INSTITUT
D'ASTROPHYSIQUE
DE PARIS

Activity Report*

2004-2007

Institut d'astrophysique* de Paris

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

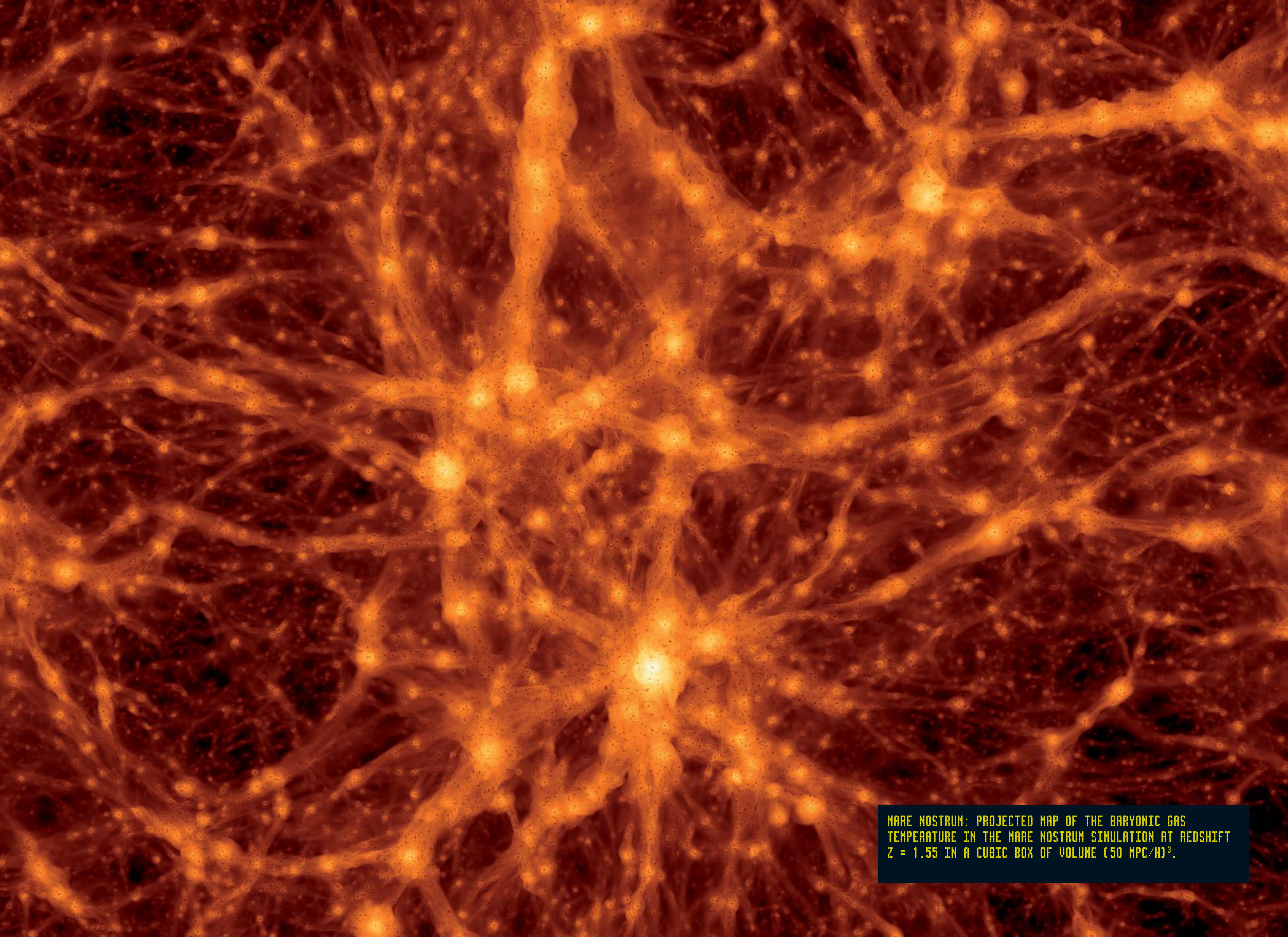
Contents*

7 PHOTO-BOOK
16 INTRODUCTION
22 EXOPLANETS
34 STELLAR PHYSICS
44 ORIGIN AND EVOLUTION OF GALAXIES
58 HIGH ENERGY ASTROPHYSICS AND COSMOLOGY
72 LARGE SCALE STRUCTURES AND THE DISTANT UNIVERSE
90 THEORETICAL PHYSICS: GRAVITATION AND COSMOLOGY
104 PROJECTS

PHOTO-BOOK

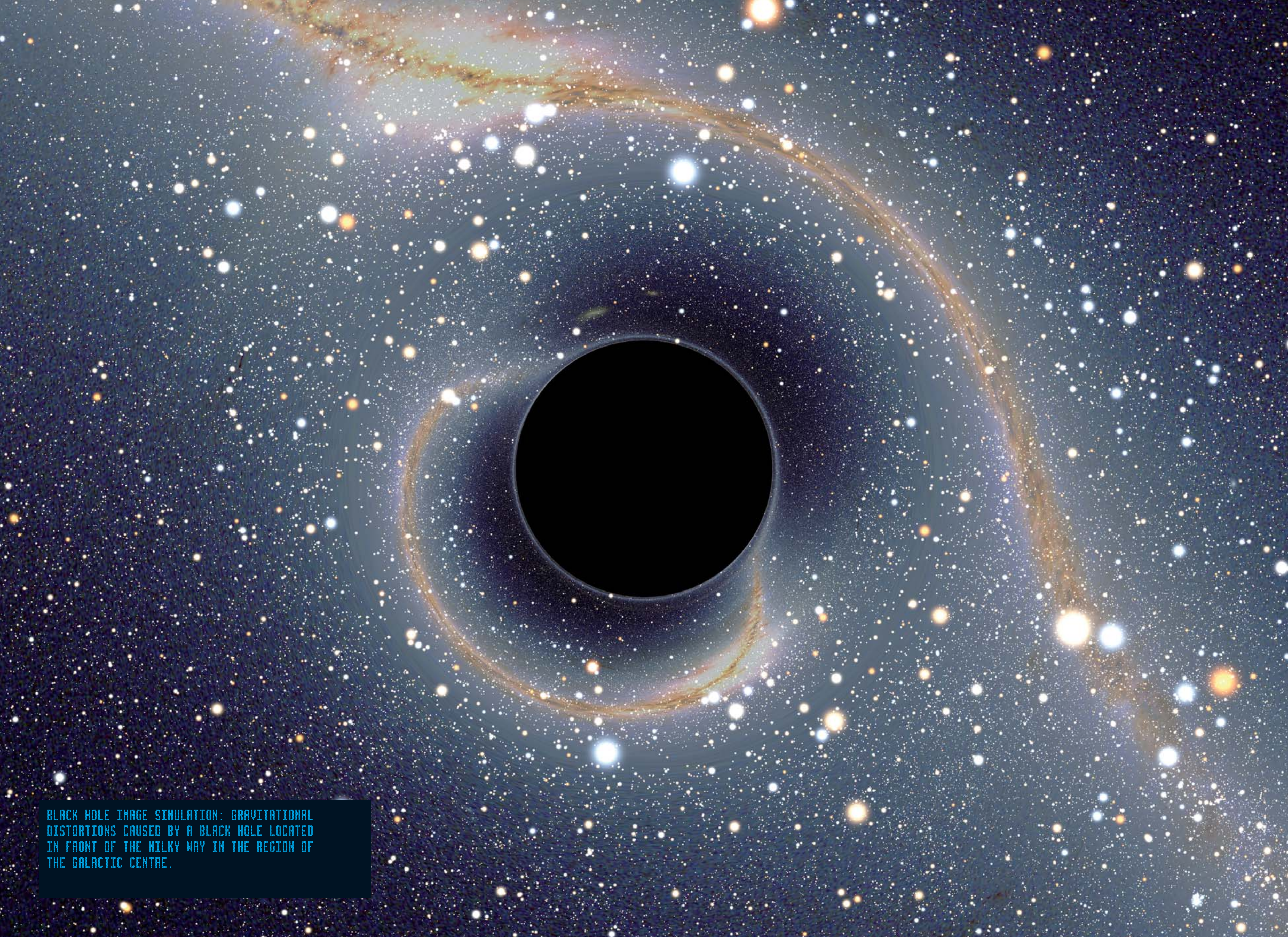
8 MARE NOSTRUM
10 TERAPIX
12 BLACK HOLE IMAGE SIMULATION
14 OTHER IMAGES

Photo-book*

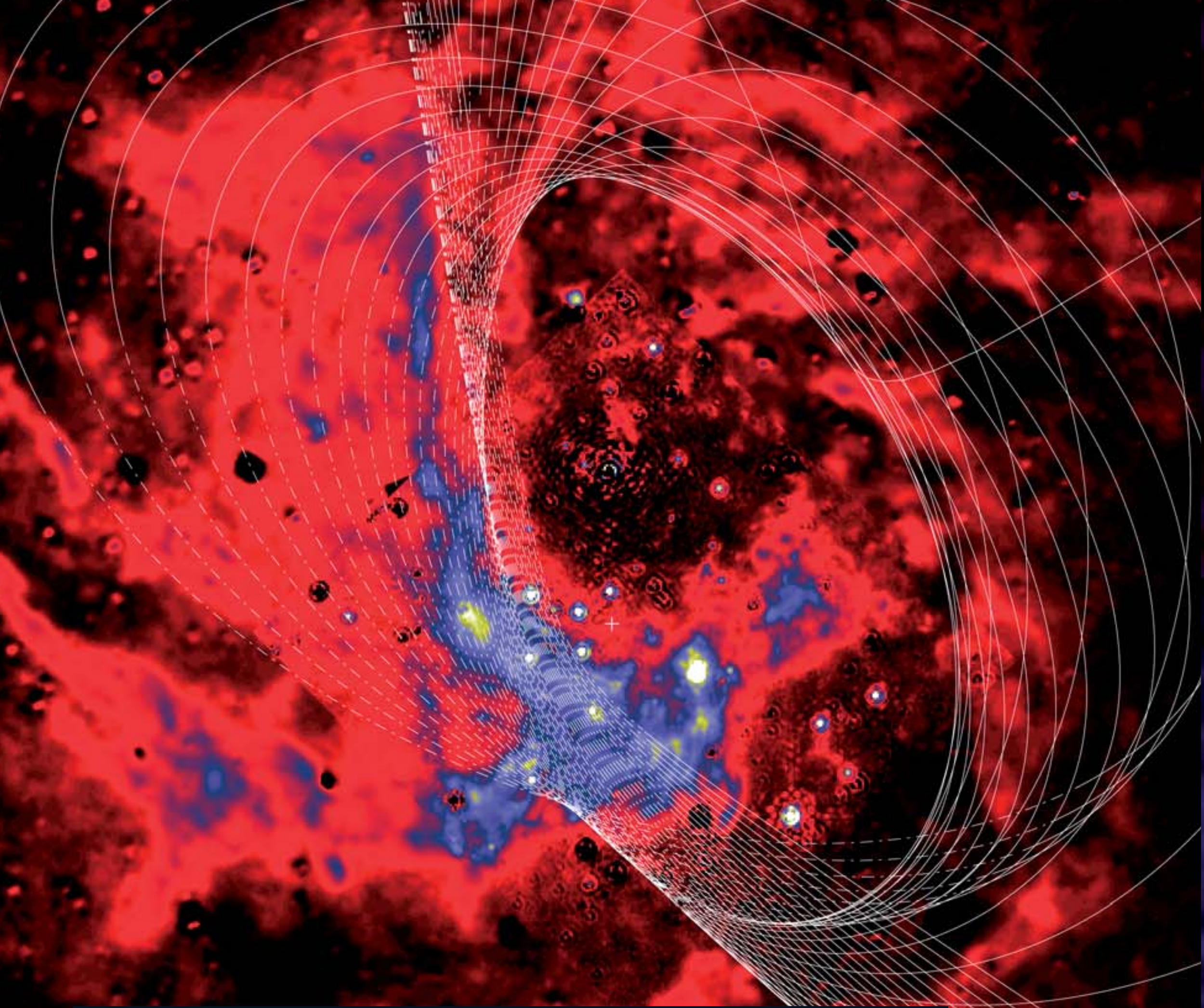


MARE NOSTRUM: PROJECTED MAP OF THE BARYONIC GAS TEMPERATURE IN THE MARE NOSTRUM SIMULATION AT REDSHIFT $Z = 1.55$ IN A CUBIC BOX OF VOLUME $(50\ MPC/H)^3$.

TERAPIX: IMAGE OF THE CANADA-FRANCE-HAWAII TELESCOPE LEGACY SURVEY DEEP1 FIELD PROCESSED BY TERAPIX (10X7 ARCMIN IMAGE IN THREE COLOURS).



