space Agency (ESA) *Cosmic Vision 2015-2025* program. In June of 2016, LERMA was officially instructed by the SWI consortium to provide the high-frequency channel of the instrument, covering the frequency range 1080–1280 GHz. This frequency band had been withdrawn from the SWI core option in 2013, following the withdrawal of the Jet Propulsion Laboratory (JPL), the only scientific institution in the world to own the technology necessary for its construction at the time. The technology of the Schottky diodes and mixers is also of key interest for the Earth science community, with the planned extension of the observations up to 700 GHz for the next generation of operational meteorological satellite, to be flown in 2020 (the Ice Cloud Imager on board MetOp-SG).

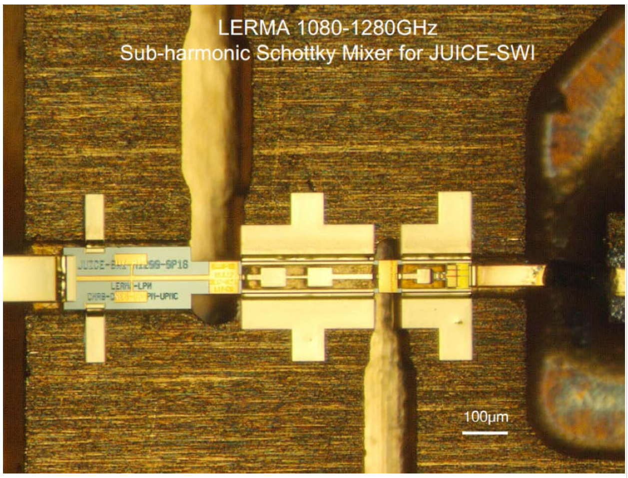


Figure 9: *The 1080–1280 GHz sub-harmonic mixer for JUICE/SWI.*

In addition to our participation in SWI, the LERMA SIS legacy mixers initially developed for band 1 of *Herschel*/HIFI are now used in the new 4GREAT instrument on SOFIA (commissioned in July of 2017; a collaboration with MPIfR Bonn), which significantly increases spectroscopic capabilities of this only FIR facility currently in operation.

Contributions to the preparation of the exploitation of the Ice Cloud Imager (ICI) on board MetOp-SG. — LERMA actively participates in the scientific exploitation of the future ICI satellite observations. With our expertise in both radiative transfer modeling and algorithm developments, an innovative retrieval scheme has been designed to estimate ice cloud parameters from the ICI observations, based on realistic cloud resolving model simulations (**D. Wang** et al., 2016). In parallel, parameterizations of sea and land surface emissivities have been established at ICI frequencies, for use in operational numerical weather prediction (NWP) centers, and it has been compared to corresponding aircraft radiometric observations (**C. Prigent** et al., 2016; **D. Wan**g et al., 2017). The codes have already been included in the community radiative transfer models and distributed to the international NWP community.

First database to map the extent and dynamics of wetlands, at high spatial resolution. — Surface waters are major component of the Earth water cycle and play an important role in the climate variability, as they are responsible for ~1/3 of the CH_4 emission, a greenhouse gas, 20 times more potent than CO_2. However, characterizing their distribution and dynamics across the Earth, from the tropics to high latitudes, is a real challenge given their diverse nature. By exploiting the synergy of a large number of satellite observations at different frequencies (visible, infrared, passive and active microwaves), we first derive an estimate of the water extent and monthly dynamics on a 25-km scale. Then, topography information from digital elevation models is carefully exploited to downscale the surface water information to 90 m. The Global Inundation Extent from Multi-Satellite Downscaled to 3 arcs (GIEMS-D3) (**F. Aires** et al., 2017) is already solicited by many communities concerned with continental hydrology, meteorology and climatology, as well as the socio-economic applications in the fields of water resource or disaster management. It is also of interest for preparation of the NASA/CNES satellite mission Surface Water and Ocean Topography (SWOT) that will revolutionize continental hydrology.

Instrumental platforms

In the past years, LERMA has developed multiple sophisticated and long-term experiments for plasma diagnostics, surface science, high-resolution atomic and molecular spectroscopy and air quality monitoring. LERMA is in charge of maintaining and developing this equipment providing original, often unique instrumentation for laboratory astrophysics in Europe and state-of-the art spectroscopic techniques for atmospheric/planetary applications.

Molecular physics and surface science at low temperatures. — The first ultra-high vacuum (UHV) chamber dedicated to heterogeneous chemistry at very low temperatures for the interstellar medium (FORMOLISM) was developed at Cergy-Pontoise in the 2000’s and has been followed by a second state-of-the-art experiment (VENUS), enabling multiple atomic/molecular beams (reactants) to impinge on the surface of interstellar dust analogs. These experiments provide one of the most sensitive and complete existing platforms for surface astrochemistry at very low temperatures (7–350 K). Another UHV chamber (SPICES), entirely mobile, has been developed in Jussieu since 2008 and upgraded in 2016 to perform experiments using either UV–X synchrotron irradiation or pump-probe experiments using 3 synchronized (ns) pulsed laser beams. This is a unique experiment providing wavelength-dependent information for the simulation of UV–X stellar radiation effects onto the surface of interstellar ice analogs (10–160 K). This entire experiment is transported to SOLEIL (DESIRS and SEXTANTS beamlines) once a year. In parallel, a high-resolution Fourier-Transform Spectrometer (FTS-CoSpiNu), operating since 2011, has been adapted to the study of nuclear-spin conversion at very low temperatures in cryogenic matrices (4–20 K). Optical pumping techniques and the preparation of enriched icy films for nuclear spin enrichment are under development.

High-resolution molecular spectroscopy. — LERMA is setting up an ultra-high precision IR spectrometer using a tunable quantum cascade laser at 10 μm, stabilized using a frequency comb at 1.542 μm (FCS-QCL). The repetition rate will be compared to a frequency standard provided by SYRTE via the REFIMEVE+ fiber network. This equipment allows precision spectroscopy for the study of molecular processes in planetary atmospheres and the solar system by providing fundamental spectroscopic data for isotope studies from space for a series of molecules, in particular for ozone and other oxygen containing species. Other instruments operated by the team are an interferometrically stabilized diode laser (MIS-DL), UV-VIS photometers, mass spectrometers that are employed as gas analyzers, and the 10-meter VUV spectrograph that is used for the study of electronic transitions and photodynamic processes of excited states of small molecules and radiative properties of heavy element ions. LERMA also currently develops an IR laser-based multi-isotope analyzer for CO_2.

Air quality and greenhouse gas station. — LERMA is operating several instruments and sensors (surface pressure, temperature, humidity, ozone and carbon monoxide) and a high spectral resolution Fourier-Transform Spectrometer coupled to a sun-tracker for continuous remote-sensing of atmospheric species (FTS-Paris, spectral range from 233 nm to 22 µm). In September 2014, the instrument has joined the Total Carbon Column Observing Network (TCCON) and has become the first such station in a European megacity. The data, widely used for satellite validation and atmospheric modelling, are provided on a regular basis and are available via the TCCON website (http://tccon.ornl.gov/). The equipment is also used for laboratory spectroscopy.

Plasmas Physics. — LERMA is involved in the definition and operation of experimental campaigns, addressing the physics of shock waves, and performed on large scale kJ laser installations in France and abroad (PALS, Orion). These experiments require the conception and realization of dedicated small-scale (mm^3) targets, which are assembled by the *Pole Instrumental* of the Paris Observatory and tested at LERMA. In parallel, LERMA defines visible diagnostics, which are then implemented in the facilities. LERMA also operates, in collaboration with LPP an electrical pulsed power device (~1 kA, ~1 kJ), which drives an electromagnetic coaxial plasma gun to create radiatively cooled shock waves over few microseconds.

3. Organization and life of the unit

Organization of the laboratory

Following intense discussions in preparation of the arrival of LPMAA and the ISM team of LUTh in 2014, LERMA was organized into 4 thematic research poles (Fig. 1), each directed by a coordinator, which all cross the geographic boundaries. This scientifically rather than geographically motivated structure has proven to work well in recent years and no reorganization is envisioned for the next 5-year period. The primary objective is to further reinforce the existing ties, collaborations, and synergies between the teams, and to develop new interdisciplinary activities.

The LERMA management team consists of the director, two deputy directors, technical director, and two administrators responsible for the financial and HR aspects. The directors are in regular contact, in person or via videoconference, as needed to support every-day activities of the laboratory. Decisions are taken collectively, although the final responsibility rests with the director. The technical director advises the director on all technical aspects, including external relations, allocation of resources to projects, animation of the technical staff (specific responsibilities have been defined by the Laboratory council). The current management team has expressed a desire to continue for a second term, subject to approval by the staff and administrative constraints.

The LERMA Laboratory council (*Conseil de laboratoire*) is composed of 11 elected and 8 nominated members, and is chaired by the director. Its responsibilities are defined in the LERMA internal regulations, in agreement with the bylaws of the Paris Observatory and CNRS. In particular, the council is consulted by the management on the repartition of the budget (basic support), organization of the laboratory, as well as health and safety issues, and routinely informed of other relevant aspects, such as recruitment priorities. The council approves yearly a list of personnel, including long-term visitors, and can create commissions, as deemed necessary. The commissions created since the start of the current contract include: Budget commission, Visitor commission, Commission for the organization of the laboratory, and Commission for the internal regulations. The council meets on average 4 times a year. The meeting agendas and minutes are widely disseminated.

Four "chargés de mission" have been appointed by the Laboratory council to oversee specific aspects related to the Scientific prospective, Communication, Seminars, Education (follow-up of Ph.D. students), and Observation services. The new "chargé de mission" for education, first appointed in 2015, introduced a system of "sponsors" for Ph.D. students to help monitor the progress of their theses, and identify early potential problems. The system was recently expanded to a monitoring committee, including a sponsor and a scientific member, to comply with the new national laws passed in 2016.

The new LERMA internal regulations were approved by the Laboratory council and the Paris Observatory Executive Board in 2016, and are awaiting signatures of other LERMA managing institutions.

The LERMA Scientific committee is composed of the 4 pole coordinators and the management team. The role of the committee is to advise the management on all aspects related to the scientific orientations of the laboratory, to monitor and support the ongoing research activities to meet the needs of the teams, taking into account the current national and international landscape. In particular, the committee has been closely involved in the preparation of the current 5-year project. The committee meets on average 4 times a year.

A general assembly is organized once a year, in January, followed by the traditional *Galette des rois*, to inform the staff of any changes in scientific priorities, recent developments concerning the budget, human resources, etc. The 2017 general assembly was devoted, in particular, to the discussion of the HCERES evaluation and the next 5-year project of the laboratory.

To encourage interaction between teams, the main LERMA seminar is organized on Fridays at the Denfert-Rochereau site, with financial support of the laboratory. Additional, smaller seminars are organized frequently on other sites. Regular meetings of scientific poles are also organized routinely. The *Molecules in the universe* and *Interstellar medium and plasmas* poles in particular often have joint meetings, rotating among different sites, to facilitate scientific interactions (e.g., *Complex organic molecules in space*, http://laboratoires.u-cergy.fr/~lerma/COMSpace/programme.html, Cergy, February 9, 2017). Student days are also organized, typically before the summer vacation, to present to the laboratory the broad range of student research projects and give students an opportunity to sharpen their presentation skills.

Administrative and IT support

The LERMA administrative team has consisted of two administrators, and 5 administrative assistants, who are responsible for external relations, personnel, budget, and contract management. There is an administrative assistant assigned to each site, although there is currently no on-site administrative support at ENS and Cergy. This is a source of difficulties in day-to-day support of the teams hosted there. A shared administrative support with other laboratories hosted at these sites is a desirable solution, currently under discussion with the two administrations, as hiring of 2 additional administrative assistants does not seem a viable solution.

The administrative team is currently in a transition phase, following the departure of the financial administrator (IE CNRS, NOEMI; April 2017 departure, with a replacement arriving in October 2017). In addition, one of the administrative assistants has recently accepted a position outside of Paris, for personal reasons, another administrative assistant has been on a long-term medical leave and another one will retire in 2018. Consequently, the whole administrative team will have to be reorganized. INSU and the Paris Observatory are well aware of the current situation and are working with the management to find a satisfactory solution.

The LERMA IT team provides support to individual users, as well as management of shared resources, some of which, such as backup and storage servers, have been financed by the laboratory.

The team is coordinated by a research engineer (20% FTE) and consists of an engineer (currently on a temporary contract, with a permanent recruitment expected in October 2017) and an assistant engineer, who provide IT support for the sites of Denfert-Rochereau, Meudon, and Jussieu. IT support for the site of Cergy is provided by an engineer hosted on that site, while support for the LERMA ENS team is provided by the ENS Physics Department. A ticket system is in place to coordinate the activities. The team has been recently reorganized following 2 departures in 2015 (retirement) and 2016 (transfer).

Office space

LERMA offices and laboratories at UPMC, ENS, and Cergy have recently been renovated. Some of the offices on the two campuses of the Paris Observatory have also been recently refurbished, although additional work is still required. Since 2014, the laboratory has been using a small fraction of its basic support to help with office renovations. In particular, to facilitate interactions between teams, a new common room has been created on the 8th floor of Building A at Denfert-Rochereau, as well as a visitor office that can be made available to the staff from other sites.

Health and safety

The laboratory is in full compliance with all health and safety requirements imposed by the managing institutions. A safety officer is assigned to each site. Information on all safety-related aspects, including psychological risks and sexual harassments, as well as information regarding training opportunities offered to the staff are widely disseminated on regular basis. Work safety is of paramount importance, given the multiple experimental setups of the laboratory, and the safety and security budget has been increased in 2017.

A day of "newcomers" is organized each Fall, at the beginning of the school year to inform the incoming students and staff about all the relevant policies and procedures.

Diversity

As of June 30, 2017, the percentage of women at LERMA is: 29% for permanent researchers/university faculty, 40% for permanent engineers and technicians, and 35% for contract personnel. During the course of the current contract, women accounted for 35% of Ph.D. students and 20% of postdocs. The recruitment of researchers and technical staff is carried out by externally appointed committees and the laboratory involvement in the selection process is limited to presenting its scientific objectives and specific needs. However, we note that women constitute 40% of the appointed members of the Laboratory council, 50% of the pole coordinators (the fraction was 75% in 2014–2016), and 60% of the "chargés de mission".

Protection and security

Aspects related to the protection of the intellectual property are handled by the legal services of the managing institutions. In particular, all contracts and memoranda of understanding are carefully reviewed before signing.

A restricted zone (ZRR) has been in place at LPMAA in Jussieu, for historical reason. LERMA is in compliance with all the requirements regarding this existing ZRR. The laboratory was reviewed by the PPST subcommittee in 2015 to identify any sensitive scientific activities. None of the activities of the former LPMAA were identified as requiring protection and we expect the existing ZRR to be eliminated. However, the subcommittee has concluded that some of the LERMA instrumentation and plasma activities may fall in the protected category. A discussion between the administration of the Paris Observatory and the Ministry regarding the implementation of the recommendations of the subcommittee is ongoing.

Aspects related to scientific integrity have been discussed by the Laboratory council. No specific problems have been identified to date, and any problems that may arise in the future will be considered by the Council on individual basis. In addition, a new representative for scientific integrity has been recently appointed by the president of the Paris Observatory. We note that most of the astronomical data used in LERMA publications are obtained using international facilities, and are publically available at the end of the proprietary period (typically one year). The analysis can thus be easily repeated and results verified. Many of the numerical models used are also publically disseminated.

The computer network is regularly monitored for suspicious activity by the host institutions, as well as the LERMA IT support team. The intranet is protected and not accessible from the outside. Information about newly-identified computer security threats is widely disseminated.

4. SWOT analysis

LERMA has evolved into a modern research laboratory with demonstrated scientific and technical leadership in many key areas of astrophysics, physics, and Earth science. The unique aspect and the strength of the laboratory is its multidisciplinary approach, including observations, theory, computer simulations, and laboratory experiments. Our combined expertise in laboratory astrophysics, computer simulations and modeling, and instrumentation enables leadership of ambitious observational programs using state-of-the-art international space and ground-based facilities. The astrophysical observations, in turn, stimulate new laboratory, theoretical, and technical activities.

➔ **Strengths:**

- Established scientific leadership in key areas of modern astrophysics, physics, and Earth science:
  - Baryonic processes in galaxy formation, fueling and feedback of black holes, nature of dark matter and dark energy, inflation models;
  - Coupling of the chemistry, radiative transfer, and dynamics of the interstellar medium in regions of star and planet formation;
  - Laboratory astrophysics: numerical simulations and laboratory experiments involving molecular physics, plasmas, and ultra-high-resolution laboratory molecular spectroscopy;
  - Superconductive and Schottky devices for THz heterodyne spectroscopy with applications for astrophysics and Earth observations;
  - Development of innovative methodologies to produce climate series of key Earth variables from multi-satellite observations.
- Tight confrontation between theory, numerical simulations, observations and laboratory experiments, providing opportunities to lead ambitious international observing programs.
- Interdisciplinary — strong connections with theoretical and experimental physics and chemistry, environmental science, and applied mathematics are an invaluable asset that we continue reinforcing.
- Thanks to its scientific attractiveness, LERMA has been able to maintain its position at the national and international stage through accretion of new teams (LPMAA, LUTh-ISM, UPD-Cosmology).
- Strong involvement in large present and future international projects:
  - Space: *Herschel*, *Planck*, *Euclid*, JUICE, MetOp-SG, SWOT (NASA/CNES Surface Water Ocean Topography);
  - Ground: ALMA, NOEMA, VLT, CHFT, ELT, SKA, SOLEIL, LMJ, TCCON.
- Strong university presence (UPMC, ENS, UCP, UPD) providing access to complementary resources, faculty positions, and high-quality students.
- Good working conditions, with newly renovated offices and laboratories at UPMC, ENS, UCP, and OP Meudon.

➔ **Weaknesses:**

- Geographical dispersion limits interaction between teams — Corrective measures include a new interaction room and visitor office in Paris, as well as regular meetings rotating among different sites. The move of the Ivry team to the Jussieu campus in 2014 was a positive development. The accretion of the UPD cosmology team, hosted by the Paris Observatory, does not increase geographical complexity.
- Recent and future departures of key personnel:
  - Administrative team in the process of restructuring, additional reinforcement needed;
  - *Instrumentation and remote sensing* pole in need of reinforcement following a recent departure of a key engineer — important for LERMA implication in future CNES and ESA missions.
  - Molecular physics group has lost a key theorist in molecular modelling — continuation of activity is at risk.
- Additional teams and activities are in clear need of stabilization or reinforcement:
  - Significant staff reduction at UCP;
  - Experimental plasma activities at UPMC;
  - Theoretical activities in ISM modeling;
  - Engineering support for experimental platforms at UPMC;
  - IT support for data analysis/big data and HP computations.
- Increasing difficulty in financing ongoing maintenance of the eight medium-size laboratory experiments (~10k€ per year per experiment).

➔ **Opportunities:**

- The widely-recognized LERMA expertise in laboratory astrophysics and numerical simulations and modeling puts the laboratory in excellent position to take advantage of the observational opportunities (at the PI or Co-I level) provided by the current and future large ground-based and space observatories: ALMA, NOEMA, JWST, *Euclid*, SKA, MetOp-SG.
- Access to collaborations and funding through the LERMA managing institutions, the Idex *PSL* and *Sorbonne Universités*, as well as the regional programs provides opportunities for developing new interdisciplinary projects:
  - Scientific Council of the Paris Observatory (federative actions and “white programs”);
  - Program “*PSL fellowships in Astrophysics at Paris Observatory*”;
  - Labex Plas@Par, MiChem, ILP, UnivEarthS, L-IPSL, ESEP;
  - PSL programs IRIS OCAV and SDDS;
  - Region *Île-de-France* programs: DIM-ACAV, DIM-ACAV+, QI2;
  - INSU National Programs: PCMI, PNCG, PNPS…;
  - CNRS PICS and Interdisciplinary Mission programs;
  - Initiative of excellence Paris/Seine and UCP Institute of Advanced Studies/MIR.
- Continuing support from the CNES and ESA for instrumental activities — development of THz instrumentation paving the way for the future FIR space projects.
- LERMA is well-positioned for participating in EU collaborative projects in laboratory astrophysics.
- Faculty recruitments at the LERMA managing institutions provide opportunities to reinforce the teams. For example, the new recruitment of the cosmology professor at ENS in the Fall of 2017 will further consolidate LERMA position in this important field.

➔ **Threats:**

- Difficulty in recruiting young researchers — the number of available CNRS, CNAP and university positions is insufficient to compensate for the foreseen departures:
  - To stay at the forefront of scientific activities (development of large computer codes, laboratory experiments, …) requires a critical mass. If the size of some teams is further reduced, some historically important activities may disappear.

- Poor advancement prospects for the university faculty, which may potentially lead to departures of bright young scientists in search of more attractive offers in France or abroad.
    - A particularly low MdC/Prof. ratio at UPMC compared to the UFR of Physics — only 2 Prof. positions compared to 14 MdC positions;
    - Several strong young candidates for promotions at UPMC, ENS, and UPD;
- Undefined future of the FIR space astrophysics:
    - A number of new space projects is under discussion (NASA OST, RAS *Millimetron*…) and LERMA is closely involved in their preparation;
    - Building the international FIR community through symposia and workshops (e.g., EWASS 2016, 2017).
- Uncertain future of PSL and the various Labex, from which LERMA has strongly benefitted in recent years (Plas@Par, MiChem, L-IPSL, ILP, ESEP).
- Increasing difficulty in obtaining ANR funding for *basic research* in astrophysics and physics.

5. Scientific project

Detailed research programs of the four LERMA poles are presented in Sections 6–9 below. Here we concentrate on the position of the laboratory at national and international levels. We also describe multidisciplinary programs, which involve multiple research poles, including observation services, education and outreach activities.

LERMA in the national and international context

LERMA research is very well aligned with the national and international scientific priorities for the next decade. LERMA researchers work on answering key science questions of the *ESA Cosmic Vision 2015–2025* and *Astronet Science Vision Update "2015–2025 – The Next Decade":* What are the conditions for planet formation and the emergence of life? What are the fundamental physical laws of the Universe? How did the Universe originate and what is it made of? Do we understand the extremes of the Universe? How do galaxies form and evolve? What is the origin and fate of stars and planetary systems?

The *National Research Strategy "France Europe 2020"* has identified *European space ambition* as one of the 10 great challenges for the society in the XXI century. The two specific research orientations, to which LERMA researchers strongly contribute are the *Earth observation services* and the *Technology for observation and exploitation of the universe*. In addition, the laboratory is strongly involved in activities related to two action programs: *Big Data* (with applications to astrophysics and Earth observations) and *Earth system: observations, forecasting, adaptation*.

Many of the LERMA research themes are prominently featured in the *INSU Prospective "Astronomie - Astrophysique 2015–2020"*. LERMA actively participates in the activities of many national programs, such as PCMI, PNCG, PNP, PNPS, PNTS, LEFE, ASA, SKA-LOFAR, research programs of the *Île-de-France Region:* DIM-ACAV/DIM-ACAV+ (*Astrophysique et Conditions d'Apparition de la Vie*) and DIM-QI2 (*Qualité de l'air*), as well as the managing institutions (e.g., Scientific council of the Paris Observatory, PSL, Sorbonne Universités, Paris/Seine…).

In the course of the current project, LERMA has actively participated in activities of 8 Labex (Plas@Par, ESEP, MiChem, First TF, ENS-ICFP, ILP, L-IPSL, and UnivErthS) and 2 Equipex (REFIMEVE+ and MesoPSL). Various LERMA teams are currently involved in 7 EUR projects submitted in response to the latest PIA3 call in June of 2017.

Computer simulations and modeling

The LERMA expertize in numerical simulations and development of complex computer codes is well recognized at national and international level. The numerical codes developed at LERMA, such as the Meudon PDR code or the Paris-Durham shock code are de facto standards used by the community to interpret observations with world-class observatories, such as *Herschel*, ALMA, NOEMA, or in the future JWST. These codes are constantly updated and improved, with user input. A time dependent PDR code is currently under development, as are radiative shock codes. The physics of HII regions is also being implemented into the Meudon PDR code in preparation for GUSTO, a long-duration stratospheric balloon project recently approved by NASA for launch in 2021. LERMA participates scientifically in this exciting project, with the CNES support.

Dynamical numerical simulations are carried out to trace the galaxy formation and the history of mass assembly, using state-of-the art codes, tree-SPH, multi-phase including sticky particles, or Eulerian AMR code. The complex baryonic physics is modelled, and comparisons made while varying methods and physical parameters. In these simulations, the highest resolution is used to trace angular momentum transfer and resonances in idealized galaxies, while boundary conditions are obtained from cosmological large-scale simulations.

Direct coupling of MHD and chemistry is another unique aspect of LERMA research. These codes, initially developed for interpretation of the observations of the Galactic interstellar medium, are now being applied to study the role of turbulence and shocks in the chemistry of early Universe. Direct simulations of stellar interiors, including the effects of geometry, compressibility, rotation, and magnetic fields are also carried out. New 3D MHD and hybrid codes are being developed to understand the production and acceleration of cosmic rays in instabilities and shocks. A new 3D radiative transfer code is being developed to model the structure of accretion flows in young stars and to produce synthetic observations.

ANO activities (see below), numerical simulations, or data analysis rely on high-level technical support. LERMA software engineers (experts in application development, HPC, data analysis, management …) work in close collaboration with the scientists. They are in charge of the technical aspects of ANO services and only thanks to them these services are sustainable. For numerical simulations or data analysis, engineers are directly implied in key projects of the laboratory (development of radiative MHD codes, ALMA data management, remote sensing…). These are long-term activities (several years) and, contrary to IT support, engineers are assigned to projects in specific scientific poles. Change of projects and participation in parallel in smaller, but important projects of the laboratory, is done in coordination with the management, the coordinators of the projects and the LERMA Scientific committee. For example, the IT team in charge of BASECOL and VAMDC, within the *Molecules in the universe* pole now also participates, at a smaller level, in *Euclid* activities within *Galaxies and cosmology* pole. Another example, is a change of the pole assignment for a senior research engineer, whose long-term activities related to ALMA data management are ending and who is now affected in priority to the ANO3 ARC and actively participating in SKA-France. This type of flexibility is indispensable to optimally use the vast technical expertise and limited manpower to best support the multiple software projects of the laboratory.

With the increase of the observing data volumes, LERMA is developing new expertise in big data techniques, such as classical data analysis (e.g., classification, compression, model optimization) and machine learning (e.g., neural networks, deep learning). These methods, which can be applied to both astronomy and Earth remote sensing, with emphasis on data fusion to exploit multi-spectral synergies, bring LERMA research into the Big Data Era.

Laboratory astrophysics

The laboratory astrophysics activities have been strongly reinforced with the arrival of the LPMAA in 2014. One important aspect is the study of the evolution of atoms and molecules on cold surfaces of astrophysical interest, with the goal of understanding their reactivity, as well as related processes such as sticking, diffusion and desorption. Atomic and molecular beams are used, targeted on surfaces (graphite, silicates, ices...) cooled down to 6K, in order to mimic the extreme conditions present in star forming regions. Recent work includes studies of the molecular synthesis of water, nitrogen oxides, and carbon dioxide, diffusion and desorption of oxygen, chemical and thermal desorption, as well as water ice morphology.

Another important aspect is the determination of the intrinsic properties of interstellar molecules, such as the nuclear spin state, which may be linked to the thermal history of these species. Majority of the complex molecules forms or condenses onto dust grains, forming ice mantles that constitute the main molecular reservoir. Sublimation of these ices continuously enriches the gas phase, influencing the intrinsic properties of the gaseous species. Desorption phenomena and exchanges between gas and solid phases are thus key steps that need to be understood to interpret the observations of cold regions of the interstellar medium.

On the theoretical side, information on the physical conditions and chemical abundances in astrophysical environments can be deduced from observations through detailed modeling of the observed line intensities and shapes of velocity-resolved atomic and molecular spectral lines. However, in order to retrieve quantitative information, it is mandatory to understand with precision the main excitation mechanisms that distribute the populations among the quantum states of atoms and molecules, namely, the radiative transfer and inelastic collisions with the main colliders, such as H, H_2, electrons, or H_2O in cometary atmospheres. In addition, the confrontation of the inferred molecular abundances with predictions of chemical models based on reaction networks serves to trace back the evolution of matter in the observed media. In that case, detailed information on a wealth of chemical and photo-induced reactions taking place in the gas phase and on dust grains is necessary to properly describe the mechanisms of molecular synthesis in astrophysical environments.

Instrumentation

The experience gained through the development of the *Herschel*/HIFI instrumentation has paved way for the present LERMA involvement in JUICE/SWI. The LERMA HIFI Band 1 legacy mixers now fly in the new 4GREAT instrument on SOFIA, successfully commissioned in July of 2017 during a series of flights from Christchurch, New Zealand (a collaboration with the MPIfR in Bonn), which will provide outstanding capabilities for studies of isotopic ratios (D/H) in cometary water. A number of future FIR space missions are currently under discussion. NASA is currently studying 4 possible flagship missions for the next decade, in preparation of the 2020 US Decadal Survey. One of the missions under study is a FIR observatory, the *Origins Space Telescope* (OST). LERMA is leading a study of a European heterodyne instrument for this facility and would be well positioned to lead the construction of such an instrument, should OST be selected by NASA. A MoU with the Lebedev Physical Institute of the Russian Academy of Sciences was signed to collaborate on the development of THz heterodyne techniques for *Millimetron*. A discussion with the Purple Mountain Observatory on a possible LERMA participation in constructing a heterodyne instrument to be flown on the Chinese space station is also under way. The technological developments in Schottky receivers will also benefit the Earth observation community, with the recent interest of the weather forecast centers for measurements in the millimeter and sub-millimeter range from satellites (MetOp-SG).

Observational projects using international research facilities

The combined expertise in laboratory astrophysics, computer simulations, modeling, and instrumentation allows LERMA scientists to lead or participate in ambitious research programs with large space and ground-based astronomical facilities. The laboratory has been closely involved in the *Herschel* and *Planck* missions. Although these missions have now ended, their scientific exploitation continues. In the case of *Herschel*, a large fraction of the spectroscopic data has not yet been published and is easily accessible through the ESA archives. Ongoing analysis of these observations continues to stimulate follow-up studies using new ground-based facilities, such as ALMA and NOEMA, or the SOFIA stratospheric observatory.

JWST will be launched in 2018, providing unmatched spectroscopic capabilities in the mid-infrared wavelength range, thus allowing detailed studies of the composition of interstellar and solar system ices. These observations will be complementary to the earlier *Herschel* observations of the gas-phase species, providing a more complete view of the chemical complexity of the interstellar medium and solar system objects, such as comets. Laboratory studies of the interstellar and cometary ice analogues are needed for interpretation of these new observations, and so are improved theoretical models of the coupled gas-phase and grain surface chemistry. LERMA excels in these fields.

With LERMA leadership, a new federative action *"Astrochemistry: From the Solar System to High-Redshift Universe"* is being created by the Scientific council of the Paris Observatory. It will provide seed funding to further strengthen synergies with other departments and outside groups in this important field.

Euclid is the M2 ESA mission designed to map the geometry of the dark Universe that will be launched in 2020. *Euclid* will observe billions of galaxies, with spectroscopic and radio follow-ups. LERMA is closely involved in scientific preparation of this mission through its participation in the *Euclid* consortium Science Working Groups on galaxy clusters and proto-clusters, their detection tools, the determination of the mass functions, and the classification of galaxies in order to follow their formation and evolution.

The Square Kilometer Array (SKA) construction is scheduled to begin in 2018. When completed, SKA will revolutionize observations at radio wavelengths. LERMA simulations of the 21 cm HI emission from the Epoch of Reionization predict which types of structures will be detectable with SKA. LERMA members actively participate in the SKA Science Working Groups and the SKA-France coordination. Observations of the HI signal redshifted into metric waves are now being performed with LOFAR (and soon with NenuFAR).

For Earth remote sensing, LERMA is actively participating in the preparation of the Ice Cloud Imager (ICI) to fly on the next generation European meteorological satellite MetOP-SG. Using this instrument, observations in the 200 – 700 GHz range will be used for the first time for characterization of the ice clouds. We are also involved in the preparation of the CNES/NASA mission SWOT, that will revolutionize the hydrology from space, with accurate measurements of surface water volumes and river discharges, on the global scale.

The LERMA plasmas group in Jussieu actively takes advantage of the new capabilities offered by the large-scale international laser infrastructures, such as Orion (UK) and LULI (France). LERMA is a member of the *Institut Laser Plasmas* and has been strongly involved in the preparation of the scientific case of the LMJ (Laser Mega Joule at CEA) for laboratory astrophysics. This upgraded installation, as well as the fully operational NIF (National Ignition Facility at Lawrence Livermore) and Z Pulsed Power Facility (Sandia) in the USA open exciting new opportunities for the team.

The smooth transitions between large instrumental projects and observational facilities used by LERMA researchers show that the laboratory responds very well to the constant changes in the research environment and can evolve, as needed, to stay at the forefront in the four respective research fields.

Observation services (ANO)

LERMA is in charge of three *Services Nationaux d'Observations*: the ANO5 BASECOL, F-VAMDC, and *Plateforme MIS & Jets*. It also participates in the ANO3 ALMA Regional Center and the ANO2 JUICE. The ANO5 activities are carried out in the context of the *Centre Régional d'Expertise* PADC (Paris Astronomical Data Center) of the Paris Observatory.

ANO5 – BASECOL — The BASECOL database is a compilation of collisional ro-vibrational excitation rate coefficients of molecules by colliders such as atoms, ions, molecules, or electrons. Such collisional rate coefficients are essential for the interpretation of spectra measured by millimeter and sub-millimeter instruments (ALMA, NOEMA, *Herschel* for example) from non-LTE astrophysical media (ISM and cometary atmospheres). The database is scientifically supervised by a molecular physicist (astronomer) and maintained/upgraded by several engineers at different levels of technicity (design, new developments, maintenance). The database is currently being totally updated in its internal structure, in the way data are ingested (thus allowing better quality checks), in its graphical user interface, and in its access through the Virtual Atomic and Molecular Data Center (VAMDC). The SPECTCOL tool connected to BASECOL and VAMDC, which matches collisional rate coefficients with spectroscopic data from CDMS/JPL/HITRAN databases to provide ready to use datasets for astronomers, will also be updated in the next few years.

ANO5 – F-VAMDC — F-VAMDC is the activity linked to the Paris Observatory VAMDC team within the VAMDC Consortium. This involves the scientific and technical coordination of the VAMDC Consortium and the maintenance and evolution of key components of the VAMDC e-infrastructure that inter-connects about 30 databases that are aimed at exposing atomic and molecular data mostly for astrophysics (planets, ISM, stars, comets, plasmas). The activity is handled scientifically and technically by the same team as BASECOL at LERMA. The F-VAMDC activities are fully imbedded in the Research Data Alliance (RDA) activities, for example with the design/implementation of software in order to allow the automatic citation of data. In addition, the current F-VAMDC activities concern the connection to the IVOA standards. In the future F-VAMDC will support the extension of the VAMDC e-infrastructure to access more laboratory data for astrophysics. This will require a complete additional design based on ontologies.

ANO5 – ISM and Jets Platform — This ANO5 gathers a set of services that give access to reference numerical models for the preparation and the interpretation of observations of the galactic and extragalactic ISM. Indeed, a real scientific return of large telescopes (*Herschel*, ALMA, IRAM/NOEMA, JWST, …) is possible only if the community has access to state-of-the-art numerical models to interpret the observations. The service is mainly based on two public and well recognized codes developed and maintained at LERMA: the Meudon PDR code and the Paris-Durham shock code. The service includes access to source codes, with help to the users, as well as specific developments asked by the users. It also includes the development of the ISMDB infrastructure that gives access to large grids of pre-computed models with advanced search tools. The access to online versions of the codes is in development. Several tools are also developed to help users to analyze the output of the codes, for example a chemical network analysis tool. Main challenge for the future is the development of services able to manage large data sets, as the development of advanced data mining in the theoretical data and online services to interpret large data-cubes. This relies on Machine Learning and artificial intelligence technics.

These past years, this service has also been the main contributor to the definition of the international standards, at the IVOA level, for the diffusion of theoretical data in the Virtual Observatory with the publication of the Simulation Data Model, the Simulation Data Access Layer as well as to the definition of semantics for theoretical data.

ANO3 – ALMA Regional Center — IRAM is in charge of one of the ALMA Regional Centers. This activity is in fact managed at the national level between IRAM, OSUG (Grenoble), the Paris Observatory, and OASU (Bordeaux). Presently, the participation of LERMA focuses on the access to the data. The ALMA archive is very rich and the potential for a larger exploitation and new discoveries is thus very high. The project ARTEMIX (Alma RemoTE Mining eXperiment) developed at LERMA is a pilot study that aims at providing data mining tools via server/client web-services that will ease and speed up the data content browsing. ARTEMIX provides, a source distribution visual inspector and selection tool, a frequency / sky coverage visual tool for a given source and an on-line quick look viewer optimized for large data cube remote inspection. The first version of the project was presented at ADASS 2016 and a beta-version release is planned for autumn 2017 with partial, but robust functionalities. Mid-term perspectives: discussions have started with our US colleagues in order to eventually interface the ARTEMIX with ADMIT package (Alma Data Mining Toolkit, that was a development supported by ALMA/NROA). Automated signal search and statistics is a natural, but longer-term perspective of this project. Up to now, the technical developments rely on a contract software engineer and finding a sustainable solution will be a priority of the laboratory.

LERMA is also in charge of two *Pôles thématiques nationaux*. The goal of these structures is the coordination of several ANO5 at the national level. The first one, *Pôle de diffusion des données de* *physique atomique et moléculaire* aggregates all the ANO5 services related to atomic and molecular data of astrophysical interest. Apart LERMA services mentioned above, the pole covers the KIDA service (chemical reaction rate database). The second one, the *Pôle de diffusion des modèles de références pour la matière interstellaire* gathers the services included in the ANO5 *Plateforme MIS & Jets* as well as the ANO5 service DustEM (model of interstellar grain emission).

LERMA develops and maintains other services, such as several databases of atomic data and opacities, GalMer – a database of simulations of mergers of galaxies, and POMME – a database of observational data of galaxies. In the coming years, one goal of the laboratory will be to consolidate some of these services to obtain ANO labels.

Education and outreach


Science Fair at UPMC, 2016.

LERMA is strongly involved in teaching and outreach activities. Teaching activities are connected to the different universities and the Paris Observatory, and thus cover a wide range of degrees and fields. Beyond classical academic lectures, teachers are involved in formation cycles in astronomy for high-school and middle-school teachers, professional insertion modules and various innovative pedagogical tools (teaching by interdisciplinary projects, laboratory work projects on radio-telescopes or high-resolution spectrometers, tutorials, use of classroom response systems, experiments in classrooms…). In recent years, effort has also offered online teaching documents, videos and interactive exercises (WIMS…). LERMA faculty have management responsibilities in a number of doctoral schools, including ED127 (J. Le Bourlot, S. Mei) and Cergy (F. Dulieu). They are also involved in pedagogical activities at the M2 level, including *Astronomie, astrophysique et ingénierie spatiale* (F. Levrier), and in optics, *Lumière, matière, interactions* (J.-H. Fillion). Through its involvement in teaching, the laboratory gains access to high quality students.

> During the course of the current contract, LERMA has trained 78 PhD students, 40 postdocs, and 241 interns.

LERMA researchers routinely participate in Science Fairs and Festivals (e.g., the annual *Fête de la Science*), give interviews and write articles for the media, participate in interdisciplinary exchanges, and collaborate with cultural associations (e.g., art-science projects, organization of round tables in cultural scientific conferences…). They participate in the welcome week for university students and regularly give conferences in schools in France and abroad, participate in festivals for young public (e.g., festival d'astronomie de Fleurance, festival Astro-Jeune, http://www.festival-astronomie.com/, festival l'Espace d'un instant at Vaureal, http://espaceduninstant95.wixsite.com/festival/blank-4).

Involvement of LERMA members in outreach activities has been significantly strengthened in the context of the Labex Plas@PAR, with numerous events organized during the year: photo/video competitions, participation in summer schools or "prof en fac" days, creation of videos, training for future teachers to use plasmas in middle and high schools, organization of young researcher's day, organization of Plas@Par industrial days, workshosp and scientific meetings etc. (see http://www.plasapar.com/en/outreach and Annex 4 for more details.) The new outreach project *Inside Plasmas*, which combines plasma science with art, organized by LERMA, Plas@Par, and *Sorbonne Universités*, in collaboration with the *Centre national d'art et de culture Georges Pompidou,* is expected to attract 50,000 visitors in 2018.

PLAS@PAR
Plasmas à Paris

LERMA researchers and teachers are also involved in major outreach projects that are reaching an even larger public. Few other illustrations of activities are highlighted below.

Permanent exhibition at « La Maison du Soleil », Saint-Véran, Hautes Alpes, France (https://www.saintveran-astronomie.com/mds.html) — In June 2016, a permanent astronomical and chemical exhibition in Saint-Veran had been inaugurated by the Minister Thierry Mandon. The contribution of LERMA is the refurbishment, the lease and the installation of a very high spectral resolution visible spectrograph (R=1,000,000) for solar spectrums analysis. This is a long-term loan of LERMA and the Paris Observatory, as a contribution to the outreach of the scientific culture based on astronomy. LERMA designed and build an instrument, coupled to this spectrograph, to show for the first time, real-time observations of solar rotation, through the Doppler effect. This is possible if we can see, at the same time, the west and east limbs of the Sun. This could be achieved because of a long experience in spectroscopic use of optical fibers. The entire spectroscopic line has been integrated at LERMA and the technical staff has installed the coelostat and an imagery line for Sun spots display on a screen inside the building. This installation has welcomed thousands of visitors in less than one year.

Inflatable planetarium at UCP (http://ama09.u-cergy.fr) — In 2015, an inflatable planetarium has been funded by the "Foundation of the University of Cergy-Pontoise". We have developed a network of primary and secondary schools interested in this project. LERMA members, as well as master students (MEEF), bring it to the surroundings schools (more than 40 days of use during the first semester of 2017). This activity is always very welcomed by children and academic staff members.

Rosetta-MIRO and Cassini radar — The contribution of LERMA to the MIRO instrument on board of *Rosetta* has led to multiple communication events : articles, conferences/lectures in schools, video for *"Cité des sciences et de l'industrie"*, exhibition *"Rosetta et les comètes*" (Salon de l'air et de l'Espace du Bourget), conference at *"Académie des sciences"* (session *"La fantastique aventure de Rosetta sur la comète"* organized by P. Encrenaz and F. Combes), organization of colloquia *"Radar-Cassini"* and *"Surface de Titan*" in Paris.

Hands-On Universe — 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 of the development of the first network of small radiotelescopes conceived for education; 3-m dishes operating at 21cm have been installed in 5 different countries, including one at the LERMA site at the 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 include a simulator of observations based on professional data, as well as an archive gathering data acquired with the EU-HOUMW radio-telescope network.

The Astronomical Platform at UPMC — LERMA has initiated in 2010 the creation of an astronomical platform at UPMC dedicated to teaching and outreach activities. In 2015, pedagogical activities actually started on the platform on the roof of the Jussieu campus. These activities were in the form of observations using optical telescopes, within the framework of L3 astrophysics courses. An

outreach manifestation was also organized for the transit of Mercury in front of the Sun (May 9, 2016).