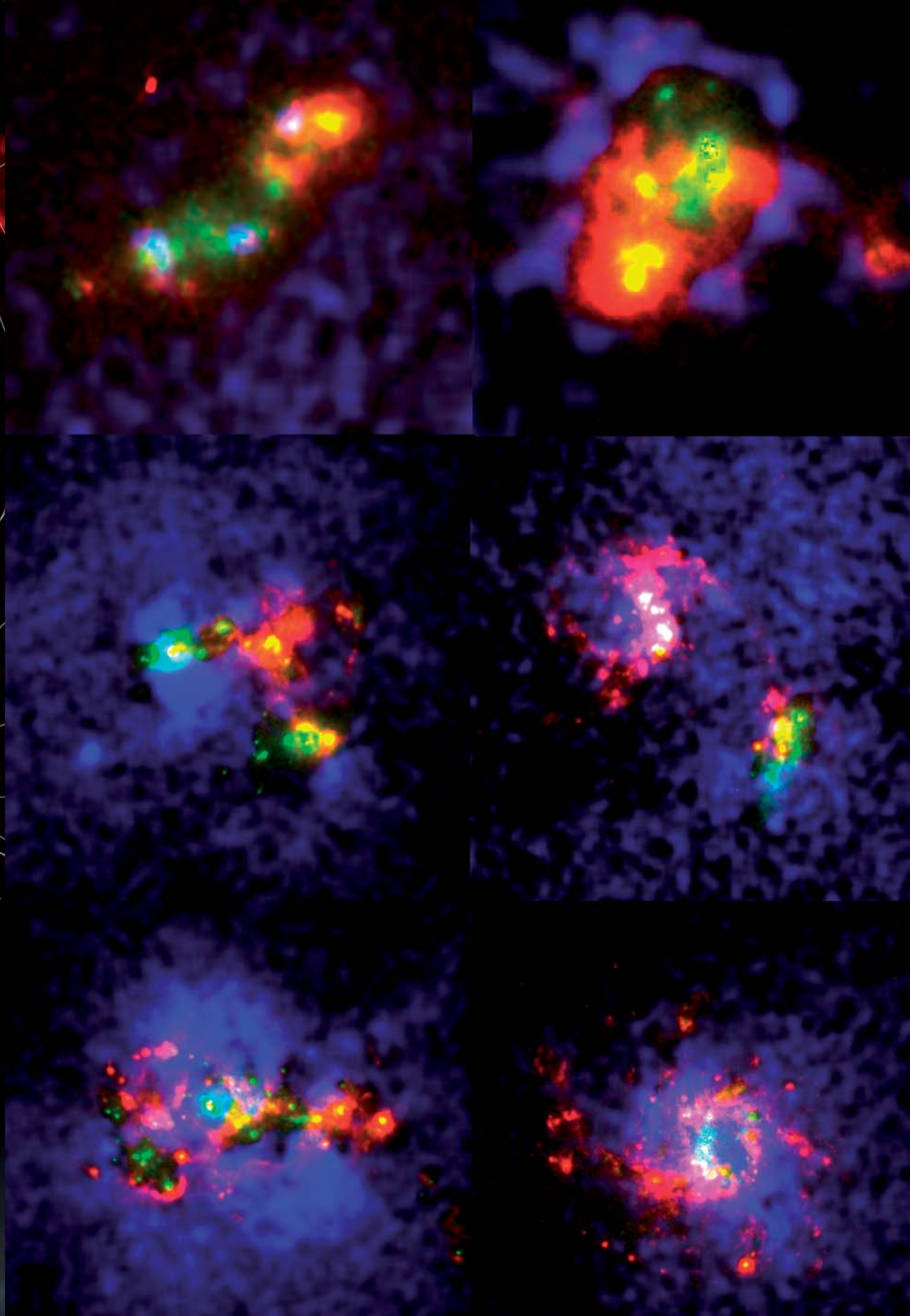
BLACK HOLE IMAGE SIMULATION: GRAVITATIONAL DISTORTIONS CAUSED BY A BLACK HOLE LOCATED IN FRONT OF THE MILKY WAY IN THE REGION OF THE GALACTIC CENTRE.

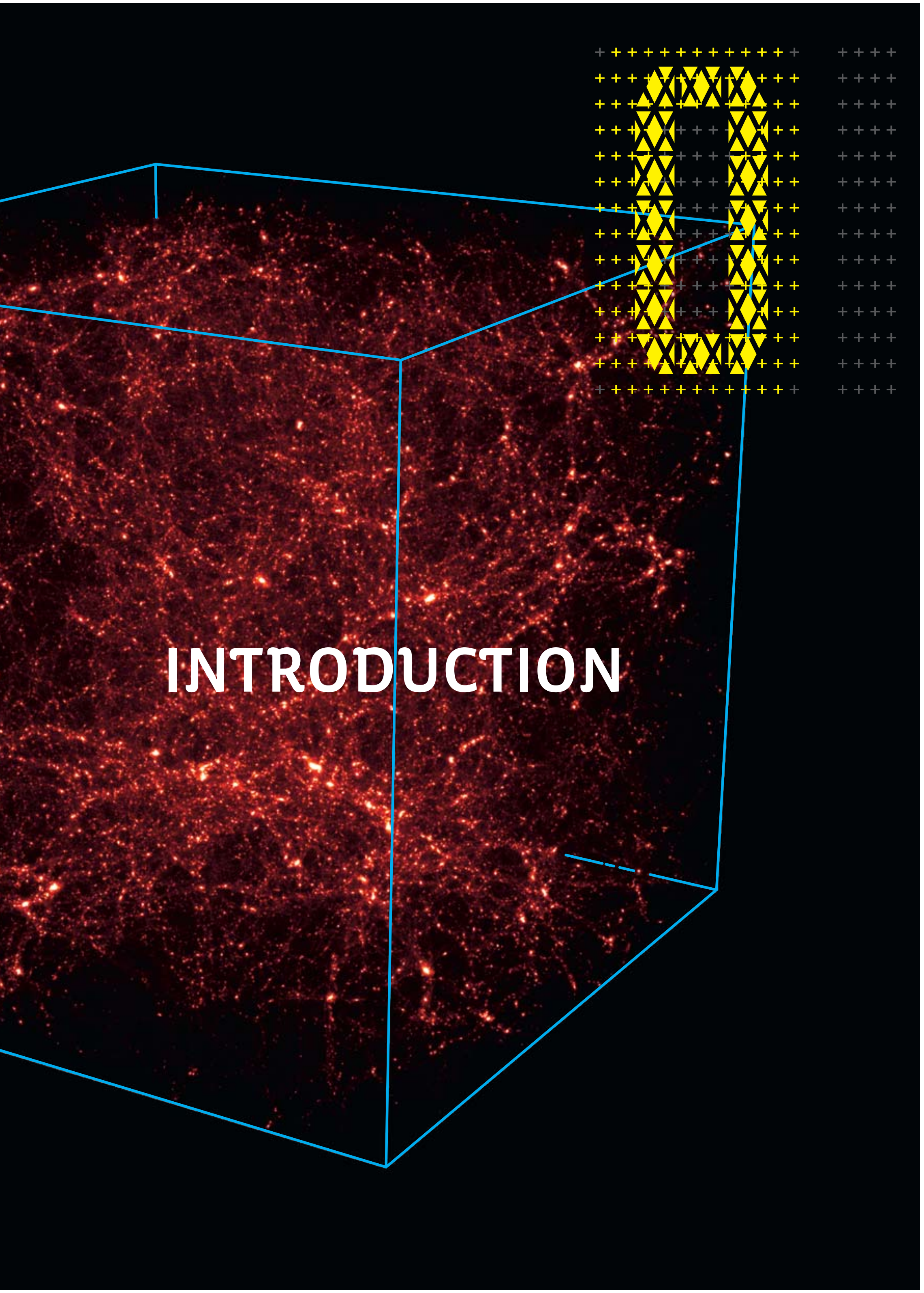


TOP LEFT PANEL: GAS AROUND THE SUPERMASSIVE BLACK HOLE SGR A* AT THE GALACTIC CENTRE IMAGED IN THE HYDROGEN PASCHEN ALPHA LINE; RECONSTRUCTED KEPLERIAN ORBITS ARE SUPERIMPOSED.

BOTTOM LEFT PANEL: ARTIST'S IMPRESSION OF THE EXOPLANET OGLE-2005-BLG-390 DISCOVERED BY THE PLANET COLLABORATION.

RIGHT PANEL: SIX BLUE COMPACT GALAXIES IMAGED IN VARIOUS FILTERS BY THE HUBBLE SPACE TELESCOPE SHOWING THE FIRST DETECTION OF A DIFFUSE HYDROGEN LYMAN ALPHA EMISSION (CODED IN BLUE).





INTRODUCTION

At a time where the organization of research in France is undergoing major changes, it might be worth revisiting the history of the Institut d’Astrophysique de Paris. The IAP was founded in 1938 by the newly created “Caisse Nationale de la Recherche Scientifique”, which became shortly afterwards the “Centre National de la Recherche Scientifique”, today’s CNRS. In the mind of its founders, the IAP was conceived as a French centre for modern astrophysics, with emphasis on stellar spectroscopy. In this respect, the Institut d’Astrophysique de Paris was already the product of a major reorganization of French research at that epoch. In the years that followed, the IAP has always adapted to follow the most topical scientific domains. During the first thirty years of its life, researchers of the IAP focused on their original goal, the observation of stars and understanding stellar physics. In the late seventies however, the IAP became progressively more involved in extragalactic astronomy, and moved slowly but steadily from instrumental design to data analysis and processing.

By the turn of the century, more than two thirds of the IAP scientists were working in extragalactic astrophysics, with particular emphasis on observational and theoretical cosmology. In parallel, ties with theoretical physics have strengthened, and a group of theoretical physicists now comprises one of the six scientific teams of the IAP. Although instrument development is no longer carried out at the IAP today, it has been replaced by a significant involvement in a data processing centre for wide field imaging, TERAPIX, and by studies of the cosmological microwave background with the Planck Data Processing Center. Administratively, the IAP became a joint research unit of CNRS and “Université Pierre & Marie Curie” (Paris 6) in 2001, and was recently granted the status of “Observatoire des Sciences de l’Univers”. Concurrently, the scientific groups within the IAP have been reorganised to better match current themes of research. Six scientific teams were created, spanning all the scientific activities of the IAP. Similarly, the advisory committee structure was reorganised to follow this new structure and change of administrative status. Finally, the creation of the “Agence Nationale de la Recherche” (ANR) has been beneficial for the IAP in supporting new ideas and talented young researchers, although one should not ignore that the life of a research institute requires long term stability and infrastructure support that can only be provided by organisations like the CNRS. These changes have now placed IAP in a privileged position to assure its position at the forefront of research in astrophysics and to tackle the most exciting scientific challenges that lie before us.

This report aims at summarizing the results obtained by IAP scientists during the last four years. Additional details, including a complete bibliography can be found in the accompanying CD-ROM. Scientific investigations at the IAP are conducted by approximately 60 researchers, 15 post-docs and 25 PhD students, and leads to about 200 articles each year in refereed journals. A few highlights of the past four years:

The hunt for exoplanets has been particularly successful, as members of the IAP participated in the discovery of the two smallest exoplanets ever found. The first was located by microlensing techniques, and the second by radial velocity measurements. Moreover, detailed observations of transiting planets have produced the first hints of the dynamical state and the chemical composition of an exoplanetary atmosphere.

In the field of stellar physics, a long-term tradition of the IAP, studies of massive stars have recently provided important results on the coupling of rotation and the onset of the “Be” phenomenon. Moving to larger scales, one has to note that galaxy evolution modelling largely benefits from the tools of galaxy photometric evolution developed at the IAP, models which have been made available to the worldwide astronomical community. The coupling of radiation in the visible and ultraviolet due to stars, and in the infrared due to interstellar matter has been improved in the latest version of these models. Furthermore, the large galaxy database of the Canada-France-Hawaii Legacy Survey (CFHT-LS) analyzed by TERAPIX will be invaluable to study the galaxy evolution up to redshift 1 to 1.5.

The long-standing issue of dark matter halos around elliptical galaxies has been solved recently thanks to a model including anisotropies in the velocity field of distant objects.

One may also note several works devoted to primordial nucleosynthesis and to the origin of light elements such as Li6 in spallation reactions at high redshift. Observationally, IAP members have been leading two large spectroscopic programs devoted to absorption features in the spectra of distant quasars. These observations have produced new results on the baryon content at large redshift, and constraints on the amount of molecular hydrogen in the absorbing systems. They have also been used to constrain possible evolution with time of the fine structure constant.

More accurate measurements of cosmological parameters have been made thanks to weak lensing measurements performed by IAP scientists. CFHT-LS weak lensing work has provided the most accurate estimations to date of weak lensing statistics and extended this analysis for the first time into the linear regime. With its unique combination of weak lensing and luminosity measurements of distant supernovae, the CFHT-LS is now, when combined with WMAP, the reference for the determination of the cosmological parameters that characterize the power spectrum of density fluctuations, the dark matter content and the equation of state of dark energy.

Whether in exo-planetary science or cosmology, numerical simulations represent a cornerstone of the theoretical research conducted at IAP. Scientists at the IAP have played a key role in the largest cosmological simulation to date, “Mare Nostrum”.