The platform is in the process of being upgraded in the framework of a project funded by *Sorbonne Universités* (FormInnov call). A dome will be installed with a more powerful telescope (35 cm) including a CDD camera, opening new pedagogical perspectives. A number of pedagogical projects will be developed using this new instrument both at the Licence and Master levels, reaching out also to computer science and engineering students. This FormInnov project involves ~10 academic staff members. The new dome and telescope will be installed during the 2017/2018 academic year. The pedagogical projects will be implemented from 2018 on.

6. Presentation of the pole "*Galaxies and cosmology*"

Introduction

The LERMA group specialized in the study of galaxies and cosmology currently consists of 10 permanent researchers, and 18 postdocs and Ph.D. students, who work both in the fields of observations and theory, and are experts in numerical simulations. Since the last AERES report, and starting in January 2017, we have accreted a new group including 2 permanent researchers (S. Mei and M. Huertas-Company), which has lowered the mean age of researchers, and recruited new postdocs, in continuity to those funded by the ERC Momentum in 2011–2015. An additional recruitment of a professor at ENS, arriving in the Fall of 2017 (N. Kaiser) will further reinforce the current research activities.

The strengths of the group are:

(1) Studies of the physical and baryonic processes: radiative transfer, formation of stars and feedback, fueling of black holes, in addition to the dynamics of dark matter;
(2) Very tight confrontation between theory, simulations and observations;
(3) Strong involvement in present and future large international space and ground-based projects: *Planck*, ALMA, NOEMA, *Euclid*, SKA...

Key science questions that the group is addressing are:

- Epoch of reionization: What are the main actors of the reionization (galaxies, quasars)? Can we predict the HI signal, which will be observed by NenuFAR and SKA, and use it to determine the properties of these actors?
- Galaxy Formation: Where are the baryons? How can we explain that 90% of them have left galaxies? Would this constrain the dark matter/dark energy models?
- AGN fueling and feedback: Why are supermassive black holes evolving in symbiosis with galaxies? Could AGN be the solution to expel baryons from galaxies? (Facilities: ALMA/NOEMA, VLT, JWST.)
- Large-scale structures (LSS) of the Universe: What is the role of environment in star formation quenching in galaxies? LSS as cosmology tracers. (Facilities: *Euclid*, SKA.)
- Star formation efficiency, history and stellar populations. (Facilities: CFHT-Sitelle, IRAM.)

Staff and resources

11 Permanent staff members (9 scientists and 2 engineers):

M. Caillat (IR), F. Combes (Prof.), A. Coulais (IR), M. Huertas-Company (MdC), J-M. Lamarre (Emeritus), S. Mei (Prof.), A-L. Melchior (MdC), P. Salomé (Astr.), N. Sanchez (Emeritus), B. Semelin (Prof.), D. Valls-Gabaud (DR-CNRS)

18 Non-permanent staff members (5 postdocs, 12 Ph.D. students, 1 CDD-IE):

S. Amodeo (PhD student), A. Audibert (PhD student), F. Bolgar (PhD student), V. Bonjean (PhD student), F. Caro (PhD student), G. Castignani (postdoc), I. Chaves (PhD student), J. Dassa-Terrier (PhD student), P. DiMauro (PhD student), H. Dominguez-Sanchez (postdoc), E. Eames (PhD student), L. Loria (CDD-IE), B. Mancillas (PhD student), G. Noirot (PhD student), C. Parroni (PhD student), M. Rodriguez (postdoc), H. Shimabukuro (postdoc), D. Tuccillo (postdoc)

Resources:

Observing Facilities: *Planck*, *Herschel* (until 2013; but archival data will continue to be actively exploited for many years to come), ALMA, NOEMA, VLT/MUSE, NenuFAR, JWST (launch in 2019), SKA, *Euclid* (launch in 2020), LSST (first light in 2019)

ANR: VACOUL (2011–2014), ORAGE (2014–2018), LYRICS (2017–2021), ASTROBRAIN (2018–2022)
ERC Advanced Grant: MOMENTUM (2011–2015)
LABEX: ILP, UnivEarthS
CNRS National Programs: PNCG, ASA, PCMI, SKA-LOFAR

Activity profile

The group activities and projects can be classified in 4 main themes:

(1) **Primordial Universe:** Cosmic Microwave Background (CMB) seen by *Planck*, sky surveys, inflation, Epoch of Reionization (EoR), preparation of SKA, NenuFAR (Semelin, Bolgar, Bonjean, Eames, Shimabukuro, Lamarre, Coulais, Sanchez, Combes)
(2) **Large-scale structures:** galaxy clusters, protoclusters, *Euclid* legacy science, galaxy mass assembly, mass-size relation, morphology (Mei, Huertas-Company, Amodeo, Caro, DiMauro, Dominguez-Sanchez, Noirot, Parroni, Tuccillo, Castignani, Combes)
(3) **Formation and evolution of galaxies:** high-redshift galaxies (ALMA, NOEMA), PHIBSS2 NOEMA legacy program (gas fraction, star formation efficiency), cool-core clusters (NOEMA, ALMA, MUSE), AGN feedback and molecular outflows (ALMA, NOEMA) (Salomé, Audibert, Castignani, Chaves-Bicalho, Mancillas, Rodriguez, Combes)
(4) **Nearby galaxies, resolved in stars:** star formation laws (Kennicutt-Schmidt scaling laws, star formation efficiency, HI, H_2 gas), CO-metallicity relation, CO-dark molecular gas (IRAM, CFHT-Sitelle), Low Surface Brightness (LSB) features in galaxies (Messier satellite proposed to the CNES) (Valls-Gabaud, Melchior, Chaves-Bicalho, Dassa-Terrier, Mancillas, Rodriguez, Combes)

Research products and activities

The group research within the various themes defined above results in highly-cited publications in refereed journals**: 360 refereed publications with 20,000 citations within the past 5 years.** These publications are listed in full on the web site, and selected 20% in the Annex 4. There is also a comparable number (~400) of conference proceedings. We have international collaborators all over the world, in Europe, America, Asia, Australia, and South Africa. The pole has high visibility, with members giving numerous invited talks at international conferences, teaching at international schools, participating in dozens of SOC per year, and organizing as chairs several conferences per year. We participate in particular in the EWASS (European Week of Astrophysics and Space Science) organization every year, as well as IAU symposia.

Members of the group have participated in time allocation committees (Herschel, IRAM, ALMA, HST, ESO...) and have frequently chaired panels. They have participated in the scientific prospective at national and European level (Astronet, CNES, INSU), and in grant selection (ANR, ERC).

The teaching and mentoring students is also intensive: among the 8 permanent researchers in activity, 6 have teaching positions. They organize *Hands on Universe* at the French and European level, and have built teaching platforms for students, including optical and radio-telescopes.

SWOT analysis

➔ **Strengths:**

- Recognized expertise in the study of the physical and baryonic processes: radiative transfer, formation of stars and feedback, fueling of black holes, formation and evolution of galaxies in the field and clusters, in addition to the dynamics of dark matter;
- Very tight confrontation between theory, simulations and observations;

- Strong involvement in present and future international facilities: *Herschel*, *Planck* HFI, ALMA, NOEMA, SKA, NenuFAR, JWST, *Euclid*;
- Study and constraints on dark matter, dark energy and inflation models;
- Formation through research: Hands on Universe – operation of 21 cm radio telescopes for students to study the Milky Way atomic gas.

➔ **Weaknesses:**

- The number of postdocs and students has decreased following the end of the ERC.
- The number of CNRS researchers (only one) is low.

➔ **Opportunities:**

- The pole has accreted a new team, composed of 2 permanent researchers, and 6 students/postdocs, strengthening its research power. A new cosmology professor at ENS has been recruited and is expected to arrive in the Fall of 2017.
- The pole has benefitted from 4 ANR during the current 5-year project (2014–18), plus an ERC Advanced Grant.
- Collaboration and funding opportunities provided by the Labex (ILP Institut Lagrange of Paris, UnivEarthS), Equipex (Genci), and Idex (PSL, Sorbonne Universités, Paris Cité).
- Chair at Collège de France provides additional research budget and a postdoc every year.

➔ **Threats:**

- Difficulty in recruiting young researchers (latest new recruitment in 2009).

Scientific project

The results of the ***Planck*** mission will continue to be exploited, with progress in the study of the **cosmic microwave background** (CMB) and its anisotropies, to test the theory of inflation. Our team works on inflationary potentials and their couplings, in order to predict the ratio between fluctuations of tensor and scalar types. *Planck* has also provided a survey of the entire sky at millimeter wavelengths, and a catalogue of sources at various redshifts. The Sunyaev-Zel'dovich (SZ) effect in clusters is used by our group, in combination with X-ray, optical, and radio observations, to study the evolution of clusters, and cosmic filaments.

Two LERMA teams study the **problem of dark matter**: the standard ΛCDM cold dark matter model cannot account for observations on the galactic scale (the core-cusp problem, missing satellites, etc.) The alternatives are studied theoretically and through simulations: hot or warm dark matter (classical or sterile neutrinos), modification of gravity. The comparison with observations will provide constraints on the various possible models.

A new team has recently joined the pole, working on **galaxy clusters and their evolution**, and the statistical view of the galaxy physics in large surveys. *Euclid*, which will be launched in 2020, will provide not only clues on the dark energy of the Universe and its time evolution, but also a huge amount of data on billions of galaxies in the legacy project, aided by ground-based spectroscopic follow-ups **(Figure 6.1)**. This will allow studies with unprecedented details of the influence, of the environment on galaxy morphology, mass-size relation, mass assembly and star formation efficiency. Members of the team are co-coordinators of Science Working Groups in the ***Euclid* consortium**, on galaxy clusters and proto-clusters, their detection tools, the determination of the mass functions, the classification of galaxies in order to follow their formation and evolution. For these tasks, deep learning reconstructions are used, as well as advanced artificial intelligence techniques, to prepare for the Big Data transition. Three projects are now funded (i) GAMOCLASS (PSL) on galaxy morphology, (ii) ASTROBRAIN (ANR) on galaxy evolution, and (iii) Google funding for deep learning techniques.

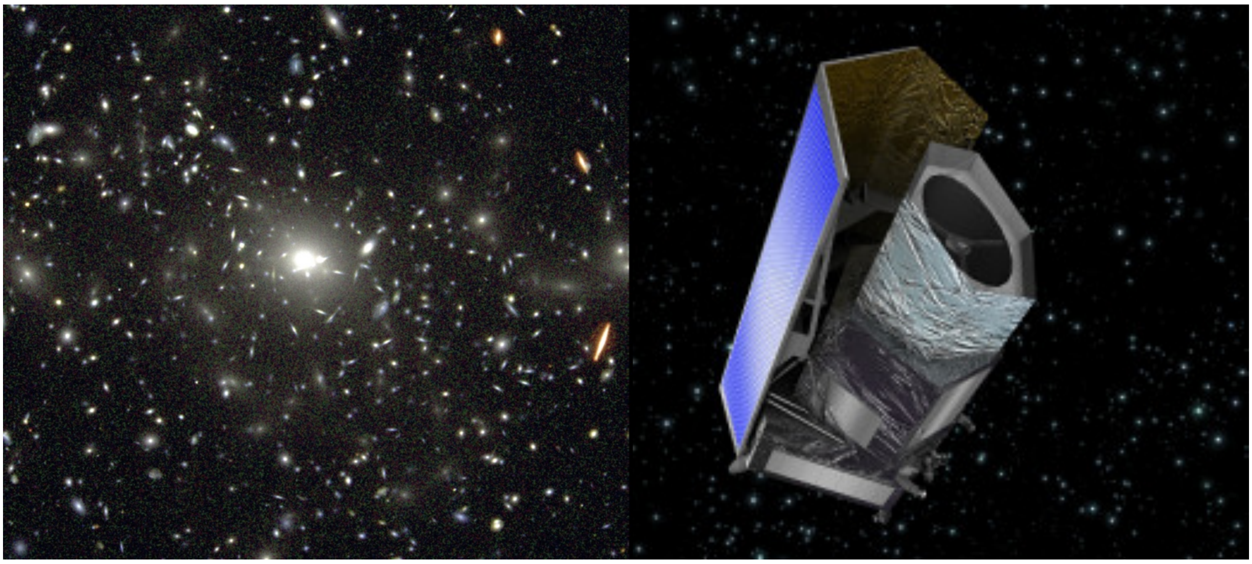


Figure 6.1: *With its 15,000-square degree wide field survey, Euclid will observe 12 billions of galaxies in visible and near-infrared, providing a huge legacy for studies of large-scale structures, physics of clusters, groups and galaxies. Here a mock image in YJH of a cluster at z=0.3 is shown, as seen by Euclid.*

Another team of the pole is carrying out simulations of the **Epoch of Re-ionization (EoR),** the time corresponding to the formation of first stars and early galaxies, whose UV radiation re-ionizes the universe between z = 30 and z = 6. Observations of the 21cm line of atomic hydrogen, redshifted into metric wavelengths, are being performed now with **LOFAR (and soon NenuFAR) and SKA** in the future. The LERMA simulations predict which types of structures will be detectable with SKA, and members of our pole are active in SKA Science Working Groups. Simulations will improve in resolution (2048^3 cubes) and the physics considered. The team develops HI tomography analysis to enable a better interpretation of the data when they arrive **(Figure 6.2).** The main goals for the next 5 years of the 21cm library project are (i) building an astrophysical parameterization of the EoR (ii) mapping the parameter space with full blown simulations (iii) predicting the 21cm signal (iv) making the database public (v) developing inversion algorithms (neural networks), and (vi) applying them to the observational data.

The LERMA group is actively engaged in the observations of **galaxies at high redshift**, to follow in real time their formation and evolution, in particular to determine the efficiency of star formation over cosmic time. It plays a fundamental role in the NOEMA Large Key Program PHIBSS2, aimed at quantifying the gas fraction and star formation efficiency across the Hubble time. Individual galaxies are followed up with ALMA. The team is leading many projects using **IRAM-NOEMA**, *Herschel*, and **ALMA**. All wavelengths are used to characterize the objects that are selected either by their infrared emission (Herschel), then detected in their molecular gas, imaged at optical wavelengths with the Hubble Space Telescope, with spectroscopic follow-ups using large telescopes on the ground (VLT, Keck…). Gravitational lensing is used to increase the spatial resolution of very distant objects, and will be a common tool with *Euclid*.

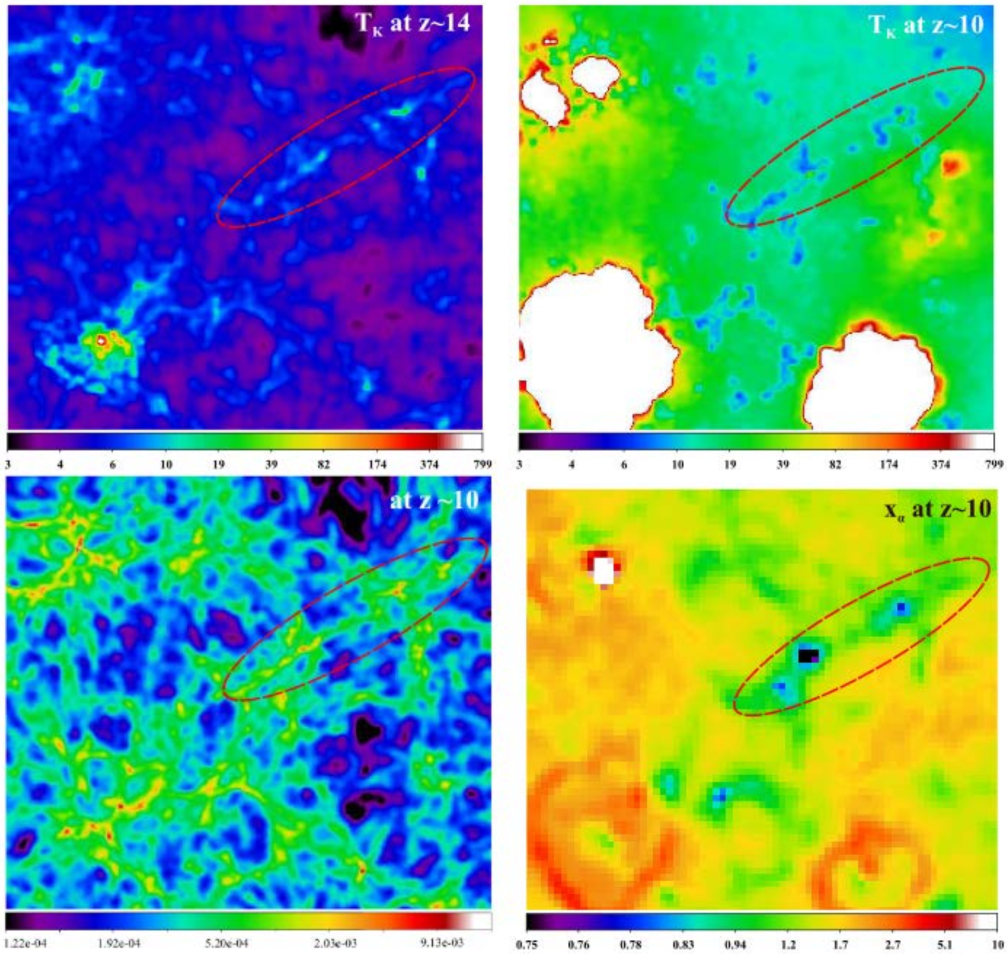


Figure 6.2: *Simulations of the EoR: the maps are ~10 comoving Mpc on a side, and correspond to a slice thickness of 35 kpc for the first three and 140 kpc for the bottom-right map. The plotted quantities are: kinetic temperature at z ~ 14 (top left), kinetic temperature at z ~ 10 (top right), number density in* cm^{-3} *at z ~ 10 (bottom left) and* x_α *coefficient at z ~ 10 (bottom right). From Semelin (2016).*

Another specialty of the group is the **physics of nearby galaxies**, approached by modeling, numerical simulations, and observations: What is the respective role of secular evolution, of galaxy interactions, in star formation and its efficiency? The interpretation of the Kennicutt-Schmidt law, local or global, is one of the challenges of these studies, which will improve considerably with the spatial resolution and sensitivity of ALMA. All types of galaxies will be studied, dwarfs, ellipticals, as well as spirals, and the CO-to-H_2 conversion factor will be determined with more details and statistics. The effects of environment, ram pressure, tidal forces, harassment, or removal of the gas supply will be studied.

The team of LERMA is also widely recognized for its work **on cooling flows**, both by its first observations of cold molecular gas, and physical processes, as AGN positive and negative feedback. The team participates in many ALMA proposals involving cool core clusters. In the future **ALMA** and **ATHENA** will be able to make large progress on the nature of the multi-phase filaments of ionized gas and cold molecular gas **(Figure 6).** Modeling with photo-ionization codes, such as CLOUDY, and numerical simulations of the possible dynamical scenarios will be performed (shocks, heating by AGN, star formation, or by cosmic rays).

Models will be constrained by observations of gas in nearby galaxies, containing either **a starburst or an active nucleus**. Observational campaigns of molecular outflows with **ALMA** will grow considerably in the coming years. The challenges are to better understand the association between supermassive black holes and galaxies bulges, and its cosmic evolution. As for fueling and feedback of AGN, ALMA and NOEMA, as well as the VLT, will provide deeper information. Up to now, it was shown in the NUGA project that fueling occurs only 35% of the time, via negative torques on the gas, at a scale of 1" or ~50–100 pc. Our ALMA projects have unveiled the molecular tori, at 4 pc resolution (0.1") in galaxies such as the prototypical Seyfert 2 NGC1068, as well as feedback in the form of molecular outflows. Positive feedback will be searched for, as in Centaurus A, where the atomic (HI) gas is transformed into H_2 at the passage of the radio jet.

Numerical simulations will be improved to study various **scenarios of formation of galaxies like the Milky Way or M31**: the role of secular evolution with accretion of gas from the cosmic filaments, or interactions/mergers (minor or major) in reproducing abundance gradients, the formation of galaxy disks without bulge or pseudo-bulge, the formation of thick disks, the migration of stars. The formation history can be searched back in relic low-surface brightness features around galaxies, which might be observed with the **Messier satellite,** a project proposed to CNES. Ultra-faint dwarfs will be explored through deep gas search.

Grand unification theories, non-standard models of dark energy, quintessence, Chamaeleon theory etc., each predicts **a variation of fundamental constants**, either temporal or spatial. Our group is competitive in this area, and will continue to observe molecular absorption lines in front of distant quasars, with ALMA and NOEMA, and is involved in key programs on the SKA precursor **MeerKAT.**

7. Presentation of the pole "*Interstellar medium and plasmas*"

IMP carries out an ambitious research program on the interstellar medium (ISM), its cycle into stars and planets, and the fundamental plasma processes involved. In particular, we have developed a recognized pioneering expertise in the study of:

- magnetic fields, turbulence, and dissipative processes to form filaments and dense cores;
- interstellar chemistry across the ISM cycle;
- star and planet formation and its feedback by winds, shocks and radiation;
- and accretion/ejection and transport processes in stellar plasmas.

Since the last AERES report, which saw the departure of 3 senior members, IMP recruited 2 young scientists (B. Godard, A. Gusdorf); a world renowned senior scientist (F. Boulanger) is joining us in the Fall of 2017 and will further strengthen our expertise in the field of cosmic magnetism.

The main originality and strength of IMP is combining top-level observations with advanced chemical modeling, theory/numerical simulations, laboratory experiments, and radiative transfer of spectral diagnostics. This enables us to achieve a deeper physical understanding of the complex processes at play in the ISM cycle and star/planet formation. Some of the key science questions that IMP is currently addressing are:

- What are the key mechanisms regulating the condensation of diffuse ISM into unstable star-forming cores?
- How do short-lived molecular clouds continuously reform from atomic ISM?
- What is the coupling between chemistry and dynamics on various spatial scales?
- How do stars and planets form, and what is their feedback on the ISM cycle?
- By which mechanism is excess angular momentum extracted to form a new star?
- How do PDRs contribute to regulate the ISM cycle (returning molecular gas to the atomic phase) and how can their signatures be used as measure of SFR in distant regions?
- What can laboratory experiments and theory tell us about the fundamental microscopic and macroscopic mechanisms of energy transport in plasmas, from stars to the ISM?

Staff and resources

As of Feb. 1, 2017, IMP counts a total of 46 members distributed over 4 interacting sub-teams (ENS, UPMC-Jussieu, OP-Denfert, OP-Meudon):

25 Permanent members:

- **18 staff scientists:** M. Gerin (DR-CNRS), A. Gusdorf (CR-CNRS), T. Le Bertre (DR-CNRS), P. Lesaffre (CR-CNRS), J.-F. Lestrade (DR-CNRS), L. Pagani (DR-CNRS), M. Pérault (DR-CNRS), L. Petitdemange (CR-CNRS), C. Stehlé (DR-CNRS); A. Ciardi (MdC), F. Debbasch (MdC), J. Le Bourlot (Prof.), F. Lévrier (MdC), J.-F. Panis (MdC); S. Cabrit (Astr.), F. Delahaye (Astr. Adj.), B. Godard (Astr. Adj.), F. Le Petit (Astr.)
- **5 emeriti**: E. Falgarone, M. Heydari-Malayeri, E. Roueff, S. Sahal-Bréchot, C. Zeippen
- **2 engineers**: L. Ibgui (IR), D. Languignon (IR)

Two of our scientists are on long term assignments at IRAM-Grenoble (J. Pety, Astr. and M. Guélin, emeritus); their independent activities are not incorporated in this report.

21 Non-permanent members:

- **13 PhD students:** P. Arnault, M. Berthet, A. Cameron, S. Colombo, J. Guyot, B. Khiar, M. Menu, T Ngoc Le, L. Nicolas, J. Orkisz, R. L. Singh, B. Tabone, L. Van Box Som
- **4 postdocs:** A. Heays, L. Oruba, A. Stan, R. Wu
- **4 CDD:** D. Lis (Prof.), M. Drouin (IR), X. Fresquet (IR), C. Mansour (IE)

We have several associates: former PhD students and postdocs, as well as senior scientists who contribute actively to the scientific life of IMP (P. Hennebelle, CEA; G. Pineau des Forêts, IAS; J.-P. Chièze, CEA, deceased in 2016).

Resources:

Observing facilities: We continue to exploit the *Planck* and *Herschel* archives, and have numerous projects on ALMA, NOEMA, SOFIA, IRAM-30m, JCMT, LOFAR, JVLA, and SKA precursors (FAST, MeerKAT). We are also actively involved in the preparation of JWST (ERS proposals), ATHENA, CTA, SKA, and future FIR/submm satellite projects (SPICA, FIRSPEX, *Origins Space Telescope, Millimetro*n).

Laboratory facilities: LULI (France), PALS (Czech Republic), Orion (UK), experimental shocks platform (Jussieu, in collaboration with LPP).

Numerical Codes: we develop and maintain original 1D codes to solve thermo-chemistry and its coupling to dynamics (Meudon PDR code, Paris-Durham shock code, TDR code for turbulent vortices, MAMOJ code for MHD disk winds); state-of-the-art 3D MHD codes with AMR (RAMSES/CHEMSES), a resistive 3D MHD code to model laboratory experiments (GORGON), and a new hybrid PIC-code to follow ion kinetics (PHARE), as well as radiative transfer codes to produce synthetic predictions (LVG modules, IRIS for output of 3D simulations).

Computing facilities: local clusters, Meso-PSL (OP), ICSD cluster in Jussieu

ANRs: STARSHOCK (2009-2014, PI), SYMPATICO (2012-2015, co-I), SILAMPA (2013-2016, co-I), IMOLABS (2014-2017, PI), LYRICS (2017-2021, co-I).

ERC Advanced Grant: MIST (2017-2022, PI).

LABEX: Plas@Par (management and allocations)

CNRS National Programs (PCMI, PNP and PNPS; ASA and AS SKA-LOFAR), CNRS PICS programs (Taiwan, Italy), Scientific Council of the **Paris Observatory** (Programme Blanc, Actions Fédératrices) .

DIM (Région Ile-de-France) ACAV, ACAV+

Activity profile

Our priority research projects can be classified under 4 main themes:

1. Structure of diffuse ISM and its condensation into star-forming cores (Falgarone, Gerin, Godard, Lesaffre, Lévrier, Pety, Pérault + PhD students and postdocs)
2. Astrochemical models (Bron, Gerin, Godard, Le Bourlot, Le Petit, Roueff + PhD students and postdocs)
3. Star and Planet formation and its feedback on the ISM cycle (Cabrit, Gerin, Guélin, Gusdorf, Heydari-Malayeri, Le Bertre, Lesaffre, Lestrade, Lis, Pagani + PhD students)
4. Plasma laboratory experiments and modeling (Ciardi, Debbasch, Delahaye, Lesaffre, Panis, Petitdemange, Sahal-Bréchot, Stehlé, Zeippen + PhD students and postdocs)

Research products and activities

IMP published 452 refereed articles in the past 5 years, totaling 16050 citations. These publications are listed in full on the LERMA web site and the most significant 20% are in Annex 4. IMP members have high visibility with numerous invited talks at international conferences and memberships in SOC, Advisory Boards, and ALMA, IRAM, and SOFIA time allocation committees. We have numerous international collaborations and attract several prestigious foreign visitors each year (USA, Vietnam, Canada, UK, Italy, Mexico, Poland, …). We are also heavily involved in training and mentoring of students (13 PhDs currently). 11 of our permanent staff members have teaching positions or give Master courses and open on-line courses (MOOC). Several IMP members also dedicate a significant fraction of their time to serve the community through science policy management at local (Plas@Par) and national (INSU) levels, and through "tâches de service" (CNAP) developing models, codes and databases accessible through the PADC data center. Below we summarize the main research achievements in our 4 themes since the last AERES report.

1. Condensation of diffuse ISM into unstable star-forming cores

Observations of B-field and its imprint on the ISM

Herschel and *Planck* images revealed that filaments are ubiquitous in the ISM, raising the question of their origin. We investigated the geometry and role of the magnetic field using *Planck* dust polarization data (*Planck* intermediate results XIX 2015, XXXV 2016; Soler et al. 2016). The magnetic field was found mostly parallel to diffuse filaments, and perpendicular to dense ones. This behavior could be reproduced by MHD turbulence simulations in the sub- and trans-Alfvenic regime.

Turbulence dissipation and its chemical tracers

The 3D structure of turbulent dissipation regions was simulated including ambipolar diffusion, viscosity, and spatially resolved ohmic resistivity (Momferratos et al. 2014, Fig. 7.1). It reveals intermittent sheet-like structures and a characteristic scale for ambipolar diffusion dissipation.

We developed a simplified model of out-of-equilibrium chemistry in dissipation regions of turbulence, based on idealized gas dynamics in a magnetized vortex (Godard et al. 2009, 2014). This model could successfully explain molecular abundances in the diffuse ISM including the endo-energetic species CH^+ and SH^+, solving a long-lasting 50-year puzzle (Godard et al. 2012).

The formation of H_2 and other simple molecules out of atomic clouds was simulated in 3D by Valdivia et al. (2014, 2016, 2017) using RAMSES MHD code and a novel treatment of UV attenuation. H_2 forms in dense clumps and mixes into the interclump atomic medium, explaining the warm H_2 observed by FUSE. CH^+ remain 3 times weaker than observed, suggesting that turbulent dissipation is not fully resolved in such large-scale simulations.

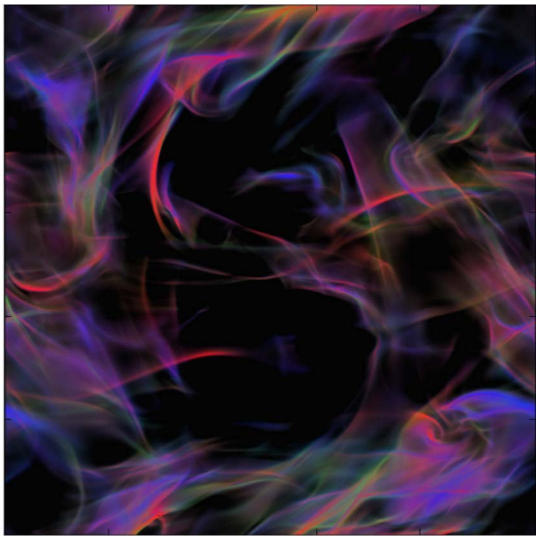


Figure 7.1: *3D spectral simulation of dissipation regions in incompressible MHD turbulence; Red: ambipolar diffusion, Blue: ohmic, Green: viscous (Momferratos et al. 2014); scale is 1pc at 100 cm^{-3}.*

Formation of molecules, chemical complexity

Hydrides: The *Herschel* key program PRISMAS, led by M. Gerin, revealed that hydrides provide new key diagnostics of the diffuse ISM: the fraction of hydrogen in molecular form, the cosmic ray ionization rate, the role of turbulence, etc. (see Gerin et al. 2016 in Annual Review of Astronomy & Astrophysics). The surprisingly high abundance and excitation of H_3^+ in the Central Molecular Zone could be modeled by diffuse gas heated by a strong cosmic ray flux (Le Petit et al. 2016).

Spectral surveys were carried out with the IRAM-30m (Horsehead Nebula, PI: J. Pety; dark clouds in *Large Program ASAI*, leading to new detections: the C_3H^+ ion, Pety et al. 2012; McGuire et al. 2014, and e.g. NH_3D^+, NO^+, $C_2N_2H^+$, for which we developed new gas-phase chemical schemes, Cernicharo et al. 2013, 2014, Agundez et al. 2015). We also developed a unique chemical network involving both D, ^{13}C and ^{15}N to model fractionation (Daniel et al. 2014, 2016; Roueff et al. 2015).

The atomic, molecular, and chemical data in *the Meudon PDR code* were updated to interpret *Herschel* and IRAM observations: Chemistry of ArH^+, F, Cl was introduced (Roueff et al. 2014, Neufeld et al. 2015). A 3-phase surface chemistry model (gas, mantles, surfaces) was implemented to interpret the distribution of methanol and H_2CO in the Horsehead (Guzman et al. 2014, 2015). A major breakthrough was reached in the modeling of H_2 formation and ortho/para conversion on grains, using **a new probabilistic formalism** to simulate grain temperature fluctuations due to UV photon absorption (Bron et al. 2014, 2016). H_2 formation on warm grains is now efficient enough to explain *Spitzer* observations of bright PDRs.

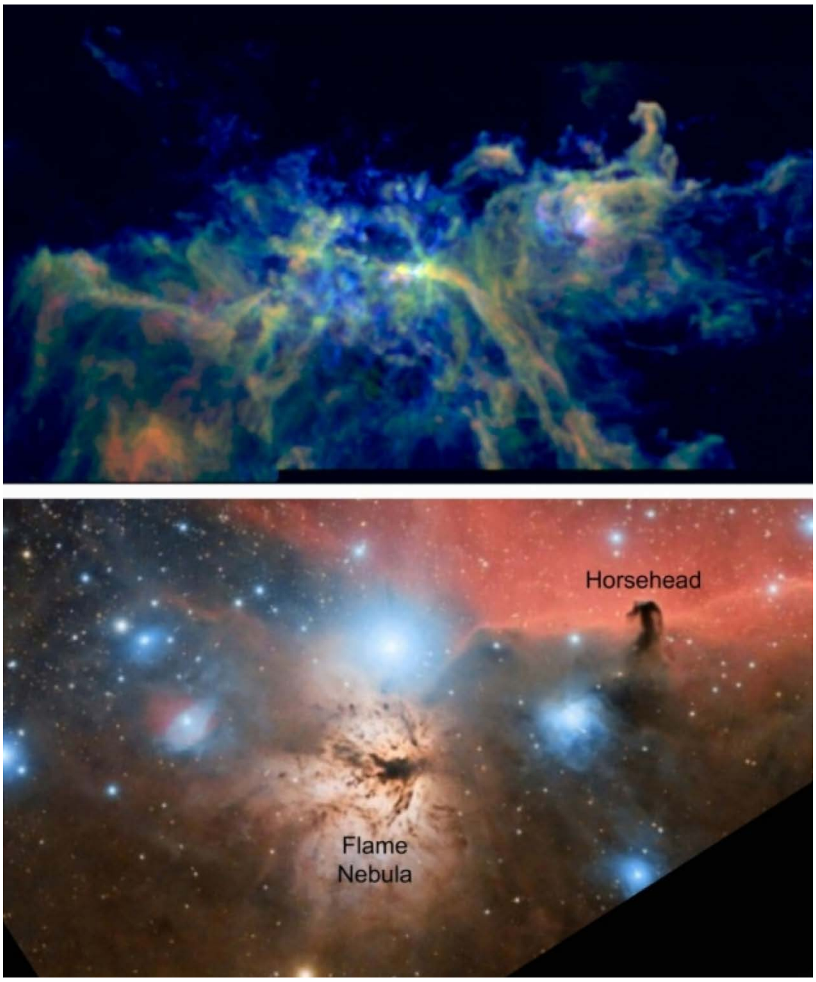


Figure 7.2: *Orion Molecular Cloud: molecular line emission (IRAM 30-m; upper panel), optical (lower panel); the Orion-B collaboration (www.insu.cnrs.fr/node/6352).*

2. Star and Planet formation and Feedback

Star formation on cloud scale: The new *Orion-B Large Program* at the IRAM-30m telescope (PI J. Pety & M. Gerin) combines large scale mapping (4.5 square degree) and spectral surveys across 72 – 115.5 GHz (Fig. 7.2). Using an original analysis method of velocity field calibrated on simulations, Orkisz et al. (2017) found that turbulent momentum is mainly in solenoidal (non-compressive) motions, which could explain the overall low star formation activity in Orion B. In a different study aimed at *dense ridges with intense massive star formation*, we showed that the narrow line width SiO emission could trace low-velocity shocks in converging flows feeding the ridges.

Prestellar dense cores

In her Ph.D. thesis, C. Lefèvre modeled in detail the “coreshine” phenomenon previously discovered by our group: scattering stays important at >8 µm, revealing the *growth of still larger grains*. Core masses derived with this effect are then much larger (Lefèvre, Pagani et al. 2016). The new spectroscopic coverage of the IRAM-30m and the NOEMA interferometer was used to probe the *chemistry* of the dense core Barnard 1, and to infer its cosmic ray ionization rate, gas-phase depletion of C, O, S, and $^{14}N/^{15}N$ ratio in several species, constraining the fractionation mechanisms (with J. Cernicharo & A. Fuente). A new method based on deuterated species (N_2D^+, DCO^+) was developed to date prestellar cores and to trace their depletion profiles of CO and N_2 into ices.

Protostars and their outflows

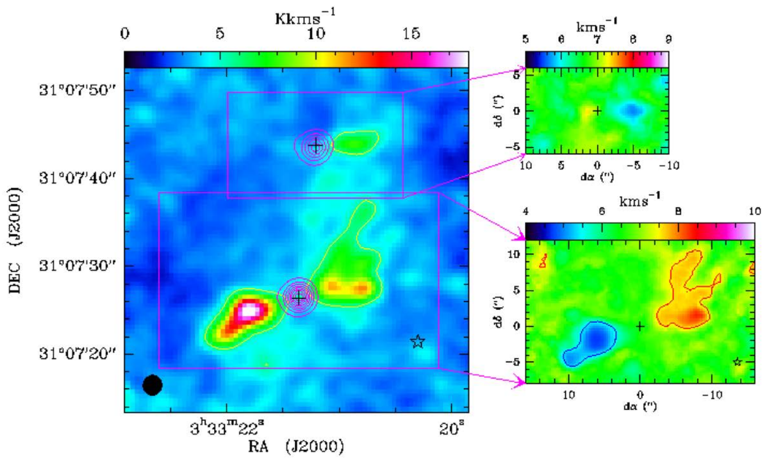


Figure 7.3: *Two very young protostars in B1b (contours) with H_2CO outflows mapped with NOEMA (Gerin et al. 2015).*

Recent 3D MHD simulations predict that gravitational collapse of a rotating, magnetized core will lead to the formation of a star surrounded by a small disk, and a slow outflow along its polar axis carrying away excess angular momentum. We observed with NOEMA and ALMA two protostars in the B1b cloud that appear to confirm this scenario (Fig. 7.3); one may be the youngest protostar known, as shown by its very low luminosity, slow outflow, and tiny dust disk ~ 50 au.

Protostellar jets: More evolved protostars drive fast and narrow jets whose exact origin is still unknown. With ALMA we discovered a striking chemical stratification in HH212, allowing for the first time to disentangle all key elements of such systems: jet, disk, envelope, swept-up outflow cavity, and complex organic molecules near the protostar. With NOEMA (*Large Program* CALYPSO) we discovered precessing and monopolar jets and high abundances of SiO, SO and SO_2, providing challenging constraints for jet models (collab. with Arcetri, IRAM/Grenoble, CEA).

Jet thermo-chemical modeling: We developed the first code to follow the temperature and chemical evolution in dusty magneto-centrifugal disk winds (Panoglou et al. 2012). This model is the first to reproduce the broad H_2O wings observed by *Herschel* in protostars (Yvart et al. 2016). Synthetic data cubes were calculated by B. Tabone (Ph.D) to test the predicted jet rotation signatures with ALMA-Cycle 4 observations.

Outflow shocks: The shock fronts where jets impact against ambient gas offer key diagnostics of the global outflow energetics. They were modeled by combining a range of tracers (H_2 from *Spitzer*, low-J CO and SiO from ALMA/NOEMA/APEX; high-J CO, H_2O, OH, [OI], C, C^+ from *Herschel*). Our leadership in SOFIA observations provided the first velocity-resolved [OI] and OH profiles, revealing a larger atomic fraction than anticipated (see Fig. 7.4). In preparation for JWST, models of H_2 emission from unresolved bowshocks were also developed (Le Ngoc, PhD thesis 2018).

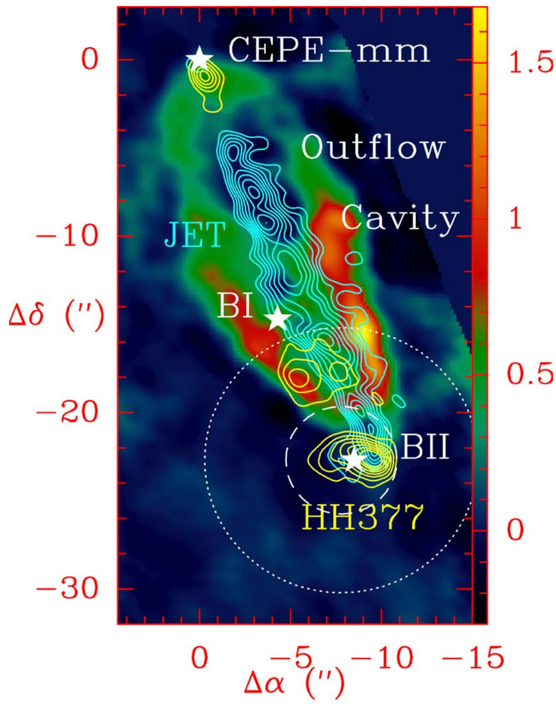


Figure 7.4: *[OI] 63 µm was detected by SOFIA at positions BI and BII in the Cep E CO outflow (low-velocity in color, high-velocity in contours). From Gusdorf et al. (2017).*

Injection of stellar matter in the ISM from evolved stars

AGB winds: With IRAM-Grenoble and Haystack, we made CO spectral maps which revealed in several stars winds faster along the polar axis than in the equatorial plane, an asymmetry that might be caused by a companion. VLA HI maps revealed that the outer shell, where outflowing stellar matter is stopped by ambient gas, exhibits a "head-tail" morphology due to the relative motion of the star with respect to its environment (see Fig. 7.5); these tails may be the main site where AGB matter mixes and enriches the local ISM.

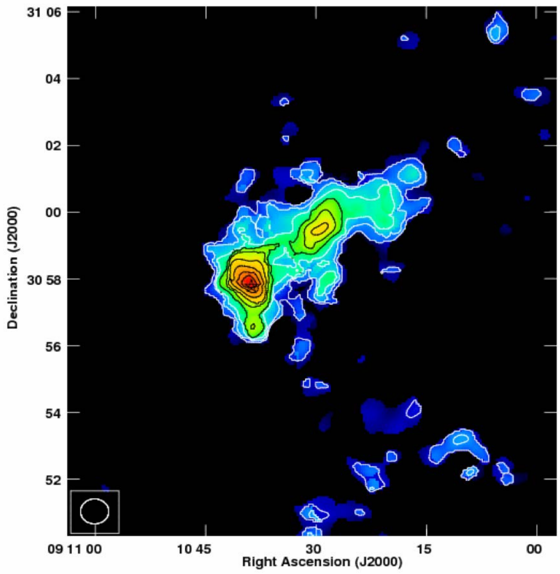


Figure 7.5*: HI tail associated with the mass-loss AGB star RS Cnc (VLA; Hoai et al. 2014). The star is moving to the southeast.*

Supernova remnants (SNRs): Our shock models were applied to estimate the large-scale energetic impact of the supernovae flows, the chemistry that they drive, and study potential triggered star formation (in W28, W44, and 3C391 in CO, H_2, and/or H_2O). An original study of magnetic field in SNR using non-Zeeman circular polarization of CO was initiated in IC443.