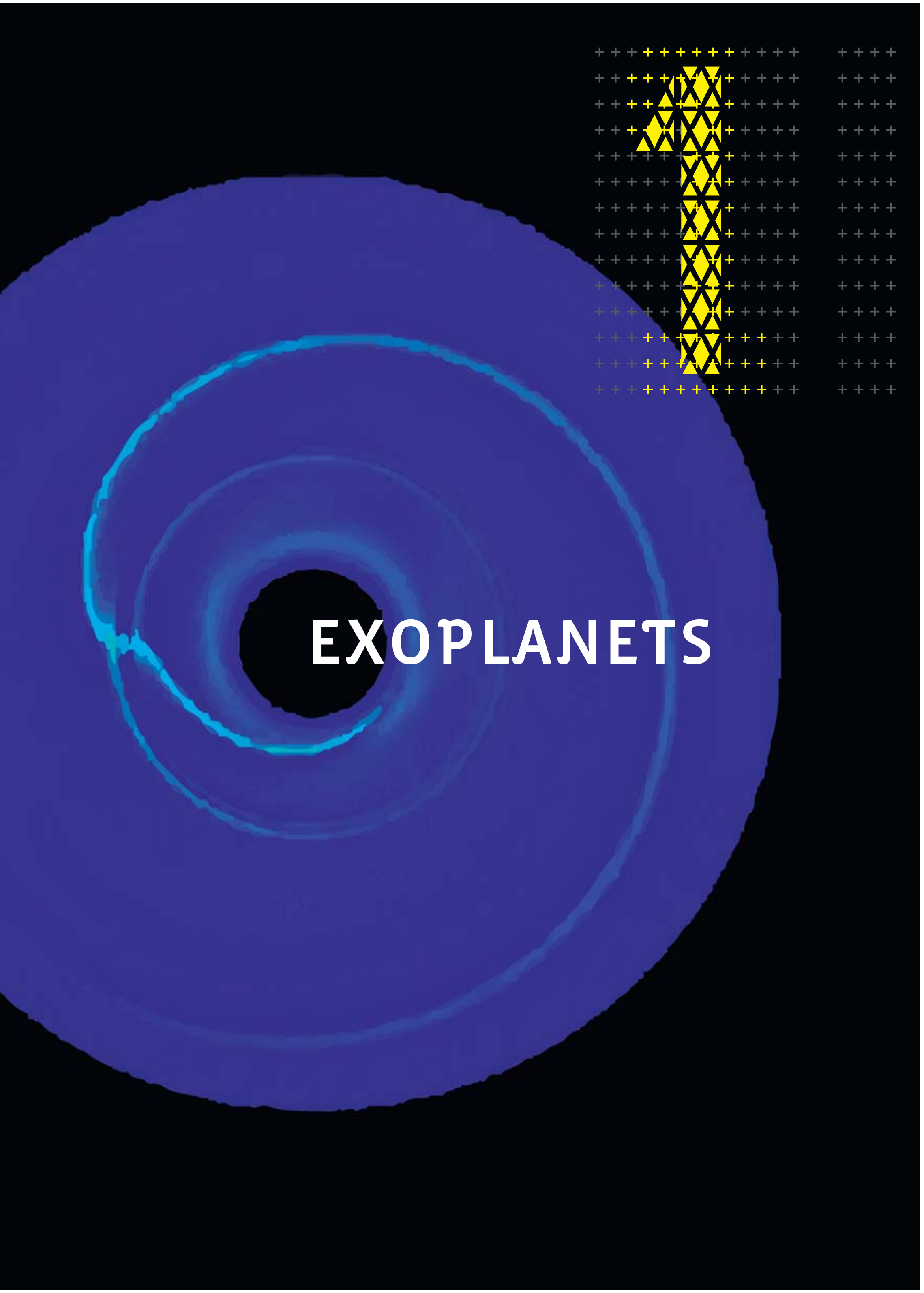
Finally, theoretical studies have been actively pursued, with notable results in early Universe cosmology on constraints on the inflaton scalar potential from WMAP data, as well as in the field of gravitation, with the elaboration of very accurate templates of the gravitational wave signal from inspiralling compact binaries. These templates will be used to search for the expected signal by the Virgo and LIGO interferometers.

Beyond these scientific results, one should also emphasize the significant effort devoted to data processing. The IAP hosts two major data processing centres: TERAPIX for wide field imaging and the Planck Data Processing Center. TERAPIX provides the French and Canadian communities with calibrated images from the CFHT-LS, and it has also processed most of the PI datasets obtained with MEGACAM and WIRCAM at CFHT. The Planck data processing centre at the IAP is responsible for the “level 2” processing of the Planck Surveyor measurements of cosmic microwave background fluctuations. This means in particular that the IAP Planck team will provide the consortium with the calibrated time-line for each channel and with the first generation all-sky maps for each band. The IAP also hosts the French data centre for the FUSE satellite.

This report describes the scientific work carried out at the IAP. Needless to say, many other activities are necessary to run the IAP. The last four years have been particularly active as a result of a substantial administrative reorganization, the IAP’s change in status and the departure of key people. Similarly, the maintenance of the IAP building and ensuring that its infrastructure can follow the pace of modern research requires a lot of effort. For example, one major endeavour has been the installation of a large server room for the Planck data processing centre computer, whose power requirements required upgrading our connection to the local electricity grid. All these tasks have been carried out successfully thanks to the dedication of all the IAP personnel.

The high quality of the research, the commitment of the personnel, the large amount of visitors, the use of the IAP conference rooms for meetings of national and international interest, all make the Institut d’Astrophysique de Paris a unique and inspiring place to work in. I hope that this report will convey a flavour of this spirit.

Laurent Vigroux



EXOPLANETS

A new research group entitled “Extrasolar planets” was created in early 2005. Its main objectives are the detection and the study of extrasolar planetary systems. From the observational point of view this team has acquired expertise in various domains, most notably the detection of exoplanets using either radial velocity or microlensing techniques. Atmospheres of extrasolar planets can be probed by spectroscopic transit observations. The team’s expertise extends to theoretical studies and numerical simulations of the formation and the evolution of planetary systems, and to three-dimensional models of planetary magnetospheres and upper atmospheres. A fraction of the team has also been involved in the FUSE observatory programs, in particular those related to the studies of the interstellar medium, of the circumstellar debris discs and of planets within the solar system. In the same spirit, the INSPIRE mission (to be launched in 2008) will measure for the first time the magnetic field at the surface of Jupiter, thereby opening the ultraviolet interferometry/polarimetry technological domain which could be used later to study the magnetic field of giant extrasolar planets.

1.1 SEARCH AND CHARACTERIZATION OF EXTRA-SOLAR PLANETS

Since the first extra-solar planet 51 Peg b was discovered in 1995, more than 230 others have been found using radial velocity measurements. Currently, the 1m/s radial velocity accuracy attainable by the ESO HARPS instrument opens up at last the discovery space to Neptunes and super-Earths (i.e. 5-20 Earth masses) class objects. Members of the group participate in the HARPS consortium, whose observations have already led to the detection of about 15 new extrasolar planets, with half of them in the 5-20 M_{Earth} range (Lovis et al. 2006, Pepe et al. 2007, Melo et al. 2007, Naef et al. 2007, Bonfils et al. 2007, Udry et al. 2007). In the near future, this collaboration will follow up the exoplanets detected by CoRoT for a total of 50 observing nights. Furthermore, HARPS also provides the most sensitive ground based instrument able to detect acoustic stellar oscillations, and observations have already allowed the detection of 30 p modes in α-Cen A (Bazot et al. 2007) as well as the detection of acoustic modes in the star ι-Her.

The group is also involved in others large scale observational programs, such as the ESO follow-up of the OGLE exoplanet candidates (Gillon et al. 2006, Pont et al. 2007, Gillon et al. 2007) and a follow-up of CoRoT for 700 stars using the ESO GIRAFFE multi-object spectrograph, notably to search for hot Jupiters which are expected in about 1% of the candidates (Loeillet et al. 2007). CoRoT candidates will be also followed up with FLAMES, FORS, UVES and HARPS in a large ESO program led by an IAP PI. The follow up of one CoRoT candidate with SOPHIE has led to the detection of the first CoRoT exoplanet: CoRoT-exo-1b.

Yet another program makes use of ELODIE on the 193cm of the Observatoire de Haute Provence (OHP), which led to the discovery of 6 new hot Jupiters (Moutou et al. 2006, Da Silva et al. 2007). One of them, HD189733b, is particularly interesting because it is a transiting exoplanet and because its parent star is particularly bright (Bakos et al. 2006). It has been the object of several spectroscopic observations inside the group aimed at probing the exoplanetary atmosphere, as discussed below. ELODIE instrument has now been replaced with SOPHIE, whose design is based on the HARPS concept, and which offers a gain of 3.3 magnitudes and 1.6 in resolution over its predecessor. Its stability over several months is better than 3-4 m/s and on-going improvements are aimed at achieving HARPS accuracy. SOPHIE has already confirmed two transiting hot Jupiters, WASP-1b and 2b, discovered in collaboration with the British Super-WASP team (Cameron et al. 2007). The SOPHIE consortium, composed of 22 French and Swiss scientists, with a PI at the IAP, was formed in October 2006. It has recently detected acoustic waves of 50 cm/s amplitude in Procyon, thereby demonstrating comparable performance to HARPS.

Another approach to discover new planets is to search for the flux variation of the parent star during the transit. Among the 250 known planets, more than 15% of them orbit at less than 0.1 AU from their star and belong to the hot Jupiters (or Pegaside) category. Sixteen of them have been seen as transits, so that their mass and radius could be determined. Such targets present a unique opportunity for further spectro-photometric studies using space observatories to probe directly their atmospheres. For instance, HST observations have showed that the planet HD209458b is surrounded by a huge hydrogen atmosphere, interpreted as the evaporating tail of this planet (Vidal-Madjar et al. 2003; Ballester, Sing & Herbert 2007). Subsequent HST observations have confirmed the presence of an extended atmosphere of neutral hydrogen and led to the detection of two new atmospheric species: oxygen and carbon. Their presence in the planet upper atmosphere shows that it must be in a violent hydrodynamic blow off state (Vidal-Madjar et al. 2004).

It has been possible to quantify this evaporation process through numerical simulations, which take into account the stellar and planetary gravitational forces as well as the effect of the stellar radiation pressure and ionization on the hydrogen atoms. These simulations further suggest that one might understand the relative lack of planets within a limit of about 0.04 UA from the star as a consequence of this evaporation process: within this limit, only the planet core could survive (Lecavelier des Etangs et al. 2004). An energy diagram of the evaporation status of these planets has also been constructed in Lecavelier des Etangs (2007). Confirming that indeed planets too close to the parent star could evaporate away in less than a billion years, it also shows that small mass “hot Neptunes” such as GJ876b are probably the expected solid residual cores of these evaporated planets.

The recently discovered transiting planet HD189733b, whose periodicity has been evaluated to one-second accuracy using Hipparcos data (Hébrard & Lecavelier 2006) raises the possibility of several new observational programs: with HST in 2007 to search for an evaporation signature; with Spitzer from simulated absorption signatures in the infrared of H_2O and CO (Tinetti et al., 2007a). Observing time was obtained by the team and observations should be completed under HST cycle 16 and Spitzer cycle 4.

Most extrasolar planets to date have been discovered through precision velocimetry; others have been found using accurate photometry to detect transiting planets. A third method relies on the sudden amplification of the flux of a background star as a result of a microlensing effect caused by the foreground motion of an exoplanet. This method turns out to be more sensitive than the other two in the regime of small orbital separation (less than a few AUs) and for low mass planets. Since the standard core-accretion model of planet formation predicts that there should be more low mass planets (Neptune- to Earth-mass planets) than Jupiter-mass planets between 1 and 10 AU from the parent star, this technique appears highly promising. The PLANET collaboration, whose PI is a member of the group, has been searching for extrasolar

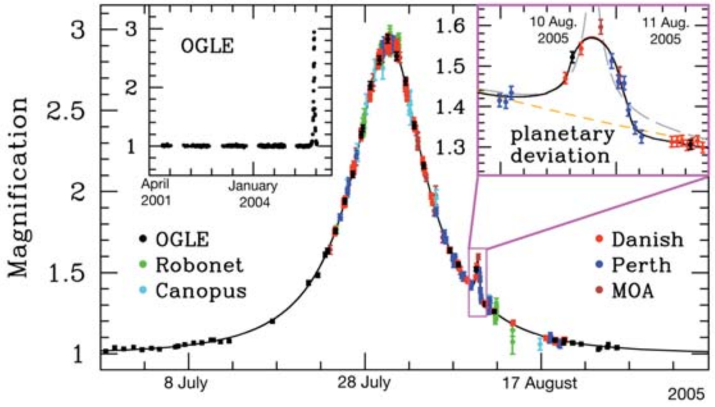


Figure 1.1: The light curve (data points collected by telescopes as indicated) and the best fit model with a planet to star mass ratio q = 7.6 ±0.7 x 10^{-5} and a projected separation d = 1.610 ±0.008 Einstein radius. The light grey curve shows the best alternative model for a binary star, rejected by the data.

planets through microlensing since 2002 by monitoring the light curves of stars in the Galactic center. After two Jupiter-mass planets orbiting M dwarfs in 2003 and 2005 (Bond et al. 2004, Udalski et al. 2005), a planet of 5.5 Earth mass has been detected at 2.8 AU from its parent star (Beaulieu et al. 2006, see Figure 1.1). This detection has demonstrated the efficiency of this method. In the coming years, it is planned to search for 1-15 Earth mass planets with orbital distance of 1 to 5 AU from M dwarfs, which are the most common stars in the Galaxy. Interestingly, the preliminary results suggest that low mass planets similar to those detected are quite common, since the efficiency of the microlensing survey is as high as 50% for Jupiter mass planets, and as low as a few % for low mass planets, yet about an equal number of each have been detected by PLANET (Cassan et al., 2007), see Figure 1.2.

As a natural extension of this program, HOLMES is a project using 8 telescopes during 3 campaigns and 48 months of work to be operated during the years 2007-2010. It is expected to discover several Earth-Neptune mass planets within 1-5 AU from the parent star, to constrain the fraction of planets orbiting M dwarfs and to place new constraints on the models of planet formation. HOLMES will be based on already existing tools (http://planet.iap.fr). Data will

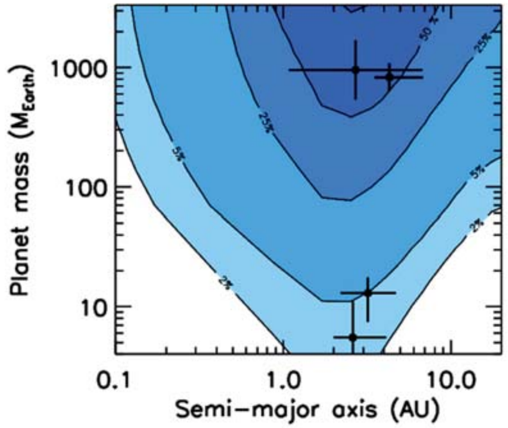


Figure 1.2: Planet detection efficiency as a function of their mass and orbital distance. Since the method is particularly sensitive to Jupiter-mass planets (although only 2 have been detected), and has low sensitivity for a planet like OGLE-2005-BLG-390Lb, it suggests that these latter planets are more numerous.

be public and combined with other team data. Discussions are underway with MicroFUN, OGLE and MOA teams.

The expertise that the team has acquired in monitoring a large number of background stars to search for microlensing signals has come from its experience in the EROS program, which had used the same technique to search for baryonic dark matter in the Galactic Halo. Observations of this long term project ended in 2003, and allowed the exclusion of 0.6x10^{-7} to 15 M_{sol} compact objects as major constituents of the Galactic halo (Tisserand et al. 2006). EROS data have also provided a huge collection of light curves (about 100 millions including 35 in the Magellanic Clouds) which can serve for stellar population studies. One may mention results such as the first detection of five R Coronae Borealis type stars detected in the Small Magellanic Cloud (Tisserand et al. 2004), the study of pre-main-sequence stars in the Magellanic Clouds (de Wit et al. 2006), the identification of a large number of double mode Cepheides (Marquette et al. 2007a in preparation), which trace the metallicity of the host galaxy (Hartman et al. 2006; Beaulieu et al. 2006), or finally the detection of a star similar to a Cepheid, but showing seven-year spectacular variations in amplitude and mean magnitude (Marquette et al. 2007b).

PHYSICS AND DYNAMICS OF EXOPLANETS 1.2

Concerning exoplanetary physics, the activity of the group has followed two main directions in the past few years. One is concerned with the development

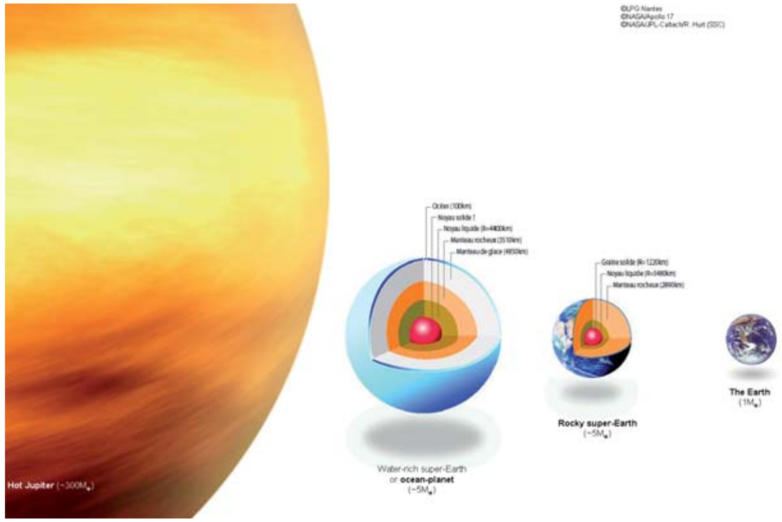


Figure 1.3: Possible types of exoplanets.

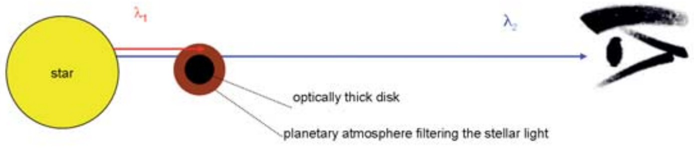


Figure 1.4: Differential absorption in an exoplanet atmosphere at two different wavelengths.

of new numerical tools to interpret observational data on the atmospheres of transiting exoplanets. The other aims at understanding the formation and the evolution of planetary systems.

In more detail, activities on the former subject have concerned the detection of the atmospheres of hot Jupiters using HST and Spitzer, the estimation of potential habitability of lower mass planets such as super-Earths and ocean-planets and the characterization of the atmospheres of super-Earths. The radius of hot Jupiters, which can be measured using transit observations is wavelength-dependent, as absorption by a given element enlarges it (see Figure 1.4).

As already mentioned in Section 1.1, transits of the exoplanet HD189733b have been followed using Spitzer in order to look for signatures of water vapour absorption, according to the model presented in Tinetti et al. (2007a). However the sought for variations remain tiny, at the level of 0.1%, and the results have been debated (Tinetti et al. 2007b, Ehrenreich et al. 2007,

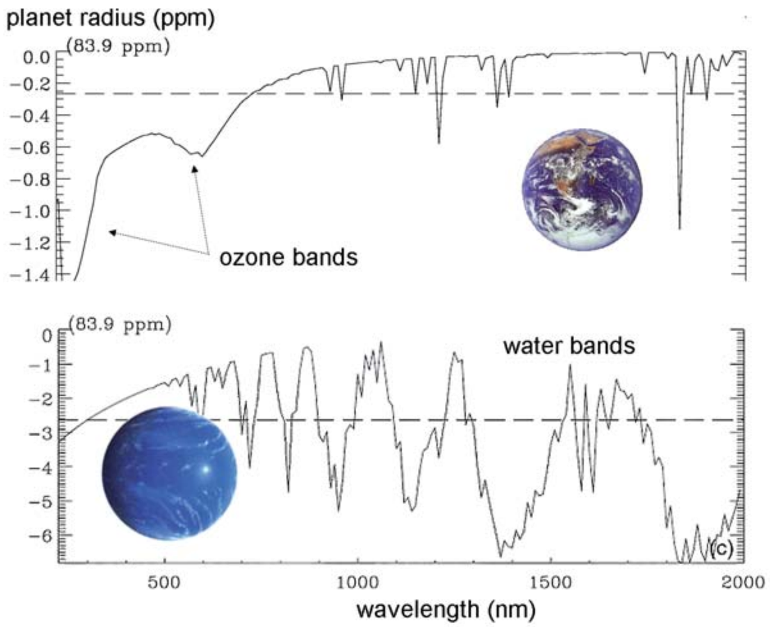


Figure 1.5: Absorption spectrum of an exoplanet atmosphere.

Beaulieu et al. 2007). Using similar techniques, the group has produced synthetic spectra similar to those that the James Webb Space Telescope will provide (see Figure 1.5). One of the science goals of this observatory is ultimately the detection and analysis of super-Earth atmospheres. The results obtained show that JWST will be able to detect the atmosphere of an ocean-planet around a low mass star but not that of an Earth mass planet (Ehrenreich et al. 2006). In the near future, it should be possible to distinguish between a rocky super-Earth and a planet-ocean using CoRoT and Kepler. The group has also been involved in the detection of elements which present an interest for exobiology (see in particular Ehrenreich et al. 2006, Tinetti et al. 2006, Tinetti, Rashby & Young 2006, Kiang et al. 2007).

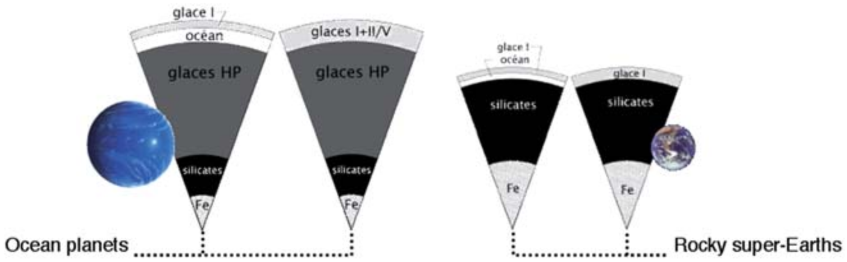


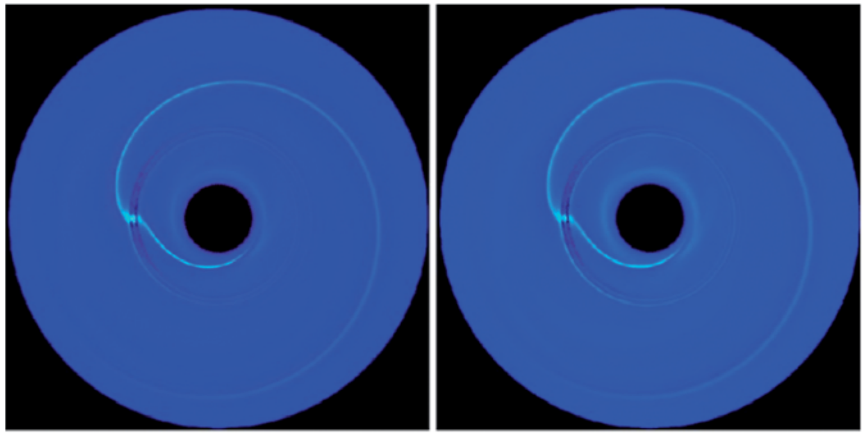
Figure 1.6: A sample of theoretical models for the composition of exoplanets..

As discussed in the previous section, microlensing techniques enable the discovery of low mass planets such as OGLE 2005-BLG-390Lb (Beaulieu et al. 2006). By modelling the structure of these planets, it has been examined whether liquid water could be present, either on the surface or under an ice later. The planet OGLE 2005-BLG-390Lb seems likely to be completely frozen, even though it may have had some liquid water under the surface during several billion years (Ehrenreich et al. 2006). Figure 1.6 presents several possibilities for the structure of this planet, from left to right: a cold ocean planet a few billion years old, the same planet aged nine to billion years, and similarly a young and old super-Earth like planet. These models also show that such frozen planets could be abundant in our Galaxy (Ehrenreich & Cassan 2007).

Members of the group are also involved in the study of the dynamics and the formation of exoplanets. One theoretical aspect of importance is the interplay between turbulence and self-gravity in protoplanetary disks. This problem is particularly relevant since very young disks are massive and to some extent subject to a magnetorotational instability which drives the turbulence. Computations have been performed using the 3D version of the **ZEUS** code, including a module which computes the self-gravitating forces. These simulations have shown that the nonlinear coupling between a high frequency self-gravity mode excited by the turbulence and the usual m=2 mode produces periodical variation of the accretion rate onto the central object (Fromang et al. 2004), a variability which is actually seen in some young stars.

Other studies have focused on the dynamics of planetary systems. Detections of short period giant planets and resonant systems suggest that planet migration, caused by disk/planet interactions, plays an important role in

Figure 1.7: Surface mass density in a magnetized disk, containing a planet, at two different times. Slow MHD waves, which mediate the interaction between the disk and the planet are seen to propagate in the azimuthal direction



shaping planetary systems. According to current theories however, migration timescales are shorter than the planet formation timescales. It is therefore important to find mechanisms that can stop or slow down migration. As shown in Terquem (2003), one of these could result from the presence of a toroidal magnetic field with a negative radial gradient, which would slow down or reverse migration. These analytical predictions have been confirmed recently using **ZEUS** numerical simulations, which could also measure the migration timescales (Fromang, Terquem & Nelson 2005), see Figure 1.7 for an illustration of these simulations.

In order to explain the existence of short period super-Earths, an N-body code has been developed to simulate the evolution of a system of cores that are subject to their mutual interactions and to the tidal interaction with the disk in which they are embedded. Orbit crossings result in collisions and growth of the cores which capture each other in resonances while migrating. The results obtained indicate that if super-Earths form according to this scenario, they should have companions on near-commensurable orbits (Terquem & Papaloizou 2007, Papaloizou & Terquem 2006). In a follow-up study, giant planets are being incorporated in these models, and the mixing of chemical elements during migration is followed.

INTERPLANETARY AND INTERSTELLAR MEDIA 1.3

Several team members have been involved during 2004-2007 in a global study of exoplanetary-star-interstellar medium systems through the development of sophisticated numerical tools (3D particle codes, a 3D MHD code, radiation transfer code including polarization effects, etc.). In conjunction, these newly-developed tools are used as a base for SWEP and FORREST, two research oriented projects of higher-level education in Southern Mediterranean countries.