Radiative feedback: Photo-Dissociation Regions (PDRs)

The Meudon PDR model (Le Bourlot et al. 2012, Bron et al. 2014, 2016) remains one of the state-of-the-art codes in the field. In collaboration with various teams (e.g., WADI, S. Madden's team at CEA) we used *Herschel* observations of CO excitation from low (~J=4–3) to very high transitions (~J=20–19) to re-investigate the structure of PDRs and their main energetic processes: in classical PDRs the edge can be modeled by an isobaric medium, with a hot chemistry initiated by UV photons (Nagy et al. 2013, Joblin et al. 2010). In the frame of the ANR SYMPATICO, we implemented the effect of X-rays to model extragalactic PDRs (e.g. Rodon et al. 2015, Chevance et al. 2016, Lee et al. 2016).

Debris disks as signatures of exo-comets and planet formation

A cold debris disk surrounding a main sequence star is an analog of the Kuiper Belt where collisions of planetesimals and exo-comets generate enough dust to be observable. We have been involved in several studies using *Herschel*, SMA, JCMT and IRAM 30m. We discovered one of the rare debris disks around an M-star (GJ581, hosting a multi-planetary system), and showed that the main dust belt around Epsilon Eridani is narrow, suggesting a planet near 60 au. These studies also uncovered for the first time a prevalence of debris in low-mass planetary systems. In addition, we participated in the commissioning of the new dual band camera NIKA2 at IRAM 30m.

3. Plasma laboratory experiments and modeling

Accretion-ejection phenomena in young stars: the role of magnetic field, radiation and inhomogeneities

In the frame of the ANR STARSHOCK, we investigated through 1D simulations the effect of radiation in the accretion shock: with a set of new LTE opacities, we proposed a model to bridge the LTE regime in the chromosphere and the coronal optically thin limit in the heated accretion column. Our results show a drastic opacity effect. We also conducted 2D/3D MHD simulations revealing the development of non-synchronous fibrils, possibly explaining the lack of periodic shock oscillations in accretion shock diagnostics.

Concerning the ejection process, we showed numerically that magnetic braking during collapse can be drastically reduced in misaligned configurations. Jet collimation by an external magnetic field was also demonstrated for the first time in scaled laboratory experiments, supporting the scenario where stationary X-ray knots seen in some YSO jets are produced in a re-collimation shock (see Fig. 7.6).

Laboratory and numerical study of fundamental astrophysical plasma processes

Magnetic reconnection plays a crucial role in the conversion of energy from macroscopic to microscopic scales. An important result obtained is the first experimental observation of plasmoids in a semi-collisional magnetic reconnection layer, as predicted by theory. These experiments also revealed the presence of very hot ions, whose source of (anomalous) heating remains unexplained.

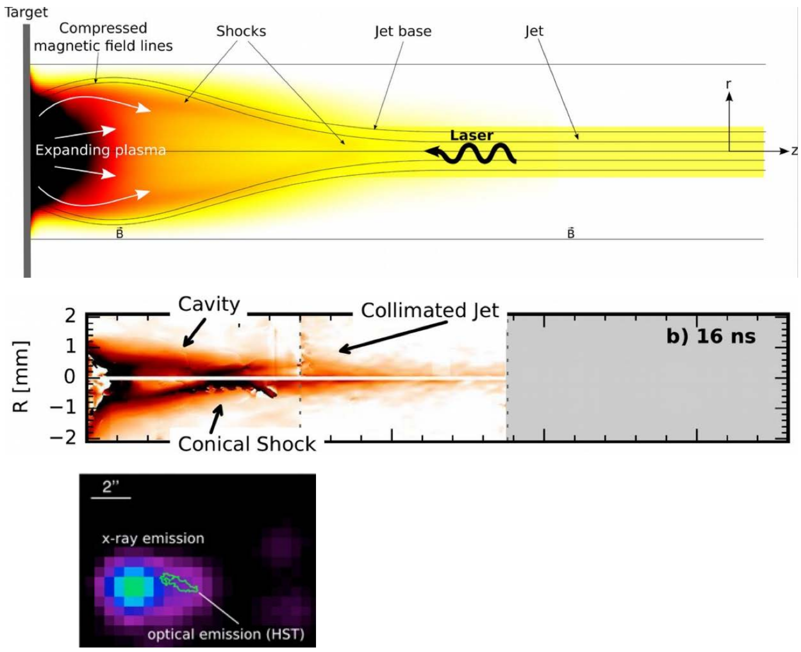


Figure 7.6: *First magnetically confined laboratory jet, obtained at LULI (Albertazzi, Ciardi et al. 2014). The stationary, X-ray emitting, conical shock may help explaining Chandra observations (bottom panel).*

Particle acceleration and streaming instability: energetic particles streaming along a magnetic field can drive unstable MHD waves, which in turn efficiently scatter them in phase space, leading to particle acceleration in shocks. We conducted a numerical study, supported by ongoing laser experiments, on the effect of collisions. We find that the instability rapidly leads to an exponential increase of the collision frequency, which quenches the growth of magnetic field perturbations.

Opacities: There still exist large discrepancies between codes and experimental results on opacities, that need to be understood. We found a difference of 10% in the Rosseland mean opacities of Ni XIV depending on the treatment of photoionization. Our theoretical developments relative to opacity, and also Stark line broadening, are integrated in our public services IPOv and STARK B.

Radiative shocks are studied both numerically and experimentally: we performed at PALS (CZ) the first imaging in the XUV at 21 nm of the full structure of the shock, which shows a curved radiative precursor in front of an irregular thin dense shock front; we provided a correct interpretation with 2D AMR simulations with up to date opacities.

Quantum Walks (QW) can be viewed as quantum counterparts of classical random walks, and are useful in quantum information, condensed matter physics and biophysics. Our group is a pioneer in this field. We showed that spatial and temporal inhomogeneity of a QW generates discrete artificial gauge fields; and that inhomogeneous QWs can thus be used to model the motion of fermions coupled to arbitrary Yang-Mills gauge fields and to gravity, and possibly study it experimentally.

Dynamo action is considered as the main mechanism for the generation of the magnetic fields of stars and planets. Direct numerical simulations in the Boussinesq (incompressible) approximation revealed fundamental properties of these models (Schrinner, Petitdemange, & Dormy 2012). We then used the anelastic approximation to investigate how the strong density stratification in stars or gas giants influences the dynamo mechanisms (Raynaud, Petitdemange, & Dormy 2014, 2015).

Convective transport in rotating stars: Using an analytical turbulence closure model for rotating axisymmetric systems, we were able to provide closed form expressions for the thermal and angular momentum fluxes with only one free parameter, the mixing length (Lesaffre et al. 2013).

SWOT Analysis

➔ **Strengths:**

- High success rate in competitive proposals on international facilities such as ALMA, NOEMA, SOFIA, IRAM-30m, Orion, LULI, PALS, and numerous international collaborations.
- Strong expertise in simulations of the physical and chemical processes in the ISM. Several of IMP codes are recognized to be reference public codes (cf. INSU ANO5 service).
- The different approaches of a common astrophysical topic by the four sub-teams are uniquely complementary.
- IMP attracts established scientists (F. Boulanger from IAS/Orsay will join our group in the Fall of 2017), as well as distinguished visitors each year, funded by OP, ENS, UPMC, and Labex Plas@Par.
- Proven success in obtaining funding contracts with ANR (STARSHOCK, SILAMPA, SYMPATICO, IMOLABS, LYRICS), and ERC (MIST).
- Labex Plas@Par (with Director and management at LERMA), and leading role in the international Opacity Project.
- Strong involvement in teaching, in particular at the Master level, influences career choices of promising PhD students who may in turn choose a career path in astrophysics

➔ **Weaknesses**:

- The age pyramid of permanent staff is inverted.
- Some of our leading scientists are emeriti (5), others (2) will retire during the next five years. The expertise in plasma experiments is particularly vulnerable.
- Geographic dispersion, including staff from the Paris Observatory, ENS, and UPMC.

➔ **Opportunities:**

- New and recent large facilities, such as ALMA, NOEMA, JVLA, JWST, LOFAR, Orion, LMJ are opening a "golden era" for interstellar medium and astrophysical plasma studies.
- Collaborations and funding opportunities provided by the Labex Plas@Par, Idex Sorbonne Universités and PSL (e.g., the program "*PSL Fellowships in Astrophysics at Paris Observatory*", IRIS SDDS, OCAV), Region Île-de-France (DIM ACAV+), Scientific Council of the Paris Observatory (e.g., federative actions).
- The in-house expertise provided by the *Molecules in the universe* pole is an invaluable asset, as well as the THz receiver development by the *Instrumentation and remote sensing* pole.
- New synergies with the *Galaxies and cosmology* pole in providing the expertise in the use of molecular tracers to constrain the physics and chemistry of local and high-redshift galaxies.

➔ **Threats**:

- We are at high risk of losing our young brilliant members presently on MdC positions, due to the lack of Professor positions available for promotions.
- Our activities require multi-disciplinary expertise. Four more senior scientists will retire in the period 2013–2023. Hence, we estimate that recruiting 3 young researchers by 2023 would be mandatory to maintain the international leadership of LERMA on IMP themes.
- Insufficient IT manpower to support needs in numerical simulations and data analysis in response to new the observational challenges: developing new generations of codes and statistical methods to interpret increasingly more complex observational data.

Scientific project

1. Condensation of diffuse ISM into unstable star-forming cores

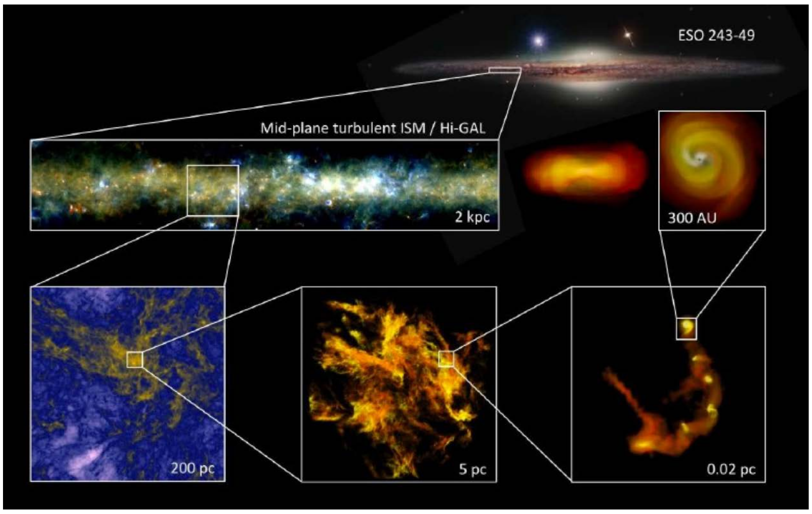


***Figure 7.7:** Magnetic fields are dynamically significant on all scales, from galaxies to planets. The evaluation of their morphologies and of their roles will be transverse to all our activities.*

Observations of B-field structure and imprint on ISM

The BxB project (ANR) led by F. Boulanger within a large collaboration in Île-de-France and beyond aims to contribute breakthroughs in two highlighted fields: (1) Galactic magnetism (by building the first coherent 3D model of ordered B from the solar neighborhood to the Galactic halo, and of its turbulent B component, Fig. 7.7) and (2) CMB polarization signatures of primordial gravitational waves (by a physical model of Galactic polarization foregrounds to constrain CMB B-modes). This will be done by combining observations (dust polarization, synchrotron emission and Faraday rotation with LOFAR), numerical simulations and theoretical/statistical modeling. The link with the *Galaxies and cosmol*ogy pole will be fostered with the hire of a cosmology professor at ENS.

Turbulence dissipation and chemistry

The MIST project, funded by an Advanced ERC, will use H_2 and CH^+ (*Spitzer,* JWST, ALMA) to unveil the physics of turbulence dissipation in the magnetized medium where gravitational instability develops to form stars in the early universe. The dissipation chemistry will be realistically captured for the first time with new irradiated 1D shock models and the optimized thermo-chemical module CHEMSES interfaced with MHD RAMSES.

Extragalactic shocks

Our shock models were applied with success to H_2 in the Stefan's Quintet and CO in several Large Magellanic Cloud regions. This application to extragalactic context will intensify and become a major objective in the coming period thanks to our close participation in the ANR of P. Salomé on extragalactic jet feedback and cooling flows, which opens another fruitful synergy with the *Galaxies and cosmology* pole.

Anatomy of interstellar clouds & Machine Learning technics

A major challenge in the coming years is the large amount of data provided by the new generation of instruments. We are involved in mapping the whole Orion B cloud in a Large Program at IRAM-30m (550 hours, P.I. J. Pety & M. Gerin), and already have 140,000 spectra. To reveal the chemical & dynamical anatomy of this region we will investigate innovative **Machine Learning techniques** (cf. our preliminary work Gratier et al. 2017, Bron et al. in prep). We plan to develop new methods (**meta-heuristic, machine learning, artificial neural networks**) to confront this large dataset with large grids of PDR models. Our goal is to provide less degenerate solutions, and be able to consider mixtures of models to interpret spatially unresolved observations such as extragalactic ones. Partnerships with statisticians will be developed, as in the context of the SDDS IRIS of PSL.

Simulating surface chemistry

The original probabilistic approach we developed to study H_2 formation and ortho/para conversion on grains will be applied to the formation of more complex molecules in ices. We also aim to develop stochastic models for other chemical processes in ices such as the impact of photo-desorption and cosmic rays (using the new results of *Molecules in the universe* pole), with application to e.g. the ice line in protoplanetary disks.

2. Star and Planet formation and Feedback

Prestellar cores

Our objective will be to combine new diagnostics of dust (e.g., polarization with CFHT, ESO/VISTA), chemical deuteration (e.g., H_2D^+ with IRAM and JCMT), and ice depletion (with JWST) to better characterize at the same time the degree of grain growth and the core inner structure and age. To this aim we have already obtained bilateral funding to start a new collaboration with a Taiwanese team on a sample of 10 new cores.

Protostars and their outflows

To test the scenario of magnetized star formation, with angular momentum extracted in protostellar outflows, we will compare high-resolution ALMA observations of jets (collaboration with Italy) and slower conical CO cavities (new collaboration with IPAG and UMI-Santiago) with our unique model predictions for MHD collapse and disk winds. The origin of strong [OI] emission in protostellar jets (*Herschel*, SOFIA) will be investigated by developing new irradiated shock models and obtaining complementary observations with JWST (H_2, Fe^+, S…). In this context, we are already involved as co-Is or co-PIs in several ERS JWST proposals and are preparing grids of shock models to help with the data interpretation.

Feedback from evolved stars

AGB stars: we will map the outer HI shells and their turbulent trails at much higher resolution and sensitivity using MeerKAT and FAST (starting in 2018) to reveal how AGB matter is injected into the atomic ISM. New thermo-chemical models of AGB winds will be developed at IMP in close collaboration with Vietnam and applied to ALMA/NOEMA maps. *Supernova Remnants and cosmic-ray acceleration:* Our main goal will be to exploit extensive maps of the SNR IC443 (in CO, H_2O, [OI], SiO, H_2, Si^+) to better characterize the shocks and the conditions for local cosmic-ray acceleration in the perspective of CTA, in which OP is involved**.**

Radiative feedback: Photo-Dissociation Regions (PDRs)

A first new objective will be to improve the Meudon PDR code to include more realistic dust models (from *Planck*) and high-z conditions (CMB pumping, low metallicity). Another key objective is to develop a new *time-dependent* (hydrodynamical) PDR code able to handle photo-evaporation and the dynamical impact of the H II region, both appearing important in *Herschel,* ALMA, and NOEMA data (e.g., Orion Bar; photoevaporating protoplanetary disks; star forming regions, …). Our new models will be used as reference to interpret data from a large ERS JWST project (200 participants) aimed at observing H_2, dust and ices in PDRs at unprecedented accuracy. The physics of ionized regions will also be implemented for interpretation of the GUSTO data.

Debris disks

Our new objective will be to obtain images of debris disks at several wavelengths with ALMA, NIKA2 at IRAM-30m, SPHERE/VLT, and MIRI on JWST to search for robust signatures of planet formation.

Evolution of chemical complexity and emergence of life

With the advent of broad-band spectral surveys in the sub/mm, an important new objective is to study the increase of chemical complexity from molecular clouds to proto-planetary disks and comets, to clarify its role in the emergence of life. New automated methods to identify the > 1000 spectral lines will be developed to this aim.

3. Plasma laboratory experiments and modeling

The group will reinforce its synergies with other partners of UPMC presently involved in the Labex Plas@Par (LPP, LULI, LPS, ICS), as well as with other teams of LERMA. We will increase our visibility in Laboratory Astrophysics, using recent and new major world class facilities like Orion (UK, Fig. 7.8), NIF (National Ignition Facility, USA) and the Quantum Technology Flagship.

Figure 7.8: *PetaW pulse beams (such as provided by the Orion laser facility, UK) will be used by the LERMA team to explore the properties of radiative shocks.*

One challenge is to understand the production and **acceleration of cosmic rays** in instabilities and shocks. We will improve our 3D MHD and hybrid codes, and also our experiments on high-power laser facilities (LULI and APOLLON). We want also to strengthen our leadership on the connection between **quantum walk theories** and real objects, with the aim of developing laboratory experiments in the fields of optics and solid-state physics. The efforts on **atomic opacities** will be extended in relation with laser experiments, within the international OP collaboration. Our theoretical work is stimulated by experiments performed on multi kJ laser facilities (LMJ and NIF) or Z pinch (Sandia). In the field of **stellar accretion**, our objective is to achieve a fully realistic multi D picture of the structure of accretion flows on young stars and to produce synthetic observations which may be compared with those obtained by X-rays satellites (ATHENA).

8. Presentation of the pole "*Molecules in the universe*"

Introduction

The LERMA research team *Molecules in the universe* develops unique experimental and theoretical tools to investigate fundamental molecular processes at play during the evolution of astrophysical objects and planetary atmospheres.

This new research focus has been established for the first time at the beginning of the present evaluation period, in January 2014, when the LPMAA laboratory joined LERMA, bringing together complementary expertise from various small research groups. The new team actually counts 41 members, including 30 permanent researchers and engineers, and 11 Ph.D. students, temporary researchers, engineers, and long-term visitors. During the current evaluation period, one permanent researcher has been recruited, reinforcing the experimental laboratory astrophysics activities. Due to retirements and incorporation of new technical staff involved in the development and maintenance of molecular databases, the team size has been stable as compared to 2014 (28 permanent and 7 contractual members).

- The team research covers a diverse range of experimental and theoretical activities that require high-level of knowledge in molecular sciences, especially in quantum effects, which play a key role in the interpretation of observations.
- It provides a unique expertise at the interface between molecular physics on the one hand and molecular astrophysics or atmospheric science on the other hand.
- The in-house developed experimental capabilities and instrumentation are unique and provide methodologies adapted to very specific physical conditions.
- The group's activities foster the coupling between laboratory studies and observations.

The driving science questions are:

- What role do grains and their interactions with the gas phase play in the physics and chemistry of the molecular universe? How important is the interaction of photons with molecular matter in the gas and solid phases (photodissociation, photodesorption, or photochemistry) for the exchange between the two phases?
- What can be learned from the observations of molecular anomalies in different environments (anomalous isotopic fractionation, molecules in non-LTE environments, ortho-para ratios of nuclear spins)? What are the driving mechanisms behind these phenomena on the molecular level?
- What contributions can modern high-resolution molecular spectroscopy and computational methods make to the interpretation, and the remote sensing of molecular probes in different environments?

Staff and resources

As of Jun 30, 2017, the group consists of 41 members distributed over 3 sites (UPMC-Jussieu, UCP-Cergy, OP-Meudon)

30 Permanent staff:

- **18 staff scientists:** C. Balança (MdC), M. Bertin (MdC), C. Boursier (MdC), H. Chaabouni (MdC), V. Cobut (MdC), F. Dayou (MdC), M-L. Dubernet-Tuckey (Astr.), F. Dulieu (Prof.), G. Féraud (MdC), J-H. Fillion (Prof.), C. Janssen (CR-CNRS), X. Michaut (MdC), A. Moudens (MdC), L. Philippe (MdC), A. Salaun de Kertanguy (Astr Adj), Y. Té (MdC), A-M. Vasserot (MdC), T. Zanon-Willette (MdC)
- **2 emeriti:** M. Glass, L. Tchang-Brillet
- **10 engineers and technicians**: Y.A. Ba (IE), C. Blaess (T), N. Champion (IE), S. Diana (IE), P. Jeseck (IR), F. Lachèvre (T), P. Marie-Jeanne (AI), N. Moreau (IE), C. Rouille (IR), C.M. Zwölf (IR)

11 Non-permanent staff:

- **2 CDD**: S. Baouche (IR), M. Congiu (MdC)
- **3 Long-term visitors**: M. Eidelsberg, N. Feautrier, S. Leach
- **6 PhD students**: A.S. Mohamed Ibrahim, R. Dupuy, M. Koshelev, T. Nguyen, T. Putaud, A. Sow

Resources:

Large national facilities: Team members have regular access to SOLEIL (PIs: Bertin, Fillion) and IDRIS (PIs: Balança, Dayou, Spielfiedel)
International platforms: VAMDC (EU)
University platforms: Instrumentation developed and provided by the group is part of university-wide experimental platforms: Astrolab (UPMC-SU, PI Fillion), Temps-Fréquence (UPMC-SU), QualAir (UPMC-SU)
In-Lab developments: The group has a strong record of maintaining and developing unique instrumentation and experimental platforms: SPICES, COSPINU, VENUS, FORMOLISM, MI-SDL, FCS-QCL, FTS-Paris/TCCON, 10-m Spectrograph
Databases: The group develops and maintains several databases for the international communities. BASECOL (Dubernet), MOLAT (Tchang-Brillet, Moreau), STARK-B (S. Sahal-Bréchot from Pole 2, Moreau), Tiptop base (F. Delahaye from Pole 2, Moreau), Sesam (E. Roueff from Pole 2, Moreau)
LABEX: FIRST-TF (co-I: Zanon), MiChem (PIs: Janssen, Michaut, Fillion), L-IPSL, Plas@par (PI: Tchang-Brillet)
EQUIPEX REFIMEVE+ (co-I: Janssen)
ANR: Gasospin (2009-2014, PI: Michaut), IDEO (2009-2013, co-I: Janssen), SUMOSTAI (2009 - 2012, co-I Tchang-Brillet)
CNRS: MI (PI: Bertin, Janssen, Michaut), PICS (PI: Fillion), CSAA (PI: Fillion);
PN-CNRS: PCMI (PI: Bertin, Dayou, Spielfiedel), PNP (PI: Janssen), LEFE (PI: Janssen, Té), PNPS (PI: Balança, Dulieu, Tchang-Brillet)
CNES: TOSCA MicCarb (2017-2018, PI: Té)
FP7: Sup@VAMDC (2012-2014, PI: Dubernet), Research Data Alliance (2016-, PI: Zwölf), ITN LASSIE (co-I: Fillion), ITN INTRAMIF (2009-2013, co-I: Janssen), COST action (WG3: UV and X-ray photochemistry of "Our Astro-Chemical History: Fillion)
Région Ile de France: DIM-ACAV, ACAV+ (PIs: Michaut, Janssen, Dulieu), HORS-DIM-AIR (2016-2018, PI: Janssen);
Paris Observatory Scientific Council: Programme blanc (Champion, Dulieu, Michaut&Lis, Tchang-Brillet), AF NOEMA-ALMA-Herschel (Lis&Michaut), AFE "Laboratory Astrophysics and analysis of stellar spectra" (Tchang-Brillet).