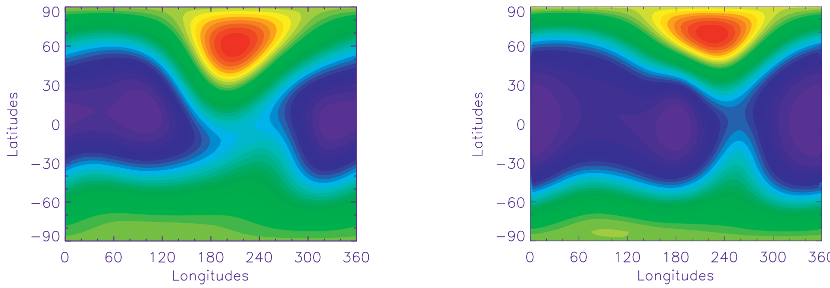


Figure 1.8: Similarity between the polarization map induced by the Hanle effect (right) and the corresponding magnetic field model distribution on the surface of Jupiter (left). Inspire will measure the polarization map of Jupiter in 2008.

For instance, the Hanle effect on the Lyman-α line of Jupiter has been proposed to measure the magnetic field at the surface of the planet (see Figure 1.8). This work made front page of the *Icarus* journal (Ben-Jaffel et al. 2005, Ben-Jaffel, Kim & Clarke 2007), notably because this was the first time the Hanle effect had been proposed in planetary science (Cooper et al. 2005). The project development is reinforced by a strong European and international collaboration.

Among the ongoing projects, ESINPLE aims at developing numerical simulation of exoplanetary magnetospheres and plasma environments using 3D MHD and 3D N-particles electromagnetic and relativistic codes. The codes allow exploring, understanding and predicting the formation and evolution of an exoplanetary magnetosphere interacting with its parent star, with the whole system being embedded in the astrosphere, the zone of influence of the stellar wind and magnetic field.

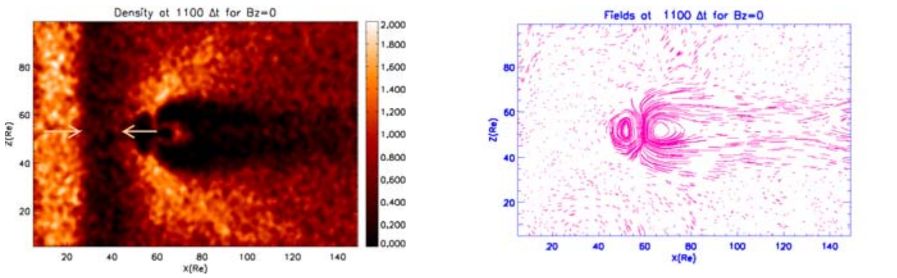


Figure 1.9: Response of a terrestrial magnetosphere (Earth's example) to a strong depression in the stellar wind. Left: plasma density distribution in the day-night plane, showing a breakup of the magnetopause that faces the depression (arrow). Right: corresponding field lines configuration. Planet's position (60,52). Particle-in-cell simulation using 2 million particles and a box of 155x105x105 planetary radii.

The simulation of a planetary magnetosphere marked the first step in validating the particle code, and is described in Baraka & Ben-Jaffel (2007), see also Figure 1.9. The final step of testing is being conducted with the simulation of the magnetosphere of Jupiter where the satellite Io and the tilt of the rotation axis are taken into account.

The self-consistent description of the different particle populations (neutrals, ions, pick-up ions, energetic neutrals, heliospheric cosmic rays, etc.) and the different physical processes in play in the heliosphere remains a critical issue. The team at the IAP aims to complete a full hybrid code (MHD for plasma, kinetic for neutrals) in the very near future. For instance, the existence of the interstellar bow shock and the deflection of the interstellar gas that were proposed in 2000 (Ben-Jaffel et al. 2000) has now been confirmed by independent studies using Voyager and SWAN observations. Also, MHD 3D simulations have allowed the team to use Voyager Lyman-α data to uncover the 3D orientation of the local interstellar medium magnetic field (Ratkiewicz, Ben Jaffel & Grygorczuk 2007).

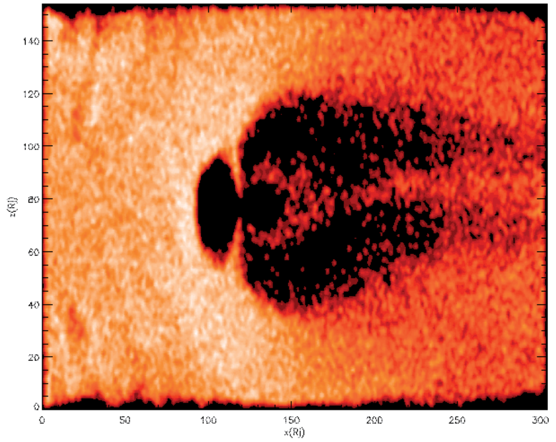
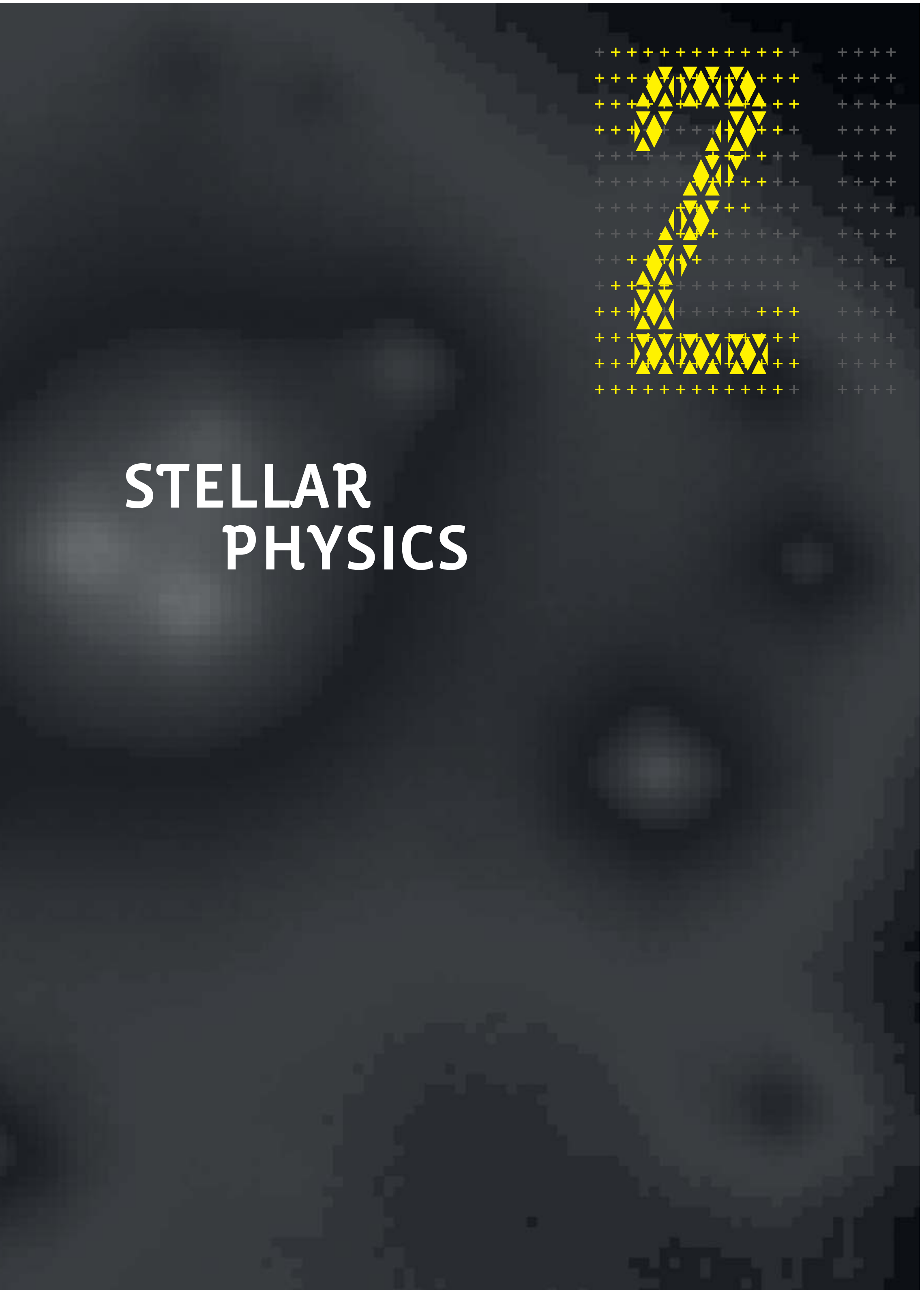


Figure 1.10: particle-in-cell simulation of a Jovian magnetosphere using 16 million particles in a box 300x150x150. Stellar wind hits the box on the left. Equatorial current sheet reproduced naturally (Right, around z=80). See animation at http://www.iap.fr/inspire/animation.html

The group has also been actively involved in studies of the interstellar medium, of its composition and its dynamics, most notably through the implication of the group in the FUSE mission. To mention a few of the results obtained, the phosphorus abundance has been shown to be a good tracer of oxygen (Lebouteiller, Kuassivi & Ferlet 2005); the D/H ratio has been measured along numerous lines of sight, revealing values about two times smaller in distant interstellar clouds than in the local bubble, a fact that current interpretations cannot explain (Hébrard & Moos 2003; Wood et al. 2004; Williger et al. 2005; Hébrard et al. 2005; Friedman et al. 2006; Oliveira & Hébrard 2006); the velocity dispersion of highly excited levels of molecular hydrogen in interstellar clouds has also been studied, particularly in the Magellanic clouds (Lacour et al. 2005); similarly, deuterated molecular hydrogen has been analysed over seven lines of sight, and has been detected in the auroral region of Jupiter (Gustin et al., 2004). In the extragalactic domain, studies of blue galaxies and cooling flows have been conducted; also, molecular hydrogen has been tracked in evolved circumstellar disks which allowed determination of the spatial extent of these objects; finally, the activity of Herbig stars has been monitored in the far ultraviolet, revealing winds and accretion, as well as oscillation of sdB stars. The FUSE mission was terminated by NASA in July 2007 following a serious instrument failure.



2

STELLAR PHYSICS

Stars are the elemental building blocks of galaxies. The physics of their structure and their evolution, whether brown dwarfs, white dwarfs or massive stars, are studied by combining numerical simulations, modelling and spectroscopic observations in the "Stellar physics" team of the IAP.

2.1 WHITE DWARFS AND BROWN DWARFS

One particular subject of interest is the physics of radiative transfer in white dwarfs and brown dwarfs atmospheres. The interactions at low energies of neutral and ionized atoms have numerous applications in physics and chemistry. At low densities, the collisional interactions can be described in terms on binary collisions. However, at high densities, multiple perturbing effects require a unified theory of spectral line broadening valid from the centre to the far wing. In particular, quasi-molecular satellites are absorption features due to transitions that take place during close collisions of a radiating atom with a perturbing atom or proton. The good agreement between the FUSE spectra and the calculations conducted in the group have led to the identification of line satellites in the wing of Lyman β and Lyman γ lines of hydrogen-rich white dwarfs (Allard et al. 2004a,b). The H_2 quasi-molecular satellite has been observed as well in laboratory plasmas (Kielkopf & Allard 2004).

Similarly, the ZZ Ceti white dwarf has been observed with the HST and its atmospheric parameters were determined through a detailed treatment of quasi-molecular structures and their dependence with the temperature (Allard et al. 2004c). This phenomenon also takes place in brown dwarfs, as illustrated in Figure 2.1. Finally, the absorption lines of Na, K and Li perturbed by He and H_2 (Allard et al. 2005, 2007), as well as rubidium and caesium (Allard & Spiegelman 2006) were also modelled using the same techniques.

Another subject of study are novae, cataclysmic binaries containing a white dwarf and a cold star, which is usually not far from the main sequence. In most cases mass transfer creates an accretion disk around the white dwarf. Thermonuclear runaways of the white dwarf are believed to violently eject its outer layers and produce an optically thick wind. In the case of a symbiotic binary, a white dwarf has a cool giant companion from which it also accretes mass. Photometric variations observed for nova V1493 Aql are difficult to explain in the framework of an optically thick wind. In a contribution to Dobrotka et al (2006), this object has been argued not to be a classical nova; another possibility, to be investigated, is that the wind is confined to a disk.

A photometric study of the old nova HR Del (see Friedjung et al 2005) and spectroscopic observations should provide information relevant to a proposal previously made by the group that weak thermonuclear burning have continued for many years. A review by Friedjung (2004) on optically thick winds (which are accelerated by radiation pressure in the continuum) is devoted to ηCar, novae and the inner regions of Wolf-Rayet winds (Kotnik-Karuza et al 2006).