Activity profile

Corresponding to our key scientific questions, the team activities are oriented along three main axes of research:

(1) **Gas-solid exchanges:** desorption mechanisms, chemical complexity, molecular evolution, (Bertin, Chaabouni, Cobut, Congiu, Dulieu, Féraud, Fillion, Jeseck, Michaut, Moudens, Philippe).

(2) **Molecular processes:** planetary atmospheres, atmospheric composition, remote sensing, high-resolution spectroscopy, multi-spectral spectroscopy, greenhouse gas monitoring, observations, long-term climatology, molecular databases, kinetics, comets (Balança, Blaess, Boursier, Champion, Dayou, Dubernet-Tuckey, Eidelsberg, Elandaloussi, Feautrier, Glass, Janssen, Jeseck, Leach, Marie-Jeanne, Rouillé, Tchang-Brillet, Vasserot, Té, Zanon-Villette).

(3) **Molecular anomalies:** ortho-para ratio of hydrogenated molecules, nuclear spin conversion, spin temperature, kinetic fractionation, oxygen isotopic anomaly, ozone, clumped isotopes

(Bertin, Boursier, Dulieu, Elandaloussi, Féraud, Fillion, Janssen, Jeseck, Marie-Jeanne, Michaut, Moudens, Philippe, Rouillé, Té, Zanon-Villette).

Research products and activities

The main outcome of our research covering the above topics are publications in refereed, highly visible journals read by a broad scientific community (Phys. Chem. Chem. Phys., J. Phys. Chem., J. Chem. Phys., Phys. Rev. A, Phys. Rev. Lett., Chem. Phys., Atmos. Chem. Phys., Atmos. Ocean, Icarus, Geophys. Res. Lett., A&A, Ap. J., Journal of Molecular Spectroscopy, JQSRT, MNRAS, Nature communication, Physica Spectra, Faraday Discuss. ,…). In the last **5 years, approximately 160 such scientific articles have been published.** These publications are listed in full on the web, and 20% in the Appendix 4.

More than 80% of our staff are university faculty who carry out research activities with a significant involvement in teaching. They are pedagogically responsible for developing teaching plans (first year of university, L1-PCGI; 2^{nd} year of master in physics at UPMC, M2; experimental L1 platform) and are in charge of course development and teaching at different levels (*Concepts and methods in physics* at the L1 level, *Quanta & relativity* at the L2 level, *Electromagnetism* at the L3 level, *Biogeochemistry of ocean and atmosphere* at the L3 level, *Atomic and molecular physics* at the M1 and M2 levels, *Sciences of the universe and space techniques* at the M1 and M2 levels, etc.) They participate in scientific outreach events towards the general public during *"Fêtes de la science"* and on other occasions.

Group members are also strongly involved in the different scientific institutions on the local level (Scientific council of the Paris Observatory, Scientific council and Council of faculty of physics of UPMC…). On national and international level, they are involved in the development and coordination of national research programs (PCMI, DIM ACAV+…) and international programs (working group of COST action *Our astrochemical history*, CCQM GAWG task group on ozone cross sections…). The group has extensive worldwide collaborators and high visibility, with members giving numerous (> 50 over the reporting period) invited talks at international conferences and participating in SOC of international conferences.

SWOT Analysis

➔ **Strengths:**

- Unique expertise in the study of fundamental molecular physics in support of astrophysical and atmospheric applications: understanding of physical mechanisms on the molecular scale; providing fundamental molecular data and measurements required for the interpretation of observations.
- A particularly strong background in method development, including the development of instrumentation, software, and theory.
- High international visibility; research activities are well integrated within the particular scientific communities.
- Despite the geographical dispersion, the organization of young sub-teams around different experimental platforms is complementary and efficient.
- The groups remote sensing activities are well embedded into national and international context.
- Strong involvement in the diffusion of atomic and molecular data, in particular via the creation of the international VAMDC Consortium and the worldwide VAMDC e-infrastructure that interconnects about 30 atomic and molecular databases.

➔ **Weaknesses:**

- The group is distributed over three different sites, which complicates communication and interaction between different parts of the team.

- Astrophysical challenges lead to experiments that are more and more sophisticated; technical support to maintain and develop state-ot-the-art experimental platforms is necessary.
- Acquisition of funding from many different sources and for assuring operability of experiments is time consuming.
- Theory team has reached critical mass following the recent and sudden departures (e.g., death of A. Spielfiedel in 2017), which impacts the scope of scientific activities in that field.

➔ **Opportunities:**

- The team has organized regular group meetings and seminars for structuring the communication and research activities at the different sites.
- Collaborations and funding opportunities provided by the managing institutions, the Labex (e.g., Michem), Region Île-de-France (DIM-ACAV+), the Idex Sorbonne Universités and PSL, as well as European programs are being actively pursued.
- The initiative of excellence Paris/Seine and the UCP Institute of Advanced Studies/MIR provide support for developing international programs.

➔ **Threats:**

- The high percentage of university personnel at the MdC level poses the particular risk that young scientific leaders may leave, due to the lack of career evolution opportunities within the laboratory.

Scientific project

1. Reactivity and interaction at the gas-solid interface and in the ice

The solid phase represents only about 1% of the baryonic matter by mass, yet it plays a major role in elemental composition of our observable Universe. For instance, the surface of interstellar dust grains, bare or covered with molecular ices, plays a key role in the cold chemistry of star and planet formation regions. Their catalytic effect is believed to be the starting point of the formation of molecules, from the simplest and most abundant (H_2, H_2O), to the more complex organic species, whose formation is inefficient in the gas phase (CH_3OH, $HCOOCH_3$, CH_3CH_2CHO...). This molecular richness is transferred to the gas phase *via* various **desorption mechanisms**, where further gas-phase chemical processes increase the **chemical complexity** as observed by the latest generation of ground-based radio (ALMA, IRAM/NOEMA) or space telescopes (*Herschel*, upcoming JWST).
However, despite of their fundamental role, many of these physico-chemical processes are still not fully integrated into astrochemical models, mainly because of a lack of quantitative understanding of the mechanisms at the molecular scale. Our research, therefore, aims at studying these processes using state-of-the-art surface science experimental setups, especially designed for identifying and quantifying the molecular physics at the gas-to-solid interface, under conditions mimicking those of the interstellar medium. All these data will be invaluable for better understanding and modelling of observations in the ISM, with ever-increasing resolving power and sensitivity, as it will be the case for instance for the coming JWST mission, will bring a quantity of new questions on the chemistry of the interstellar medium. The main research axes that will be developed are depicted below.

Atom and radical chemistry on cold surfaces

Dust grains are known to be catalytic centres in the cold interstellar medium and molecular clouds that provide competitive and complementary reaction pathways as compared to the gas-phase chemistry. In fact, the surface route contributes significantly and is often crucial to the chemical complexity observed in the universe. Previous common thinking was that hydrogenation is the main driving mechanism for the molecular evolution on grain surfaces. But recent experiments, in part conducted by our group, have shown that (i) the diffusion of O and N atoms on grain surfaces cannot be neglected, and also has to be taken into account, and that (ii) reactions with atomic hydrogen do not automatically lead to an increase of the molecular complexity (i.e., $H_2CO+H \rightarrow HCO+H_2$), as H addition is not necessarily the most competitive reaction mechanism. We are thus facing the question in as much surface reactions are determined by the competition of different addition pathways and the effect of functional groups on reactivity. We intend to study both of these effects systematically using a comparative approach, first by identifying the products of isomeric reactions, e.g., CH_3CN+H versus CH_3NC+H and second by exposing known products of a simple reaction to different chemical agents, such as H and O. Another subject will be the study of the reactivity of small hydrocarbons on surfaces and, in the quest to explain observed molecular abundances, we will newly include sulphur chemistry in our studies, and investigate to which extent the substrate (water, carbonaceous or silicates) takes part in the chemistry. At the same time, the formation of H_2 remains an open and central question in astrochemistry. The study of this reaction will therefore be continued in relation with the upcoming new observational capabilities of JWST.

Database for adsorption, diffusion and thermal desorption

Chemical models of increasing complexity aim more and more at reproducing the observed gas-phase molecular abundances by computing chemistry and desorption from ice mantles. Key parameters are the adsorption energy, diffusion barriers and associated pre-factors of the chemical species adsorbed onto the ice. Some reliable experimental studies already exist in the literature for the determination of these thermodynamic parameters, but they concern mainly small species, and some important properties, such as co-adsorption effects, are not fully understood so far. Over the last years, we have developed systematic methods and studies based on thermal desorption experiments, whose validity has been confirmed by *ab initio* quantum chemistry calculations. We aim at performing these thermal desorption studies in a systematic way and for a variety of molecules, from the simplest to the more complex ones, with the goal to produce a set of quantitative data directly available in databases for astrochemistry, such as the KIDA database. Effects such as co-adsorption, thickness dependencies, and nature of the surfaces (amorphous *vs* crystalline, carbonaceous *vs* hydroxylated, role of defects...) will be further investigated, and their assessment will allow for a better representation of the adsorption and thermal desorption processes in astrochemical modelling.

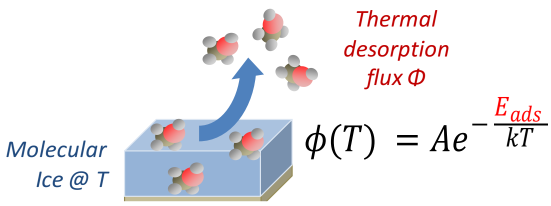


Figure 8.1: *Determination of the adsorption energy by thermal desorption studies.*

Non-thermal desorption and origin of gas-phase organics in the cold ISM

In colder regions of the ISM, the still-unexplained presence of complex organics (methanol, methyl formate...) in the gas phase, at temperatures where these molecules should actually be frozen on grains, suggests that non-thermal desorption processes are at play. With regard to this issue, we aim at bringing new insights into these mechanisms by quantitatively studying two processes: the desorption induced by photons – or photodesorption – and the desorption induced by exothermic recombination reactions, also called chemidesorption.

Concerning UV-photodesorption, current studies progressively move towards the determination of photodesorption rates and mechanisms using more complex and realistic ices than those having been investigated in the past. These ices include frozen mixtures containing H_2O or CO and small organic molecules. The laboratory studies will be based on the generation of VUV laser pulses obtained from laser frequency mixing, coupled to gas-phase probing of the desorbed species using multiphoton ionization spectroscopy. This approach will allow determining the total energy balance of the photodesorption phenomenon by simultaneously accessing the internal and kinetic energy of the desorbed molecules. The mechanisms can thus be unveiled at the molecular scale by identifying the weight of the different contributions, such as dissociation, photochemistry and intermolecular electronic energy transfer. The energy partitioning of the desorption process will be studied by comparing measurements with quantum molecular dynamic simulations (collaboration with PhLAM, Lille). Complementary to these laser-based studies, the synchrotron-based approach at SOLEIL will still allow studying the photon-energy dependency of photodesorption over a wide energy range, which has proven to be a very powerful diagnostic tool for simple model ices. The synchrotron experiments also open up the possibility of studying processes at shorter wavelengths (X-rays), for which almost no quantitative data is available, but where effects are thought to be important, in particular in protoplanetary disks and in PDR. Other, possible non-thermal desorption routes such as chemical desorption will be taken into account when necessary. In addition to X-ray, we will investigate electron-induced desorption using specific set-ups in the framework of two new collaborations with ISMO (Paris-Saclay) for low-energy electrons (1-20 eV) on the one hand, and with CERN (technical vacuum group) for higher energy electrons on the other hand, with the aim of understanding desorption from technical surfaces used in accelerators, such as the superconducting magnets of the Large Hadron Collider (LHC). Indeed, these particles are present in the condensed systems under UV and X illumination, and are expected to play a significant role in the overall photodesorption processes. Systematic comparisons with photon-based experiments are expected to bring valuable information that is interesting both for fundamental astrochemical aspects and for applied technological issues related to large instruments. Finally, the ultimate aim of these studies is to provide sufficient qualitative and quantitative information on non-thermal desorption processes to be included into astrochemical models of the interstellar medium. Due to the high number of parameters that are at play, it currently is a very challenging task to correctly take into account these non-thermal processes, and we aim at contributing to this challenge by strengthening our collaborations with ongoing ISM-modelling activities in the LERMA, such as the PDR code developers in Meudon.

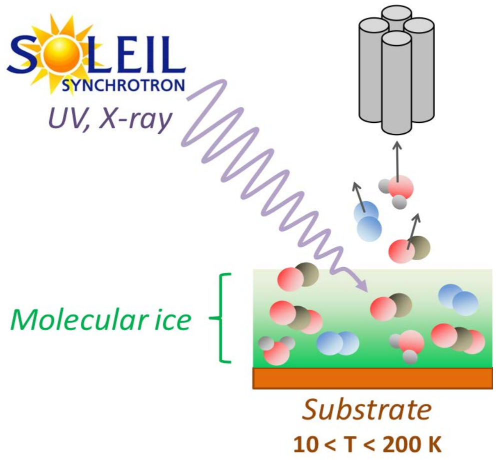


Figure 8.2: *Synchrotron-based study of the photodesorption of interstellar ice analogues.*

2. Molecular parameters and processes for atmospheres and interstellar medium

Molecules are unique tools for probing the physics and chemistry of atmospheres and astrophysical environments. The science developed within this theme is aimed at obtaining reliable **molecular parameters** for probing and modelling a large variety of these environments, ranging from interstellar and circumstellar media to stellar and planetary atmospheres. The project is built upon complementary approaches, involving **spectroscopic measurements**, **theoretical calculations, atmospheric remote sensing** and **the development and operation of database structures.**

Reactive and collisional processes

The theoretical investigations focus on **reactive** and **collisional processes** in the gas phase, which are relevant to probing and modeling astrophysical media. Based on a long-term expertise in both **quantum chemistry** and **dynamics calculations**, the fundamental properties of a variety of molecular processes, such as **reaction rate coefficients** can be determined from theory. Building on our experience in reactions between unstable neutral radicals (e.g., Si+OH $\rightarrow$ SiO+H) at low temperatures needed for the chemical modelling of cold interstellar clouds and difficult to realize in experiments, our work will be directed towards the investigation of **low-temperature isotopic effects**. A joint theoretical and experimental study of a series of reactions involving fully hydrogenated and deuterated species ($C+H_2^+/HD^+/D_2^+$), in collaboration with the group of D.W. Savin at Columbia University is under way. One of the main objectives is to derive kinetic fractionation factors that will help the modelling of **isotopic fractionation** in cold clouds. A challenging issue is the treatment of the complex electronic system due to the interaction of open-shell species. In parallel, we will pursue our recent work on photo-induced processes, with special emphasis on the determination of **rotationally state-resolved photodissociation rate coefficients** of small molecules. These parameters usually suffer from large uncertainties. The impact of the updated data on the modelling of diffuse media will be explored by astrophysical groups (*Interstellar medium and plasmas* pole).

Over the last few years, we have started to develop a new research theme focussing on heterogeneous chemical processes at the gas-solid interface. The project aimed at developing **reduced dimensionality models** using isolated clusters of increasing size to achieve a realistic description of **gas-grain interaction**. Studies have been performed along these lines to model the formation of H_2 on dry silicate dust grains, and promising results have been obtained concerning the reactivity of hydrogen atoms with large silicon bearing molecules (tetramethylsilane, $Si(CH_3)_4$) and on magnesium silicate nanoclusters (nano-olivine and nano-pyroxene clusters). The team leader of this project, Annie Spielfiedel, has recently passed away. New recruitment is urgently needed to continue this theme and, more generally, to reinforce the coupling between the theoretical and experimental activities on solid-gas exchange in our group.

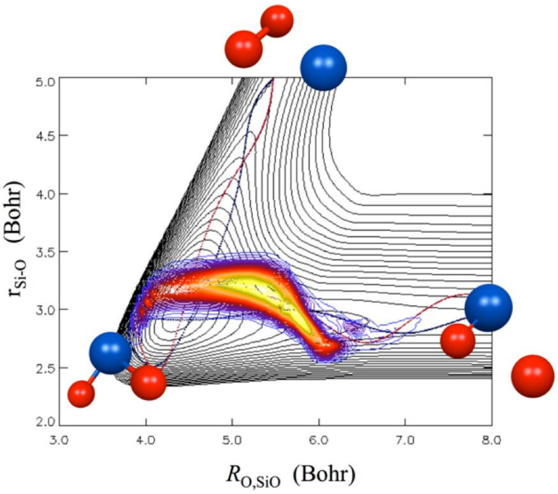


Figure 8.3: *Time evolution of a wave-packet and classical trajectories for the Si+O_2 → SiO+O reaction.*

Our activities on **gas-phase collisional processes** have been mainly concerned with the **rotational excitation** of molecules (H_2O, SO_2, N_2H^+, HCN, C_2H, HCS^+, CS, SiO...) by He and H_2 species. The related rate coefficients are necessary for the modelling of spectral lines originating from interstellar environments under **non-LTE conditions**, which are observed by ground and space instruments (ALMA, *Herschel*, ...). Other studies were dedicated to **electronic excitation** and **ion-pair formation** processes in atomic collisions (Mg+H, Mg^++H^-...), in connection with *Gaia* observations of stellar atmospheres. The work towards providing collisional data relevant to the analysis of spectra from interstellar media on a case-by-case basis and depending on collaborations will be continued. In parallel, a new challenging program has been launched concerning the study of the rotational excitation of molecules (H_2O, HCN, …) in collisions with water, which is relevant to the analysis of cometary atmospheres. Our collisional rate coefficients, which are highly demanded by the astrophysical community, are provided through the BASECOL database and via VAMDC (see Observation services in section 4).

Because of the close link between scientists involved in calculating collisional rate coefficients and the software engineering team developing and maintaining the BASECOL/VAMDC databases, their technical and **method development** activities are included here. Their products are described elsewhere (Observation services in section 4).

Precision molecular spectroscopy, spectroscopic parameters and remote sensing

Traceable spectroscopic data are crucial for **quantitative remote sensing** of planetary atmospheres, motivating our experimental activities in **molecular metrology** through **multi-spectral investigations,** where spectroscopic key quantities are simultaneously determined in different wavelength regions that cover the range from the UV to the mid and far-IR. **Ultra-precise** spectroscopic data are especially required for the

Figure 8.4: *Frequency comb in preparation for laser stabilization.*

use of isotopes as **new tools** for the exploration of atmospheric, physical and chemical molecular processes via remote sensing and in astrophysical laboratory settings. We thus continue the development of our very highly resolved **frequency comb stabilized** mid-IR spectrometer (Fig. 8.4) for the study of small IR active species, such as CO_2, O_3, H_2O… In the past, we have set up a quantum cascade laser (QCL) at 10 µm, with which first line shift measurements of ozone have been performed. The stabilization of this laser system within the frame of FIRST-TF/REFIMEVE+ is currently under way and will allow the determination of line shape parameters beyond the Voigt profile approximation, necessary for the remote sensing by the novel generation of satellite instruments (OCO-3, etc.). The close link to atmospheric observations with our FTS-Paris instrument (see below) will allow for a tight connection between laboratory spectroscopy and remote sensing that permits a good quality control of the spectroscopic data for atmospheric remote sensing.

These experimental activities in molecular spectroscopy are complemented by **modelling new laser interrogation protocols** to improve current precision limits of spectrometers on a fundamental level. Applications range from high precision atomic and molecular spectroscopy over frequency standards to mass spectrometry.

Experimental and theoretical studies of high resolution **VUV spectra** will provide information on electronic transitions of **small molecules** (H_2 and isotopologues, CO, etc.) and photo-dynamical processes of their excited states. At the same time, measurements of **absolute absorption cross-sections** in the UV and visible regions will be continued. High-resolution emission studies **of heavy element multiply-charged ions** (transition metals and rare earths) using the 10-meter normal incidence grating spectrograph in Meudon will yield **precise wavelengths, energy levels and radiative properties** of these ions. This provides laboratory **references** for the detection of a possible variation of fundamental constants from white dwarf spectra of HST and serves the modelling of solar, stellar and laboratory plasmas. The possibility of coupling an EBIT ion source to the vacuum spectrograph for studying ions in coronal conditions will be explored.

We operate the ground based remote sensing FTS-Paris instrument, which continuously monitors the urban atmosphere above Paris (see Fig. 8.5). Since 2014, the instrument is part of the worldwide **greenhouse gas monitoring** network TCCON and fulfils the corresponding operation requirements. Total column measurements will be used to **validate** ongoing (OCO-2, GOSAT2) and planned **satellite missions** (MicroCarb, Merlin). The instrument will also perform **long-term climatological studies**. It is integrated into the observational platform OCAPI of IPSL, where it provides valuable **vertical information** with respect to **atmospheric composition change** in a megacity area. In this context, we particularly aim at understanding on how the spatially integrated information can be used for improving chemical transport modelling on the regional scale.

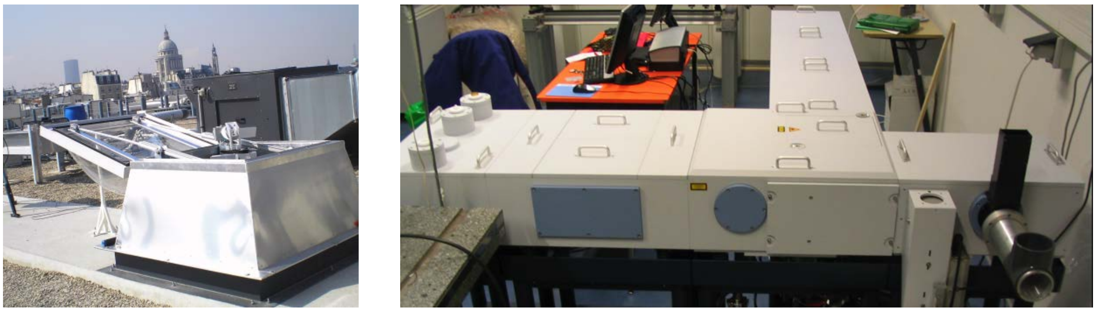


Figure 8.5: *TCCON station at Paris (left: sun tracker, right: FTS instrument). The FTS-Paris is dedicated to regular and continuous long-term measurements of the atmospheric composition. Due to its privileged location in a large urban area (only two such instruments worldwide), it is a preferred target for actual and upcoming international satellite missions (OCO-2/3 (NASA 2014-), MicroCarb (CNES/ESA: 2020-), Merlin (DLR/CNES: 2021-2024), GOSAT2 (JAXA: 2017-2022)).*

3. Molecular anomalies

Figure 8.6: *Illustration of nuclear spin conversion in water. The OPR of molecules in star forming regions, such as in the Orion bar, may provide important information on the physico-chemical history of the medium.*

The science developed within this theme aims at identifying and interpreting molecular processes that lead to hitherto incompletely understood molecular abundance signatures, such as isotope effects or nuclear spin ratios. These have the potential to serve as unique tracers of the physics and chemistry in remote environments. Our aim is to address the mechanisms responsible for the observed molecular anomalies in planetary and cometary atmospheres, and in space.

Unusual abundances of ozone isotopologues

The thermochemical reaction of ozone formation in the gas phase leads to a large and unconventional, **molecular symmetry-driven** distribution in the heavy isotopes of oxygen. We continue to explore this yet not completely understood **isotope anomaly** by studying the inverse process, i.e. the **thermal decomposition** of ozone in the gas phase and on the surface, using laser spectroscopic techniques. In contrast to mass spectrometer investigations, the technique is non-destructive and thus allows direct and online observation of the decomposition process. The bath gas dependence on ozone formation has shown unexpected results. In our decomposition studies, we will therefore in particular focus on the **bath gas** and **temperature dependencies** of ozone decomposition for improving our understanding of the physical-chemical origin of the isotope fractionation process. The quest for other chemical reaction systems, where similar symmetry driven fractionation effects might occur, is another field of future activity. Here, we will concentrate on the spin-forbidden association of oxygen atoms with carbon monoxide and the **isotope transfer** from ozone to CO_2. Past studies, including those that we have performed in the framework of the ITN-INTRAMIF, in collaboration with Copenhagen, have not been successful in demonstrating unambiguous evidence due to the presence of interfering reactions. We currently work on reducing these interference effects. Moreover, the development of a new **multi-isotope spectrometer** for CO_2 in a bi-national collaboration with Prof. N. Frank from Heidelberg University (Germany) will allow unprecedented level of information due to the inclusion of very rare or "**clumped**" isotopes in the analysis, meaning that six different isotopologues of CO_2 can be analysed simultaneously. This will be particularly useful for the study of isotope transfer processes.
The unusual oxygen isotope fractionation observed in ozone formation has led to the idea that ozone like association reactions in the gas or at the surface could possibly explain the unusual oxygen isotope distribution found in the oldest oxygen containing refractory solids of the solar system. Our laboratory experiments might provide the physico-chemical clues to better understand the origin of this meteoritic record.

Isotopic fractionation on icy films

Low-temperature isotope fractionation processes relevant to cold molecular cloud chemistry are another interesting research topic, and we intend to study the diffusion of oxygen atoms in low-temperature ices of different composition. Here, large and anomalous isotope fractionation effects are expected due to **quantum tunnelling** effects in surface hopping, which in our previous studies has been shown to be important. The reactivity of H and D will be studied in systems, where barriers towards the reaction are present. We also plan to study **proton exchange** processes in the thin film desorption of water in order to investigate its effect on the **D/H ratio** in cometary water.

Nuclear spin ratios of hydrogenated molecules

Water and other multiply hydrogenated molecules (like H_2CO, CH_4, or NH_3) can exist in several spin configurations, because of the fermionic character of the hydrogen nucleus. These configurations are called ***ortho*** or ***para***, depending on whether two H-spins are parallel or antiparallel. The ***Ortho-to-Para Ratio*** (OPR) in various astrophysical objects (cometary atmospheres, protoplanetary disks, diffuse clouds, photon dominated regions) can be determined from rotational and ro-vibrational spectra recorded by space or ground-based telescopes. Observed OPR values are often very different from those expected for the probed gaseous environments and the interpretation of these anomalies therefore remains speculative. It is generally assumed that observed OPRs reflect the temperature of the environment where the molecules formed. However, the link to the physico-chemical history of the molecules is not well established, and particularly the role of icy films and adsorption/desorption mechanisms (thermally or photon induced) remains unclear.

Our group has long-standing expertise of studying the physical processes involved in **Nuclear Spin Conversion** (NSC), which allows the change of the total nuclear spin of the molecules. The physical origin of this inter-conversion is the flipping of the hydrogen nuclear spin under the action of inhomogeneous magnetic fields (produced by rotations or spins of the particles) and the local electrical environment.

As it has been demonstrated within the GASOSPIN collaboration (ANR), NSC is a very slow process in diluted gaseous media, as compared to the time scale prevailing in astrophysical environments. But we have recently shown that confinement effects in rare gas solids dramatically accelerate the conversion rate and NSC in solids can be tens of orders of magnitude faster than in the gas phase. The interaction of molecules with cold solid grains in space may thus provide a very efficient mechanism for reinitializing the OPR, as well as for modifying the total OPR of molecules after release to the gas in the ISM. In order to further investigate this issue, we update our experimental set-ups COSPINU (Conversion de SPIn NUcléaire) and SPICES (Surface Processes and ICES). The SPICES experiment will investigate the influence of the wavelength on photodesorption and the capacity of the ice to preserve the OPR during condensation and desorption (PhD MiChem). In collaboration with the University of Sherbrooke (Canada), we develop a method for nuclear spin enrichment in the gas phase using magnetic focalization to control the OPR during the fabrication of the icy films. The new COSPINU setup will allow investigating the possibility of alternative enrichment techniques using optical pumping, first, in rare gas matrices, then in the gas phase. In the meanwhile, we will reinforce the collaboration with the ISM observational group of LERMA, to identify the conditions existing in the spatial environment (density, temperature, flux of UV photons, grain density) and influencing the OPR in the ISM. It is anticipated that this close tie between laboratory astrophysics, observations, and modelling will be very fruitful to identify keys for the interpretation of the origin of OPR found in astrophysical environments.

9. Presentation of the pole "*Instrumentation and remote sensing*"

Introduction

The **Instrumentation Group** has been involved for several decades in building of space-borne and balloon-borne heterodyne instruments dedicated to astrophysics, planetology or the sciences of the Earth's atmosphere. The group has built its R&D activities to master the design, technology and characterization of devices, circuits, or entire heterodyne instruments. It has the required expertise and instrumentation to take part in competitive international projects. The group chooses its R&D projects to fulfill the needs of the astronomical and Earth Remote Sensing community and possibly to open new fields in astronomy and Earth science. It also applies its technology to other disciplines, such as laboratory molecular spectroscopy. In the coming 5 years, the THz instrumentation group will on the one hand exploit its expertise to participate or lead future space projects, and on the other hand it will push the technological frontiers with dedicated R&D work to produce innovative instruments.

This group includes 2 researchers, 2 emeriti, 8 ITA (3 IR, 2 IE, 1 AI, and 2 T), 3 CDD (2 IR and 1 IE), and 3 PhDs.

The **Earth and Planet Remote Sensing** activity at LERMA is originally strongly linked with the instrumentation group, with a large activity on the exploitation of the passive microwave observations from satellites, for the analysis of the Earth atmosphere and surfaces. It includes the analysis of satellite observations, the modeling of radiative transfer, the development of inversion methods, and the exploitation of multi-satellite observations, mainly for a better understanding of the Earth's energy and water cycle.

This group includes 2 researchers, 1 IR, and 4 PhDs.

The strengths of the group are:

- Unique expertise in THz devices, covering both supra-conductive and Schottky devices, in partnership with C2N.
- Innovative methodology to estimate the atmospheric and surface variables from space (e.g., integrated ice content, soil moisture, surface water extent, surface skin temperature), from multiple-satellite observations, at global scale.

Key science questions that the group is addressing are:

- Optimizing the detection of millimeter to terahertz radiation for astrophysical and planetary studies.
- Improving the quantification of key variables of the Earth water and energy cycle using multiple satellite observations.

Staff and resources

15 Permanent staff members (4 researchers, 9 ITA, 2 Emeriti):

F. Aires (DR-CNRS), M. Ba Trung (T), F. Dauplay (IE), Y. Delorme (IR), P. Encrenaz (Emeritus), A. Feret (IE), L. Gatilova (IR), J.-M. Krieg (IR), A. Maestrini (MdC), L. Pelay (T), C. Prigent (DR-CNRS), F. Viallefond (Emeritus), T. Vacelet (AI), X. Wang (IR), M. Wiedner (CR-CNRS).

10 Non-permanent staff members (7 Ph.D. students, 3 CDD):

S. Caroopen (CDD IR), D. Delfini (PhD student), G. Gay (CDD IR), F. Joint (PhD student), L. Kilic (PhD student), J. Mathieu (PhD student), S. Mignoni (CDD IR), D. Moro-Melgar (PhD student), V. Pellet (PhD student), D. B. Pham (PhD student).

Resources:

The pole builds its development upon contractual activities that account for more than 90% of its funding.

These contracts are mainly institutional (CNES, ESA, UE, ANR...), but also with private companies (RPG, Estellus...). Details can be found in Annex 4.

CNES contracts:

- Juice-SWI development: from phase 0 to B, phase C starting mid-2017.
- R&D for instrumentation: 4 contracts covering Schottky and HEB activities (multipliers and QCL for LOs, mixers, receiver arrays...)
- Several TOSCA projects for the remote sensing activities.

ESA and EUMETSAT contracts:

- 2 ESA contracts on Schottky terahertz activities, one as Prime and the other one as Subcontractor
- 2015 Participation in 'Study on surface emissivity at microwave and sub-millimeter frequencies' (EUMETSAT).
- 2012-2015: 'Use of spectral information at microwave region for Numerical Weather Prediction' Contract No. 4000105721/12/NL/AF (ESA).

UE:

- 2 successive Radionet contracts (FP7/AETHRA task 4, H2020/AETHER).

PICS:

- 2 HEB projects in collaboration with PMO in Nanjing.

ANR:

- IMOLABS dedicated to laboratory spectroscopy in the THz field, in collaboration with LPHAM/Université de Lille.

CNRS National Programs:

- PNTS

Industrial contracts:

- 2 contracts for fabrication of HEB and Schottky devices, in collaboration with C2N.
- 1 contract for space cryo-cooler technical investigation.

Activity profile

The group activities and projects can be classified in 4 main themes:

(1) **Development of Schottky receivers**: devices, multipliers, mixers, receiver systems, instruments (Maestrini, Gatilova, Vacelet, Feret, Caroopen, Moro Melgar, Mignoni, Gay, Dauplay, Ba Trung, Pelay, Krieg)

(2) **Development of HEB receivers:** devices, mixers, receiver systems, instruments (Delorme, Wiedner, Joint, Vacelet, Feret, Gay, Dauplay, Delfini, Ba Trung, Pelay, Krieg)

(3) **Multi-satellite retrieval of surface parameters:** Land surface temperature **(**Prigent, Aires**),** Ocean surface temperature (Aires, Prigent, Kilic), Surface water mapping (Prigent, Aires, Pham), Microwave emissivity calculation (Prigent, Wang), Closure of the water budget (Aires, Pellet), agricultural yield (Mathieu, Aires), Roseta mission **(**Encrenaz, Beaudin**).**

(4) **Multi-satellite estimation of atmospheric parameters**: characterization of the ice clouds with millimeter frequencies (Prigent, Aires, Wang), atmospheric retrieval with hyperspectral infrared observations (Aires, Pellet, Prigent)

Research products and activities

The research team has published ~70 publications in refereed international journals since 2013. The group has also participated in many conferences, with proceedings. For some of these conferences, a team member was invited to give a talk. See Annex 4 for more details. We participated in the organization of workshops and conferences. Members of the team are regularly solicited to review projects nationally and internationally, and are frequent reviewers for international journals.

The technical group has developed several prototypes and demonstrators for future satellite missions, or for ground-based instruments. This includes a heterodyne demonstrator at 1.2THz that convinced ESA to rely on our group to build this channel for the JUICE-SWI instrument.

The remote sensing group distributes software that is integrated in radiative transfer community codes, used by the weather prediction centers. It also distributes satellite-derived geophysical products, to a large national and international scientific community.

Several members of the team are teaching in Engineering Schools and in Universities.

SWOT analysis

➔ **Strengths:**

- The pole has a strong expertise in high-frequency (THz) heterodyne receivers and is well prepared to participate in satellite missions.
- We build instruments for large international missions, such as JUICE (JUpiter Icy Moon Satellite Mission) and gain space experience, as well as international recognition.
- We are part of several international workgroups (e.g. H2020 Radionet, ESA R&D).
- The mixers initially developed for HIFI band 1 are currently used in the 4GREAT instrument on SOFIA, commissioned in July 2017.
- Strong implication in the preparation of the Ice Cloud Imager on MetOp-SG; only group in France to work directly on this topic.
- Production of unique multi-satellite land surface products at global scale, and over long-time series (e.g., microwave land surface emissivity, surface water extent, surface skin temperature) distributed to a large community.
- Big data expertise to optimally process large volumes of space observations.

➔ **Weaknesses:**

- Limited number of permanent positions in the pole. Difficulty to keep the PhD students that have been trained in the pole.
- Participation in a very large diversity of projects that is often difficult to handle with a decreasing number of permanent positions, only partly compensated by temporary positions.

➔ **Opportunities:**

- The LERMA instrumentation team is actively involved in several planned astrophysics satellite missions, thanks to a combination of scientific and technical expertise:
  - *Millimetron* (a Russian 10-m class cooled FIR telescope);
  - FIRSPEX (Far IR Spectroscopic EXplorer submitted to the ESA M5 call);
  - Leadership of the heterodyne instrument study for the *Origins Space Telescope* (a candidate for a NASA flagship mission for the 2020 decade).
- The remote sensing team has worked closely over many years on the preparation of several future international meteorological missions:
  - ICI on MetOp-SG corresponds perfectly to the expertise that the team has developed;
  - The Surface Water and Ocean Topography (SWOT) mission (NASA/CNES) that will measure the continental surface waters with unprecedented accuracy;

- The ESA Earth Explorer call, where an ocean mission is proposed with PI in the group.

➔ **Threats:**

- The R&D and space projects are highly dependent on the cleanroom engineers. The staff has declined from 4 positions (3 permanent and 1 temporary) to one permanent position in 2016. Though anticipated, this reduction has not yet been compensated and puts our activities at high risk.
- Although many potential future FIR spectroscopic astrophysics missions are under discussion, none is currently funded.

Scientific project

Instrumentation group prospective

Instrumentation for Astronomy

The astronomical community requires the most sensitive receivers possible to detect the faint emission from the universe. One of the new frontiers is the THz or far-infrared universe, which is little explored so far. A necessity for the formation of stars is the cooling of the interstellar gas, and the most important cooling lines of the interstellar medium (e.g., [CII], [NII], [OI]) lie between 1 and 5 THz. Therefore, we are developing heterodyne receivers for this THz frequency range: on the one hand, we are developing Hot Electron Bolometer (HEB) mixers which are the most sensitive devices above ~1THz, and on the other hand we are developing Local Oscillators (LO) for these receivers. There are two classes of LOs: multiplier amplifier chains and quantum cascade lasers (QCLs). We will further develop both. In the last 5 years, our Schottky group has made technological advances of the multipliers to obtain powerful LOs of up to about 1 THz. In the upcoming 5 years, we will develop powerful LO chains up to 3 THz. QCLs are a new technology that have sufficient LO power but cannot yet be used for satellite missions, as they have too high power consumption, too low operating temperatures, are not continuously tunable and require phase lock loops. We will carry out R&D work in all of these fields, to advance the QCL technology for space mission.

Another astronomical requirement is the mapping of large areas in molecular lines. Traditional heterodyne receivers have a single pixel and take a single spectrum. Small array receivers with a few pixels have been built. The next step forward will be to design large (of order of 100 pixels) heterodyne arrays. This requires rethinking of the receiver design and substantial changes to facilitate the construction of large heterodyne arrays, with close packaging and heat dissipation being important aspects.

Besides this R&D work, we will also exploit our previous developments by applying them to the next generation of far-IR satellites. We are part of the Russian led *Millimetron* consortium and will contribute to its conceptual design. We have also been part of a UK lead M5 proposal for the FIRSPEX heterodyne mission. Next, we are leading a European study of a heterodyne instrument for the *Origins Space Telescope*, currently under study by NASA in preparation of the US 2020 Decadal Survey. First reflections of proposing our own satellite project THEO to map the Galactic plane in the major THz cooling lines will also be made.

Instrumentation for Planetary Missions

The solar system can be studied in great detail by sending probes to the planets and theirs moons, or comets and meteors. Planetary missions take a multi-wavelength approach to study different aspects. They require instruments with long lifetimes and radiation hardiness, as the flight to the planet/moon often takes a very long time. This makes cryogenic cooling impossible. Our laboratory has developed Schottky mixers for submm to THz frequencies that are slightly less sensitive but can operate at any temperature. In the last 5 years, the laboratory has not only provided an LO at 600 GHz for the Submillimeter Wave Instrument on JUICE, but is also delivering the entire front-end receiver at 1200

GHz. Some follow up for the JUICE mission is expected to take place.

After delivering space-qualified receivers for JUICE in 2018, the Schottky development will concentrate on R&D work to push to higher frequencies, but also to increase sensitivity. An ANR with the university of Lille will be submitted to develop Schottky diodes out of GaN to make more powerful LOs. We will also apply for missions of opportunity such as the Next Mars Orbiter (NEMO) or the satellite program proposed by India. A joint project with PMO for the Chinese space station is also under discussion. The Schottky developments also strongly benefit the Earth observations community, especially with the decision of having millimeter to sub-millimeter satellite observations, up to 700 GHz, for operational meteorology.