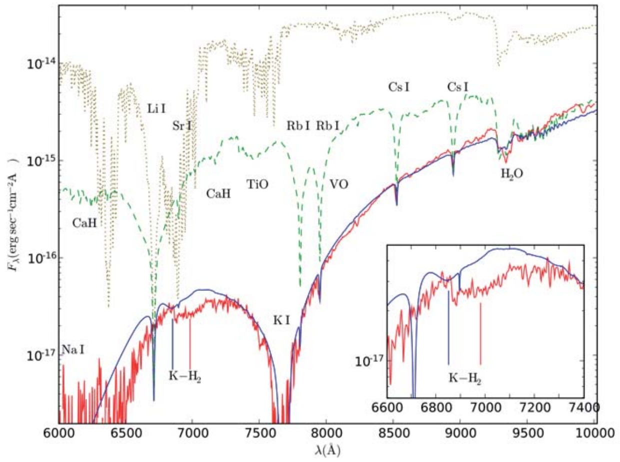


Figure 2.1: The observed energy distribution of a brown dwarf (red line) is fitted with a model of stellar atmosphere that takes into account the absorption line profiles of alkalis (blue line). The dashed line represents a model where alkalis are not considered. The dotted line corresponds to a model where the absorption by dust was neglected. This shows the degree of completeness of models needed to account for the structure of a cold stellar atmosphere.

The redshift of resonance lines in the ultraviolet spectra of symbiotic binaries, previously discovered by the group, was confirmed for CI Cyg (Mikolajewska et al. 2006) and later for other symbiotics (Friedjung et al. in preparation). Other line shifts in ultraviolet spectra are also studied. Finally, RR Tel is a symbiotic Mira surrounded by dust and studies in the optical and infrared, suggest that dust condensation is in separate clouds, as for R Cor Bor stars.

MASSIVE STARS 2.2

By using a novel instrument, an astronomical imaging Fourier transform spectrograph that allows integral field spectroscopy at high spectral resolution in the near infrared, the young stellar population of the central parsec of the Galaxy has been studied through the HeI 2.06 µm and the Br γ lines (Paumard 2003). This work was followed by a particular study of one of these massive stars IRS 13E. By combining high angular resolution images between 1 and 3.5 µm of the source environment, and applying deconvolution processing, the source previously considered as a peculiar massive hot star appears as a compact star cluster of hot stars (see Figure 2.2). The survival of this cluster in the vicinity of SgrA* is an open question, which led to propose the presence of an intermediate mass black hole (~1300 M_{sun}) at the center of the cluster (Maillard et al. 2004).

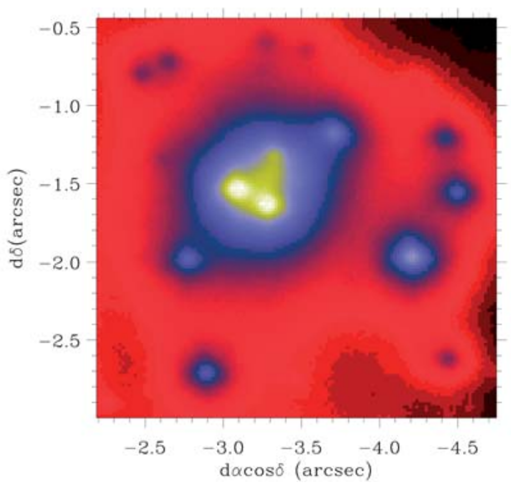


Figure 2.2: Adaptive optics image in the K' band at the Gemini North telescope of the IRS 13E field, showing the compact hot star cluster located 3.6" south-west of SgrA*, the central galactic Black Hole. The coordinates are in offset from SgrA*.

With the same instrument a typical galactic HII region Sh-106, excited by the winds and the far ultraviolet flux of a massive young star, has been observed in the Br γ line and the H_2 2.12 μm line. Velocity maps of these lines were obtained that allow building a precise model of the environment of such a source, with jets originating from the central source (Noel et al. 2005). This type of work could be made in a more sensitive and systematic way with a similar instrument in space. This has been a major drive in the proposition of the Molecular Hydrogen Explorer or H2EX, for the 2007 Cosmic Vision Call issued by ESA. With a 1.2 m telescope and a wide-field imaging Fourier transform spectrograph the goal is the spectro-imagery of the first four H_2 rotational lines (28.2, 17.0, 12.3 and 9.7 μm). This project should enable the direct detection of a large quantity of molecular gas, basic material for stars and galaxy assembly.

In this respect, Dome C in the Antarctic plateau is a promising site for infrared astronomy. A European network called ARENA in which the team participates actively has been working with 21 other laboratories in the preparation of a roadmap for the development of astronomical observation in this difficult site. Two instruments which would benefit from the properties of the site are particularly relevant to stellar physics, a spectroscopic sismometer (SIAMOIS) and a wide-field, high-resolution imaging Fourier transform spectrograph for the 2 to 5 μm range.

The team has also investigated the physics of Be stars, which are quasi-critically rotating main sequence objects with masses between 2 and 30 solar masses that have shown at least once some Balmer line emission.

Two questions need to be resolved regarding the Be phenomenon: a) what is the origin of the observed atmospheric fast rotation; b) what are the mechanisms that produce the mass ejection to form the circumstellar envelope. Using the in-house **FASTROT** code (Fremat et al. 2005) to calculate the spectra of gravitationally darkened fast rotating stars, it has been shown that Be stars rotate on average at 90% of their critical rotation. Moreover, using **FASTROT** and models of stellar evolution with rotation has shown that in our Galaxy the Be phenomenon can appear at whatever moment on the main sequence (Zorec et al. 2005). In particular, it appears that the rotational velocities of Be stars in the zero age main sequence form the fast-tail of a Gaussian distribution of rotational velocities. From spectra obtained with the VLT-FLAMES-GIRAFFE, it was shown that Be stars in the Magellanic Clouds rotate faster than those in the Milky Way, which is probably due to the lower metallicity in the Magellanic Clouds than in our Galaxy (Martayan et al. 2006, 2007).

The **FASTROT** code is currently used to determine the atmospheric abundance of CNO elements in atmospheres of fast rotating B stars with and without emission lines. Through the combination of VLTI-AMBER interferometric observations with 2D models of stellar structure with internal differential

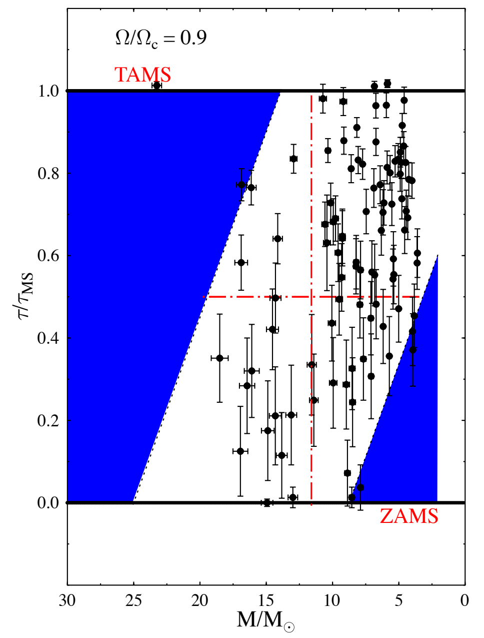


Figure 2.3: Fractional age τ /τMS [τ = age; τMS = time that stars can spend in the main sequence evolutionary phase] of Be stars in our Galaxy as a function of mass. Massive Be stars seem to display the Be phenomenon earlier than those with lower masses. The high mass-loss rates in massive stars may inhibit fast rotation near the TAMS, which would explain the lack of evolved massive Be stars

rotation and synthetic spectra obtained with **FASTROT**, the fundamental parameters of the Be star Achernar have been determined (Vinicius, Zorec et al. 2005). This study has shown that the core of this star might be rotating three times faster than its atmosphere (Zorec et al. 2007).

VLTI-AMBER observations and models of circumstellar envelope formation due to several scenarios that encompass discrete mass-ejection, viscous dissipation and so forth are being explored (Meilland et al. 2006). The analysis carried on FeII emission lines has shown that the circumstellar envelopes of Be stars do not always have Keplerian, physically thin circumstellar discs (Arias et al. 2006, 2007).

Finally, grids of synthetic far-infrared emission line and continuum spectra were constructed to prepare the automatic characterization of stars during the GAIA spatial mission (Fremat & Zorec 2007).

The B[e] phenomenon, characterized mainly by forbidden lines in the visual spectrum and a strong flux excess at about 2µm, appears in AeBe Herbig-type stars, symbiotic stars, supergiants (LBV variables), compact planetary nebulae and objects whose evolutionary status is difficult to unravel. Studies carried with the "self absorption curves" method (Muratorio et al. 2006) have enabled to characterize some physical characteristics of circumstellar envelopes of objects with the B[e] phenomenon like HD 45677, MWC 314, etc.

λ Boo stars belong to a dwarf Population I of A-type stars with a measured under-abundance metallicity as compared to the Sun, except for C, N, O and S elements, which has been interpreted as reflecting the chemical characteristics of the environments where they were formed. Gerbaldi et al. (2003, 2004, 2006) have shown that many λ Boo stars are undetected binaries. This hidden binarity can lead to ill-determined abundances. This effect will be treated in detail with synthetic line profiles of the OI 777 nm triplet calculated with non-LTE model atmospheres (Gerbaldi & Gros in preparation; **TLUSTY** models by Hubený & Lanz). Studies are presently ongoing concerning the ultraviolet energy distribution of γ Dor stars, which cannot be represented with normal model atmospheres (Gerbaldi et al. 2007).

2.3 THE SOLAR MAGNETIC ACTIVITY AND CORONAL RESEARCH

Observations from SoHO, Coronas and TRACE spatial missions offered an unprecedented and efficient analysis of the role of the magnetic field on heating mechanisms of the solar corona. The mass balance in the corona and the interplanetary medium in particular have been considered. These issues

were also addressed with observations at the time of total solar eclipses (Koutchmy et al. 2004; Koutchmy & Modolensky 2005; Koutchmy & Nikoghossian 2005; Wang et al. 2007). The magnetic structure of the corona was indirectly studied using comparisons with numerical model predictions of eclipse coronal images taken in white light. Other aspects like plasma-magnetic field interactions, coronal heating by waves and precursors of coronal mass ejections were spectroscopically explored with observations done in Hα (at Pic du Midi; Romeuf et al. 2007) and in other visible wavelengths combined with ultraviolet from space (Stellmacher & Wiehr 2005) and ground-based data. The ovalisation of the solar chromosphere deserved special attention (Filipov, Vilinga & Koutchmy 2007).

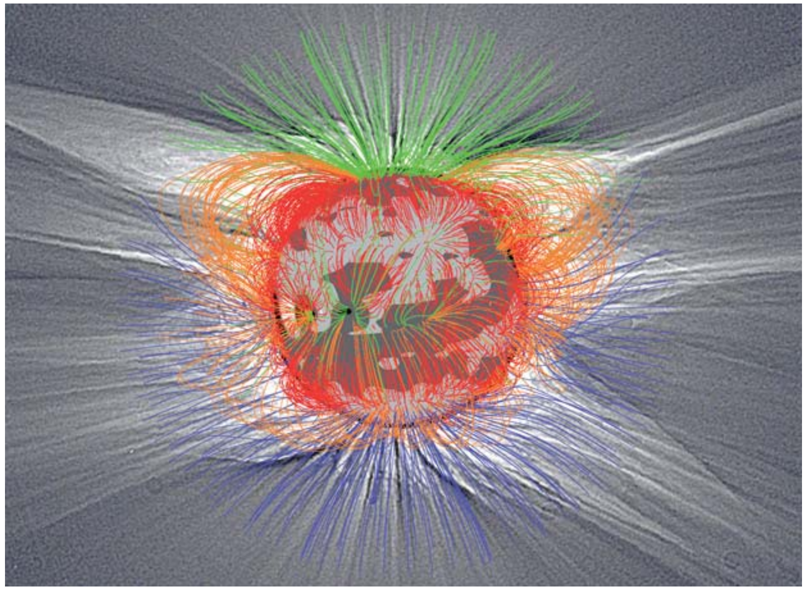


Figure 2.4: Numerical simulation of the coronal magnetic field lines based on observations of the photosphere, with superimposed W-L structures inferred from observations done by our team during the 2006 total solar eclipse in Egypt (Wang et al. 2007).

Spectroscopic observations carried out at Sacramento Peak (USA) enabled a study of the turbulence in the corona (Contesse et al. 2004) and new spectro-coronographic observations are planned at Pic du Midi Observatory. Several other contributions were made regarding the solar irradiance variability from satellite observations, due to Coronal mass ejections and flares (Veselovsky & Koutchmy 2006; Panasenko et al. 2005).

Instrumental developments are also carried out in collaboration with research teams in other laboratories. Theoretical papers on coronal mass ejections, eruptions, XR jets in coronal holes are currently prepared, based on the analysis of space-borne data from missions SoHO, Trace, Hinode (especially XRT), Stereo. Finally, the 2008 and 2009 total eclipses will be spectroscopically observed in the frame of international collaborations with USA, Russia, China and Iran.

2.4 THEORETICAL PROBLEMS IN STELLAR PHYSICS

Among the theoretical studies conducted by the group, a new method has been developed which allows calculating the thermal structure of the outermost stellar atmospheric layers, where the density is very low and the medium is in monochromatic radiative equilibrium (Crivellari et al. 2004, Simonneau et al. 2007). The "integral implicit method" has been used to calculate the structure of the external stellar atmospheric layers where the ultraviolet spectra are formed, which are not well accounted for by the usual radiation transfer methods. Such ultraviolet spectra are seen in the visible range when galaxies have sufficiently high redshifts.

Furthermore, using new methods to treat inverse problems, a huge amount of images of non-barred spiral galaxies have been used to demonstrate that their bulges are triaxial ellipsoids. This work also produced the probability distribution of the ellipticity of the galactic bulge-equatorial ellipses (Simonneau et al. 2007).

A new thermostatic description of mixing of gases in terms of a partitition of particle available spaces was suggested by Rohrmann & Zorec (2006). This method can be used for low density environments, such as stellar atmospheres.

Finally, the group is also interested in the physics of superfluid and superconducting fluids such as found in neutron stars. For instance, various aspects of the superfluidity and superconductivity in rotating frames and in curved space-time were studied using the tetrad formalism, so that physically measurable quantities could be defined in terms of tetrad components in the corresponding tensor field. An important feature of the tetrad approach is the appearance of correction terms containing the object of anholomity C, whenever a mathematical expression with respect to a natural frame is transformed with respect to an anholomic frame. This geometrical object expresses either the influence of the gravitational field or of the rotation (Krikorian & Sedrakian 2005, Sedrakian & Krikorian 2005). From the anholomic formulation of the London equations the expressions of the electric and magnetic field intensities inside a superconductor at rest in a stationary Universe could be derived (Krikorian 2007). Finally

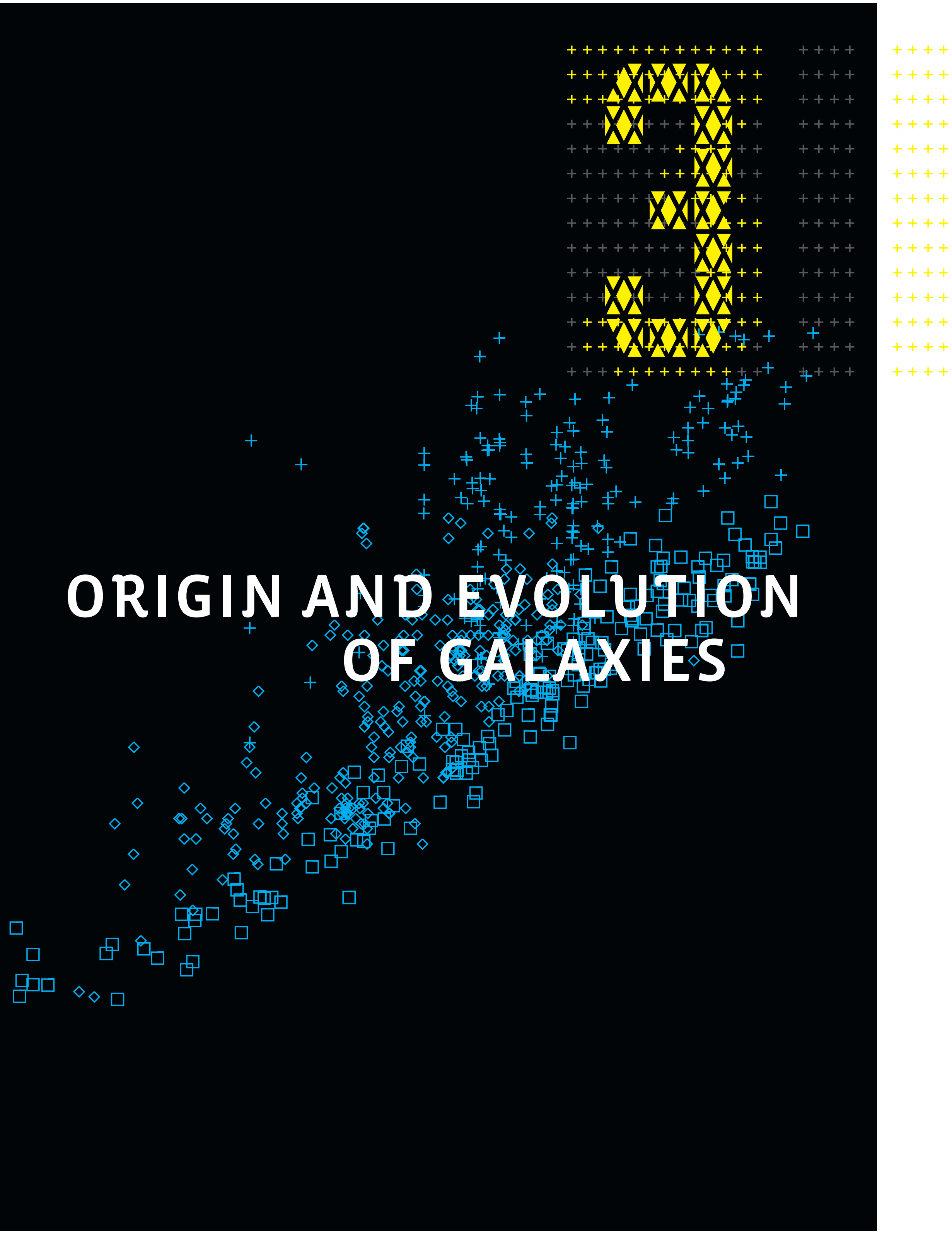
the generation of electric and magnetic fields inside a relativistically rotating superconductor has been interpreted as an electromagnetic effect of anholomity (Sedrakian & Krikorian 2006).

FUTURE RESEARCH DIRECTIONS 2.5

Stellar physics underlies several research themes of interest at IAP. In particular, studies of the structure and evolution of galaxies depend on stars; the analysis of data of extra-solar planets requires a detailed knowledge of parent stars; star formation was the main motivation of the space mission project H2EX. This fundamental topic remains the main objective of the ground-based observations planned for the Dome C site in Antarctica. The long-term observations of stellar seismology in Dome C will produce high temporal resolution data, which are not even possible with the CoRoT space mission which will end in 2009. Conversely, TERAPIX produces data useful for statistics on stellar populations just as data on stellar variability is the main by-product of EROS, MACHO and OGLE experiments discussed in other chapters of this report.

It thus appears worthwhile to develop further the existing synergies with the other research teams. Possible developments in this direction might be as follows: for example, the expected arrival of a new team member will lead to the development of cloud models in the atmospheres of brown dwarfs and extra-solar planets by investigating their radiative hydrodynamics. This will be paralleled by the continued modelling of alkali absorption line profiles necessary for the studies of brown dwarfs and extra-solar planets.

Massive stars are the motors of the galactic evolution through the stellar populations that they lead to (O, Of, LBV, WR and supergiants), and by recycling the cosmic matter that they provide with mass-loss phenomena. The ongoing work on fast rotation of Be stars needs to be pursued and generalized to other types of stars. Rotation has an important effect on the interpretation of observational data for obtaining stellar fundamental parameters and the determination of atmospheric abundances of chemical elements. It is also important for stellar evolution, in particular, for the changes in the production of several stellar populations that enter the diagnoses of the evolutionary stage of galaxies. Moreover, the effect of rotation depends on the initial stellar metallicity. For this reason understanding the interplay between observations and modelling of stellar evolution including rotation can be productive in studies of the initial mass function and star formation rate functions, or the durations of starbursts at different redshifts.



ORIGIN AND EVOLUTION OF GALAXIES

IAP scientists in this team seek to establish and understand the cosmic history of the different components of galaxies (stars, gas, dust, active galactic nuclei and dark matter). The hierarchical nature of the Universe means they must consider the environments of galaxies (close neighbours, groups, clusters and the large-scale features in the galaxy distribution), which alter galaxy properties through tides, mergers, ram pressure stripping of their interstellar gas and similar events.

The fundamental questions in this field are diverse. How are the mass and light of galaxy structures assembled? Are galaxy properties acquired during their formation or through subsequent evolution? What is the history of heavy element synthesis? What is the link between star formation efficiency, Active Galactic Nuclei and central black holes? What is the role of dynamical interactions with neighbouring galaxies, including mergers, and with clusters as a whole? How do galaxies contribute to background fluxes in the various spectral domains?

To answer these questions, the group combines observations, modelling and simulations. The observations are both ground-based (CFHT, VLT and other ESO telescopes, IRAM, VLBI) and space-borne (ROSAT, XMM-Newton, Chandra, GALEX, HST, ISO, Spitzer), covering the radio, infrared, optical, ultraviolet and X-ray spectral domains. The modelling is based upon numerical codes of spectro-photometric and chemical evolution, kinematics, and dynamical simulations of galaxies as well as groups and clusters.

INTERNAL PHYSICS OF GALAXIES 3.1

Scientists in this group have strong experience in the detailed study of the different components of galaxies and in their interactions. Galaxy formation can be traced by analyzing the chemical composition of the Milky Way and of distant galaxies. Because high and intermediate mass stars play a crucial role in the chemical evolution of galaxies, regions of star formation are used to characterize the distant Universe. Nuclear activity and radio jets play an important role in galaxy evolution.

Our understanding of the chemical evolution of the young Milky Way has improved considerably in the past few years, due to progress in: i) the use of efficient spectrographs on large telescopes (VLT, SUBARU, Keck), and ii) the development of a new generation of realistic models of stellar atmospheres which implement a non-LTE treatment of radiative transfer. These developments have multiplied by more than a factor of ten the quantity of data on the chemical composition of old metal-poor stars in the Galactic halo, and placed significant constraints on the early phases of Milky Way's life. In particular, the metallicity distribution of long lived stars of the Galactic halo is one of the most stringent constraints on the history of this system. The observed distribution is smooth and peaks at a metallicity [Fe/H] = -1.6. In the classic "monolithic collapse" scenario of the Milky Way, this is interpreted as due to strong outflow from the system (Prantzos 2003). Numerical simulations in the modern framework of hierarchical galaxy formation give distributions which are less smooth, and peak either at higher or lower metallicities than observed. It has been demonstrated that the observed distribution can be obtained analytically in the hierarchical merging scenario under the hypothesis that the chemical properties of the merging sub-halos are similar to those of the dwarf satellites of the Milky Way (Prantzos 2006b,c).

On the observational side, the analysis of a sample of more than 150 Planetary Nebulae in the Magellanic Clouds has indicated that abundances of oxygen and neon are modified during the evolution of the progenitor stars. Therefore, these elements cannot be used as tracers of the chemical evolution of the parent galaxy (Leisy and Dennefeld 2006). The effect seems to be metallicity dependent, and is being further studied in other galaxies of the Local Group (Leisy et al. 2005).

The FUSE satellite has been used to investigate in detail the neutral phase in H II extragalactic regions. The method makes use of the absorption lines from metals (i.e. N I, OI, PII etc.) in order to derive elementary abundances. Dwarf galaxies, which are chemically unevolved and gas rich, are ideal probes for testing chemical evolutionary models by comparison of both the ionised and the neutral phases. Results show that neutral gas is not pristine.

The method has been tested using the well known H II region NGC 604. Moreover, N, O and Ar are more deficient in the neutral gas than in the ionised component surrounding the ionising stellar complex (Lebouteiller et al. 2006). Further tests are required to investigate the influence of unresolved saturated lines.

The study of the Lyman α line in local galaxies is at the forefront of this team's activities. Results obtained recently using the ACS imager and the STIS spectrograph onboard the HST have underlined the importance of kinematical effects, which are generally neglected. New codes have been implemented to properly extract Lyman α images and these have revealed for the first time the presence of diffuse Lyman α emission scattered by the neutral gas across the main body of starburst galaxies (Hayes et al. 2005; see Figure 3.1). Analyses of the link between massive star formation and active nuclei have shown the importance of massive star formation in circumnuclear regions of active galactic nuclei (Cid-Fernandes et al. 2004, Cid-Fernandes et al. 2006, Gu et al. 2006).

IAP scientists continue to be active in modelling radio galaxies. The observations of compact radio sources can be explained if their nuclei contain binary black hole systems. Under this assumption, one can model the time variations of the positional coordinates of a VLBI component (observed using intercontinental interferometric techniques), and determine the inclination angle of the source, the bulk Lorentz factor of the ejected plasma, and the characteristics of the binary system (size, and ratio of the accretion disk precession period and the binary period). Moreover, flux variations of compact radio sources show rapid variations on the order of one day or less. Part of these variations can be explained by interstellar scintillation. The remaining optical variations suggest another mechanism intrinsic to the sources. The perturbation of the ejected plasma due to the formation of a warp in the central part of the accretion disk has been proposed.

3.2 GLOBAL PROPERTIES AND GALAXY EVOLUTION

The team also possesses world-class expertise in the spectral modelling of galaxies, which allows one to interpret observed spectral energy distributions of galaxies in terms of combined constraints on the stars, gas and dust within them. By performing these analyses at different cosmic epochs, the histories of star formation and chemical enrichment of galaxies can be constrained.