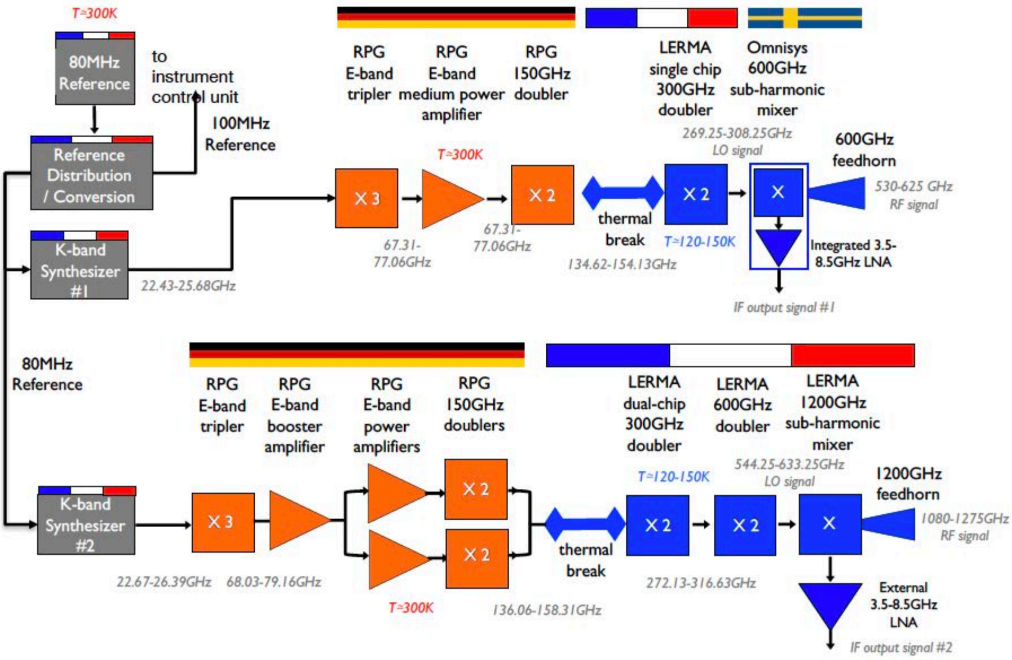


Figure 9.1: *The LERMA contribution to the JUICE/SWI instrument (indicated with French flags).*

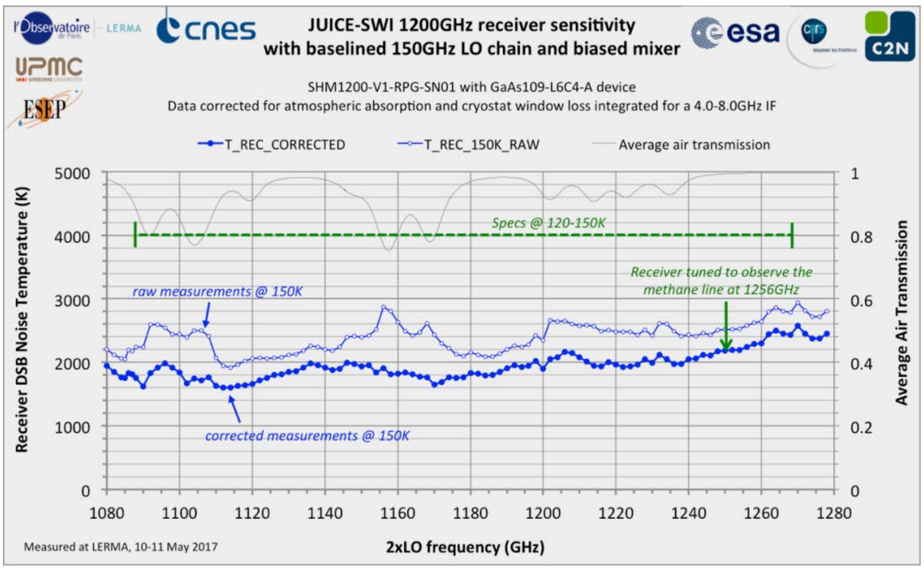


Figure 9.2: *The performances of the JUICE-SWI receiver at 1.2THz, well below the requested specifications.*

Instrumentation for Earth Atmospheric Studies and Remote Sensing

Earth remote sensing also involves observations of the emission/absorption/scattering by the constituents of our atmosphere (gas and hydrometeors), as well as observations of the surface emission. Measurements in the millimeter to submillimeter wavelength range have so far been very limited, but the selection of a heterodyne radiometer to fly on the next generation of the operational meteorological satellite in Europe is triggering new developments. At LERMA, we have the technology to participate in airborne missions or to develop ground-based instruments. One anticipated project is to build radiometers to measure the cloud cover above the ALMA astronomical interferometer. It will allow the astronomical community to use the observing time most efficiently by switching to the observing frequencies least affected by the clouds. It will also provide the atmospheric community with needed statistics on the scattering properties of ice clouds.

Interdisciplinary application

Within the ANR IMOLABS we applied our heterodyne technology to laboratory molecular spectroscopy. We will continue our fruitful collaboration with our colleagues in molecular spectroscopy, where we provide innovative instrumentation and they carry out spectroscopic measurements, which are in turn essential for the astronomical community. We will look for other such interdisciplinary collaboration, where we provide heterodyne instrumentation, such as at the SOLEIL accelerator for absorption spectroscopy.

Infrastructure

LERMA has a well-equipped laboratory for construction and testing of instruments. We are planning to upgrade this laboratory slightly to allow us to conduct larger space project in clean environments.

The fabrication of our HEB and Schottky devices, which are the heart of our components, is taking place in the clean rooms at the C2N laboratory. We have one LERMA research engineer working full time at C2N. To facilitate the exchange between the LERMA and the C2N group, we will establish a THz components group to bring together engineers working in the same field in both laboratories.

Earth and Planet Remote Sensing group prospective

Characterization of ice clouds with millimeter and sub-millimeter satellite observations for MetOp-SG

The next generation of European meteorological satellite (EUMETSAT Polar System Second Generation EPS-SG), to be launched in 2021, will provide continuity of observations with the current EPS, in the microwave domain up to 200 GHz, but will also include innovative measurements in the millimeter range up to 664 GHz, with the Ice Cloud Imager (ICI). Our group is already deeply involved in the preparation of the exploitation of ICI and will reinforce this activity in the years to come. It will include the analysis of the observations from the ICI airborne demonstrator that will continue flying in different campaigns, in diverse environments. We will refine the radiative transfer understanding in this wavelength range, especially in presence of frozen clouds and snow. We will also contribute to the development of the operational retrieval methodologies, with our expertise in statistical inversion.

Ocean and land surface temperature from satellite passive microwave observations

The ocean and land surface temperatures on global scales are traditionally estimated from IR satellite instruments. However, under cloudy conditions, the IR cannot provide surface temperature estimates. Over ocean, we proposed to CNES and ESA a new satellite mission (MICROWAT) to estimate sea surface temperature with microwave observations, at a 10-km spatial resolution. This mission has not been selected yet, but more investigations have to be conducted to reach maturity. This will be one of our main topics in the years to come. Over land, we developed a new methodology to estimate robust land surface temperatures on a real-time basis, and to produce climate quality time series (40

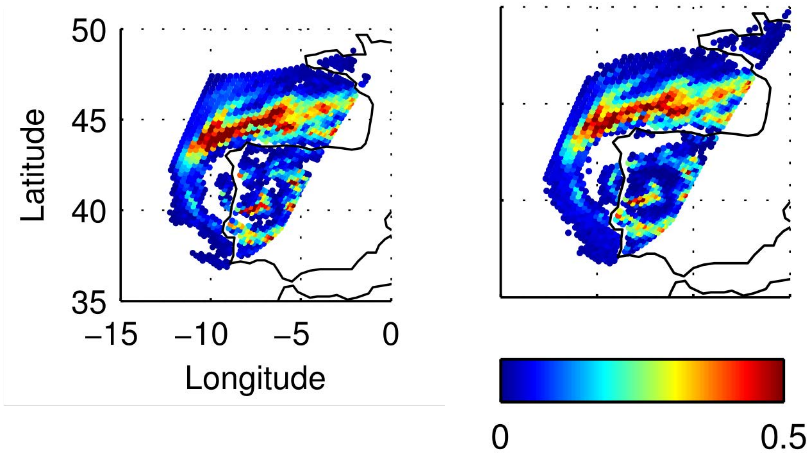


Figure 9.3: *The initial (left)) and retrieved (right) integrated quantities of frozen hydrometeors (Frozen Water Path in kg/m^2) for a storm over Portugal, on January 19th, 2013, as could be observed with a combination of ICI and MWI on board MetOp-SG mission.*

years). This methodology will be applied in the next years and the climate analysis will be conducted.

Surface water extent and dynamics in the SWOT area

The NASA/CNES Surface Water and Ocean Topography (SWOT) mission, with its innovative large swath altimeter, will provide surface water extent and slope with an unprecedented accuracy and spatial resolution. Our group has a long experience in the detection of the surface water surfaces and the analysis of their dynamics, using multi-satellite observations, first at low spatial resolution (25 km × 25 km) and now at much finer resolution, thanks to downscaling methodologies. Our contribution to the SWOT mission involves the development of realistic surface water masks at global scale, including their dynamics, for the testing of the SWOT continental retrieval methodology, as well as to prepare the cal/val program. We will also help developing the retrieval algorithms, combine several types of Earth observations to build optimized and comprehensive hydrology databases, and exploit these data in terrestrial hydrology, e.g. by developing river discharge parameterizations or study the water budget.

Earth water budget using multi-satellite observations

Despite the abundance of satellite observations in recent decades (and the advances in climate modeling), the understanding of the water cycle complex dynamics is still a challenge, and the water cycle intensification/acceleration with climate change is still being debated. Precipitation, sea-level, soil moisture, water storage, evapo-transpiration and atmospheric water vapor are all components of the water cycle that can be obtained from satellite Earth Observations (EO), at a global scale. However, uncertainty on these EO estimates are such that closing the water cycle is still impossible, limiting the use of the EO data. LERMA has developed an internationally recognized expertise in methodologies to integrate multi-satellite observations in a consistent way, for an optimal monitoring of the water cycle, along with an evaluation of the modeling efforts. This activity has been tested with success so far at basin scale (e.g., Mississippi or the Mediterranean region). In the next years, efforts will be made to extend it to the global scale, offering to the scientific community a full satellite analysis of the water cycle. This will impact many socio-economic applications.

Despite limited manpower in the group, all these activities will be made possible thanks to a large network of strong and stable collaborations with different institutes all over the world (in France, e.g., LMD, LEGOS, CESBIO, LA; in Europe, e.g., University of Chalmers, Koln University, UK Met Office; and in the US, NASA/GISS, City College NY, NOAA, AER), and active participation in a number of international projects and committees (GEWEX, ITOVS).

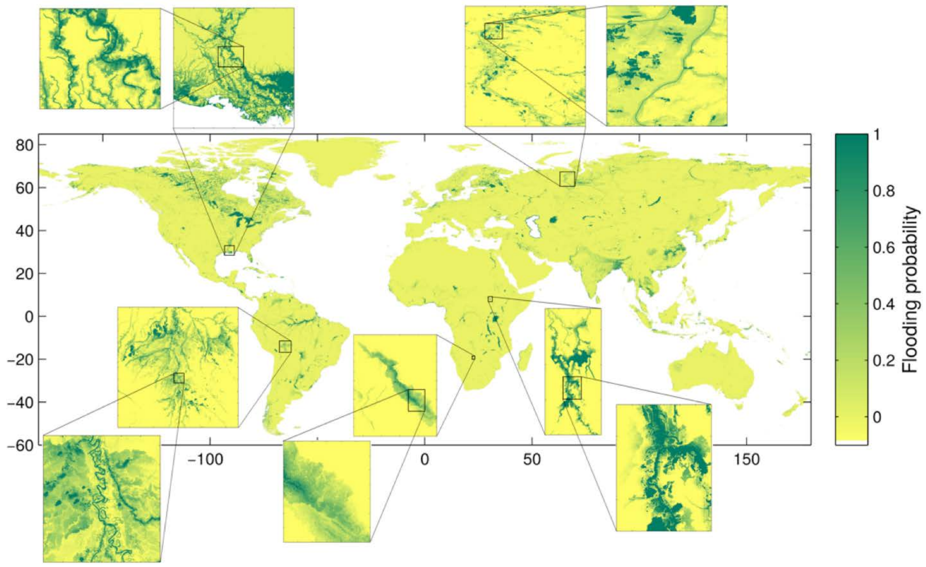


Figure 9.4: *Flooding probability derived from the combination of multi-satellite data and digital elevation model.*

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List of acronyms

ADASS – Astronomical Data Analysis Software and Systems
ADMIT –ALMA Data Mining Toolkit
AERES – Agence d'Evaluation de la Recherche et d'Enseignement Supérieur
AF – Action Fédératrice
AGB – Asymptotic Giant Branch
AGN – Active Galactic Nucleus
AI – Assistant Ingénieur
ALMA – Atacama Large Millimeter/submillimeter Array
ANO – Action National pour l'Observation

ANR – Agence National de la Recherche
APEX – Atacama Pathfinder Experiment
ARC – ALMA Regional Center
ARTEMIX – ALMA Remote Mining Experiment
AS – Action Spécifique
ASA – Action Spécifique ALMA
ATHENA – Advanced Telescope for High-Energy Astrophysics
C2N – Centre for Nanosciences and Nanotechnology
CCQM – Consultative Committee for Amount of Substance
CDD – Contrat à Durée Déterminée
CdF – Collège de France
CDM – Cold Dark Matter
CDMS – Cologne Database for Molecular Spectroscopy
CEA – Commissariat à l'Energie Atomique et aux Energies Alternatives
CERN – European Organization for Nuclear Research (originally Conseil Européen pour la Recherche Nucléaire)
CFHT – Canada France Hawaii Telescope
CMB – Cosmic Microwave Background
CNAP – Conseil National des Astronomes et Physiciens
CNES – Centre National d'Études Spatiales
CNRS – Centre National de la Recherche Scientifique
Co-I – Co-Investigator
CR – Chargé de Recherche
CTA – Cherenkov Telescope Array
DESIRS – Dichroïsme Et Spectroscopie par Interaction avec le Rayonnement Synchrotron
DIM– Domaine d'Intérêt Majeur
DIM-ACAV – Domaine d'Intérêt Majeur Astrophysique et Conditions d'Apparition de la Vie
DR – Directeur de Recherche
EADS – European Aeronautic Defense and Space company
EBIT – Electron Beam Ion Trap
ED – École Doctoral
ENS – École Normale Supérieure
EoR – Epoch of Reionization
Equipex – Equipements d'Excellence
ERC – European Research Council
ERS – Early Release Science
ESA – European Space Agency
ESEP – Exploration Spatiale des Environnements Planétaires
ESO – European Southern Observatory
EU – European Union
EWASS – European Week of Astrophysics and Space Science
FAST – Five Hundred Meter Aperture Spherical Telescope
FIR – Far-Infrared
FIRSPEX – Far-Infrared Spectroscopic Explorer
FORMOLISM – Formation of Molecules in the ISM
FTE – Full Time Employee
FTS – Fourier-Transform Spectrometer
FUSE – Far Ultraviolet Spectroscopic Explorer
GAWC – Gas Analysis Working Group
GIEMS-3D – Global Inundation Extent from Multi-Satellite Downscaled to 3 arcseconds
GOSAT – Greenhouse Gases Observing Satellite
GREAT – German Receiver for Astronomy at Terahertz Frequencies
GUSTO – Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory
HEB – Hot Electron Bolometer
HIFI – Heterodyne Instrument for the Far-Infrared
HOU – Hands On Universe
HPC – High Performance Computing

HST – Hubble Space Telescope
IAS – Institut d'Astrophysiaue Spatiale
IAU – International Astronomical Union
ICFP – International Center for Fundamental Physics
ICI – Ice Cloud Imager
Idex – Initiative d'Excellence
IE – Ingénieur d'Etudes
ILP – Institut Lagrange de Paris
IMP – Interstellar Medium and Plasmas
INSU – Institut National des Sciences de l'Univers
IPSL – Institut Pierre Simon Laplace
IPAG – Institut de Planétologie et d'Astrophysique de Grenoble
IR – Ingénieur de Recherche
IRAM – Institut de Radioastronomie Millimétrique
IRIS – Initiative de Recherches Interdisciplinaires et Stratégiques
ISM – Interstellar Medium
ISMO – Institut des Sciences Moléculaires d'Orsay
IT – Information Technology
JCMT – James Clerk Maxwell Telescope
ICS – Institute du Calcul et de la Simulation
JPL – Jet Propulsion Laboratory
JVLA – Jansky Very Large Array
JUICE – Jupiter Icy Moons Explorer
JWST – James Webb Space Telescope
LAB – Laboratoire d'Astrophysique de Bordeaux
Labex – Laboratoire d'Excellence
LEFE – Les Enveloppes Fluides et l'Environnement
LHC – Large Hydron Collider
L-IPSL – Labex Institut Pierre Simon Laplace
LMJ – Laser Mégajoule
LO – Local Oscillator
LOFAR – Low-Frequency Array
LPMAA – Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique
LPN – Laboratoire de Photonique et de Nanostructures
LPP – Laboratoire de Physique des Plasmas
LPS – Laboratoire de Physique Statistique
LSB – Low Surface Brightness
LSST – Large Synoptic Survey Telescope
LULI – Laboratoire pour l'Utilisation des Lasers Intenses
LUTh – Laboratoire Univers et Théories
LVG – Large Velocity Gradient
MdC – Maître des Conférences
MetOp-SG – Meteorological Operational Satellite Program of Europe – Second Generation
MesoPSL – Mésocentre de calcul PSL
MHD – Magneto Hydro Dynamics
MIR – Maison Internationale de la Recherche
MIRO – Microwave Instrument for Rosetta
MIS – Milieu Interstellaire
MoU – Memorandum of Understanding
MPIfR – Max-Planck-Institut fur Radioastronomie
MUSE – Multi-Unit Spectroscopic Explorer
NenuFAR – New Extension in Nançay Upgrading LOFAR
NIF – National Ignition Facility
NASA – National Aeronautics and Space Administration
NOEMA – Northern Extended Millimeter Array
NRAO – National Radio Astronomy Observatory
NWP – Numerical Weather Prediction

OASU – Observatoire Aquitain des Sciences de l'Univers
OCAPI – Observation de la Composition de l'Air de Paris
OCO – Orbiting Carbon Observatory
OP – Observatoire de Paris
OPR – Ortho Para Ratio
OST – Origins Space Telescope
OSUG – Observatoire des Sciences de l'Univers de Grenoble
PADC – Paris Astronomical Data Centre
PALS – Prague Asterix Laser System
PCMI – Programme National de Physique et Chimie du Milieu Interstellaire
PCGI – Physique, Chimie, Géosciences, Ingénierie
PDR – Photon Dominated Region
PIA – Programme d'Investissement d'Avenir
PI – Principal Investigator
PMO – Purple Mountain Observatory
PNCG – Programme National Cosmologie et Galaxies
PNP – Programme National de Planétologie
PNPS – Programme National de Physique Stellaire
PNTS – Programme National de Télédétection Spatiale
PSL – Paris Sciences et Lettres
QCL – Quantum Cascade Laser
QI2 – Qualité de l'air, Impacts sanitaires et Innovations technologiques et politique
RAS – Russian Academy of Sciences
REFIMEVE+ – Reseau Fibré Metrologique à Vocation Européenne+
RPG – Radiometer Physics GmbH
SIS – Superconductor Insulater Superconductor
SKA – Square Kilometer Array
SNR – Super Nova Remnant
SOFIA – Stratospheric Observatory for Far-Infrared Astronomy
SOLEIL – Source Optimisée de Lumière d'Energie Intermédiaire du LURE
SPICA – Space Telescope for Cosmology and Astrophysics
SPICES – Surface Processes and Ices
SWI – Submillimeter Wave Instrument
SWOT – Surface Water Ocean Topography
TASQ – Télédétection Atmosphérique et Spectroscopie Quantitative
TCCON – Total Carbon Column Observation Network
TOSCA – Terre Solide, Océan, Surfaces Continentales et Atmosphère
UCP – Université Cergy-Pontoise
UHV – Ultra-High Vacuum
UMI – Unité Mixte Internationale
UPD – Université Paris Diderot
UPMC – Université Pierre et Marie Curie
VAMDC – Virtual Atomic and Molecular Data Center
VENUS – Vers de Nouvelle Synthèse
VLA – Very Large Array
VLT – Very Large Telescope
VUV – Vacuum Ultra Violet
ZRR – Zone à Régime Restrictif

ANNEXES

Annex 1: Lettre de mission contractuelle

Such document does not exist for LERMA.

Annex 2: Équipements, plateformes

This information is included in the main text, page 12-13.

Annexe 3 : Organigramme fonctionnel

Tutelles
CNRS DR5 INSU
Etablissements : OP ENS P6 UCP

Partenaires
Agences **Co-contractants** **Fournisseurs**
CNES Labos
ESA Industriels
ANR
ERC

Direction
Directeur D. Lis
Directeurs adjoints J-H. Fillion et F. Le Petit
Directeur Technique J-M. Krieg
Attachée de direction V. Audon
Administrateur financier L. Girot

Equipe administrative (moyens communs)
Personnel V. Audon
Formation permanente P. Landry, D. Lopes, N. Roger
Budget – Finances N
Accueil et évènements V. Bigot
Cellule Communication V. Audon

Conseil de laboratoire

Comité scientifique
Coordinateurs des Pôles
Equipe de direction

PILOTAGE

Chargés de mission
Prospective scientifique S. Cabrit
Communication F. Combes
Séminaires J-F. Lestrade
Enseignement M. Wiedner
Services d'Observation F. Le Petit

Comité hygiène et sécurité

Galaxies et cosmologie
Coordinateur : F. Combes

Moyens humains

Chercheurs/ens-chercheurs : 9
ITA/IATOS : 0
Post-doctorants : 4
Doctorants : 12

Projets instrumentaux sol/espace
Design study ou Développement

SKA design study

Equipements/Plateformes

Clusters
MESO-PSL

Hébergement

OBSPM 80%
UPMC 20%

Dynamique des milieux interstellaires et plasmas stellaires
Coordinateur : T. Le Bertre

Moyens humains

Chercheurs/ens-chercheurs : 25
ITA/IATOS : 4
Post-doctorants : 2
Doctorants : 13,5

Projets instrumentaux sol/espace
Design study ou Développement

Logiciels pour ALMA
VO-Theory / Big Data & data mining tools

Equipements/Plateformes

MESO-PSL
Lasers de puissance
Spectro UV
Labo. Plasmas Diagnostics
Spectrographe VUV

Hébergement

OBSPM 30%
ENS 40%
UPMC 30%

Molécules dans l'Univers
Coordinateur : F. Dulieu

Moyens humains

Chercheurs/ens-chercheurs : 20
ITA/IATOS :8
Post-doctorants : 0
Doctorants : 4,5

Projets instrumentaux sol/espace
Design study ou Développement

JUICE co-I

Equipements/Plateformes

FORMOLISM, VENUS
SPICES, COSPINU
FTS-PARIS
MS-TDLAS, PRESPASS, MBMS, SIMCO
Spectrographe VUV
Ateliers de mécanique et d'électronique

Hébergement

UCP 30%
UPMC 50%
OBSPM 20%

Instrumentation et télédétection
Coordinateur : C. Prigent

Moyens humains

Chercheurs/ens-chercheurs : 6
ITA/IATOS : 17
Post-doctorants : 0
Doctorants : 9

Projets instrumentaux sol/espace
Design study ou Développement

Projets télédétection : - Ice cloud
- ISMAR
JUICE
R&T détection Supra
R&T Schottky

Equipements/Plateformes

- Labo. micro-ondes
- Labo. micro-montage
- Salle blanche
- Atelier mutualisé de mécanique

Hébergement

OBSPM 80%
UPMC 20%

POLE SUPPORT

LERMA Organigramme fonctionnel par pôles au 1er Janvier 2017

Annexe 4 : **Sélection des produits et des activités de recherche**

Included in a separate Word document.