For instance, using a new set of models with improved spectral resolution, it has been possible to show that the stellar absorption features and the

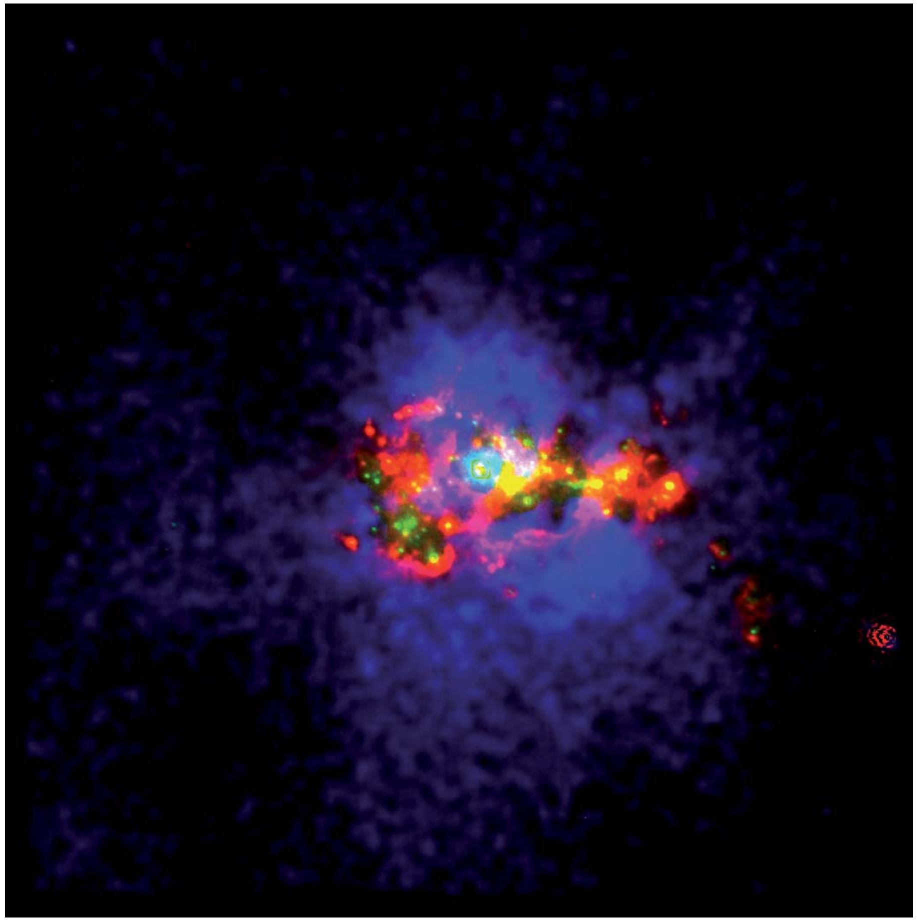


Figure 3.1: HST/ACS image of ESO338-IG0 galaxy. The newly detected diffuse light is shown in blue while the star-forming regions appears in white.

spectral continuum shape at ultraviolet, optical and near-infrared wavelengths provide valuable constraints on the history of star formation, stellar mass and stellar metallicity of a galaxy (Gallazzi et al. 2005). In addition, detailed fits of the emission-line spectrum can provide strong constraints on the current star formation rate and the parameters of the star-forming gas (Brinchmann et al. 2004). The analysis of the ultraviolet emission provides further constraints on the dust content (Kong et al. 2004; Salim et al. 2005).

In parallel to these studies, two new versions of the **PÉGASE** code (http://www2.iap.fr/pegase) have recently been developed. While **PÉGASE.2** only computed the stellar emission from the far-ultraviolet to the near-infrared, the new version **PÉGASE.3** (Fioc, Dwek & Rocca-Volmerange, in preparation) calculates the dust emission of galaxies and extends the wavelength domain

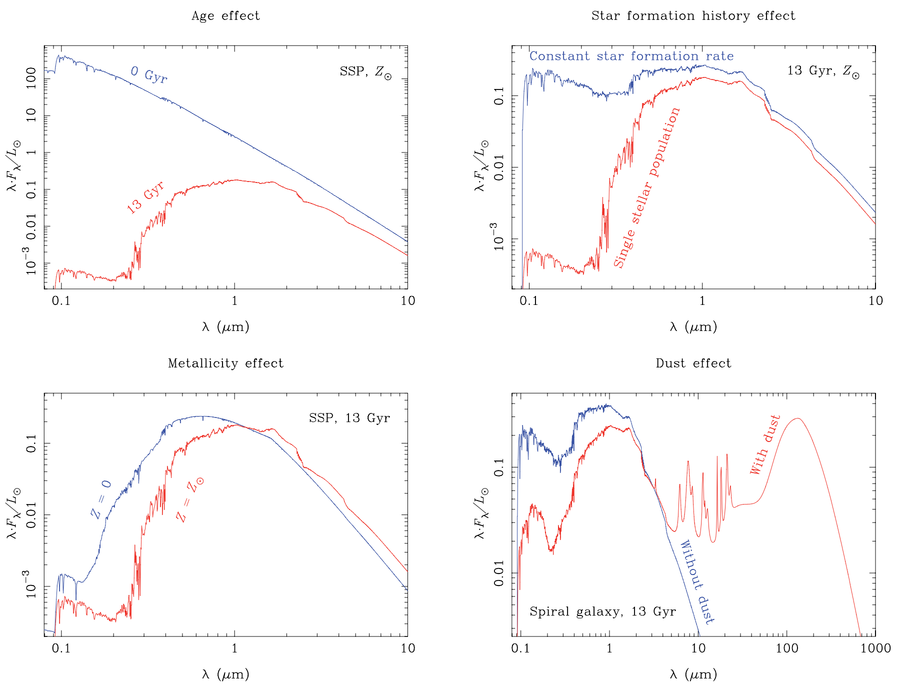


Figure 3.2: Sensitivity of **PÉGASE** spectra to various effects. Note in particular, in the bottom right panel, the emission of dust, as computed by **PÉGASE.3**.

to the mid- and far-infrared (see Figure 3.2). Computing the infrared spectrum is a difficult task, which requires modelling the radiative transfer within the galaxy, the stochastic heating of grains by the radiation field, the absorption of far-ultraviolet photons by dust and gas in H II regions. However, the infrared domain puts strong constraints on the recent star formation history and the opacity of galaxies. Evolved galaxies observed in the optical and in the infrared with ISO are currently being analyzed with this code. In parallel, **PÉGASE-HR** (Le Borgne et al. 2004; Ocvirk et al. 2003) has been developed to study the stellar populations and the kinematics of galaxies in the optical at high spectral resolution (R ~ 10,000). It is based on a library of stellar spectra obtained with the ÉLODIE spectrograph. Sets of synthetic spectra of galaxies have been produced with **PÉGASE-HR** and **PÉGASE.2** for the GAIA satellite (Tsalmantza et al. 2006, 2007).

Spectral models of galaxies have proved essential to interpret the data collected by modern multi-wavelength galaxy surveys, such as the Two-degree Field Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS) in the optical, the Galaxy Evolution Explorer (GALEX) survey in the ultraviolet, and infrared surveys carried out with the ISO and Spitzer satellites.

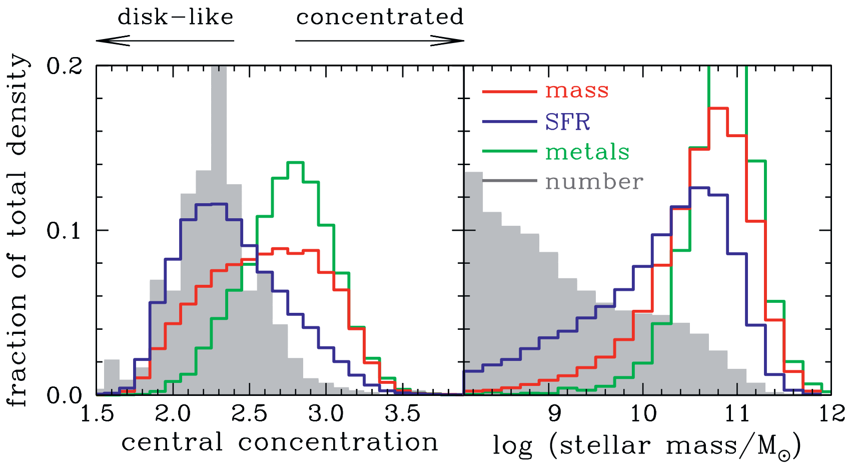


Figure 3.3: Contribution to the total densities of stellar mass, metals, and star formation rate of galaxies with different morphological types (characterised by the central concentration of light) and with different stellar mass, in the local Universe.

The spectral analysis of a sample of about 400,000 SDSS galaxies has allowed an unprecedented census of the physical properties of galaxies in the nearby Universe (e.g. Brinchmann et al. 2004; Tremonti et al. 2004; Kong et al. 2004; Heckman et al. 2004, 2005; Galazzi et al. 2005, 2006; Salim et al. 2005; Kauffmann et al. 2006). These results show that stars tend to form today in moderately massive, low-concentration (i.e. spiral) galaxies, while massive galaxies dominate the mass and metal densities in stars (see Figure 3.3). These properties represent an important local reference point for galaxy evolution models. At higher redshifts, an analysis of high-quality data for 48 galaxies from the GOODS survey has allowed the study of the relation between stellar mass and dynamical mass in early-type galaxies (Rettura et al. 2006).

Comparison of the models of spectral synthesis with the observed Universe at large redshift allows one to study the evolution of the different galaxy types, and to compare different evolution scenarios. The ESO-Sculptor Survey (comprising BVR photometry of 13000 galaxies at R_c<23.5 and spectra and redshifts of 900 galaxies at R_c<21.5 and z<0.6), has shown a marked evolution of late spiral Sc galaxies models (de Lapparent et al. 2004), in good agreement with the luminosity evolution predicted by the spectrophotometric models. The follow-up of this survey with the ISOCAM camera onboard the ISO satellite has been performed at 12 microns over 680 square arcmin (Seymour et al. 2007). The ISO data confirm the strong mid-infrared excess in the galaxy number counts (Rocca-Volmerange et al. 2007), also observed at 24 microns with Spitzer. By coherently linking the extinguished stellar emission to the

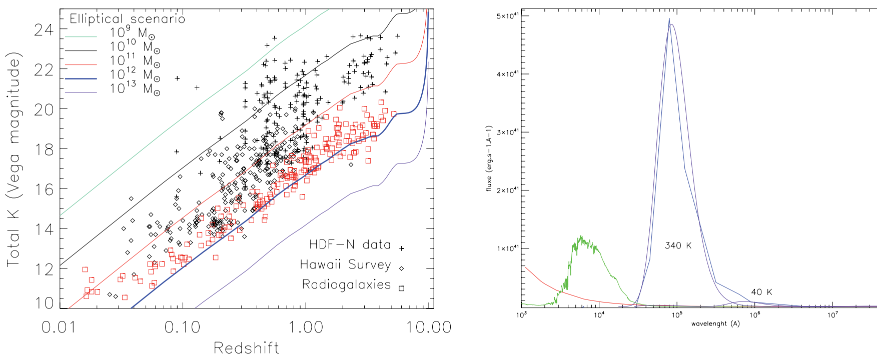


Figure 3.4: Observed K-z diagram for radio galaxies at z<4, compared with the predictions for elliptical galaxies (left panel). Modelling of the thermal emission of 3CR radio sources (right panel).

dust grain emission of the various galaxy types over time, **PEGASE.3** shows that the normal galaxy populations fail to match the excess in counts, whereas an additional 9% of distant and massive dusty elliptical galaxies that are ultra luminous in the mid-infrared is sufficient to fit both the 12µm and 24µm counts with no need for numerous episodic starbursting galaxies as proposed by others.

With the initial goal of resolving the far-infrared cosmic background, the analysis of the 170 micron sources from the ISO/FIRBACK survey, completed with Spitzer data, has been continued. Optical identification of the brighter sources with 2-4m telescopes has shown that these are in fact cold, local, moderately star forming galaxies, which had been previously neglected, despite their significant integrated star formation rate (Dennefeld et al. 2005; Taylor et al. 2005). Their luminosity function has been established (Takeuchi et al. 2006) and their spectral energy distribution measured (Sajina et al. 2006). The fainter, presumably more distant, sources are under study with the VLT to establish their formation history and possible links with sub-mm galaxies. In the far-infrared at 90µm, the team has pursued its implication in the large European program ELAIS (Rowan-Robinson et al. 2004; Héraudeau et al. 2006).

In the more distant Universe, an analysis of the Hubble K-band diagram with **PEGASE.2** suggests that the stellar counterparts of distant radio galaxies are elliptical galaxies of 10^{12} solar masses already in place at redshifts z>4 (Rocca-Volmerange et al. 2004; Rocca-Volmerange 2006; see Figure 3.4). This implies a short timescale for mass accumulation (<1Gyr), in agreement with the fragmentation theory (Rees & Ostriker 1977). Other observations in the near- and mid-infrared (De Breuck et al. 2004; Seymour et al. 2007) extend the mass measurements of radio galaxies. Moreover, 3D optical spectroscopy gives clues on radio galaxy sizes (~150 kpc) that are coherent with the fragmentation

theory (Moy & Rocca-Volmerange 2003). Disentangling the various infrared spectral components for 3CR powerful radio galaxies (Rocca-Volmerange & Remazeilles 2005) has provided estimates of their dust content (Figure 3.4), which allows one to predict the amount of sub-mm emission detectable with the future Herschel satellite.

ENVIRONMENTS OF GALAXIES AND LARGE-SCALE STRUCTURES 3.3

The long-range nature of gravity gathers galaxies into groups, clusters, and very large scale structures. Studying the distribution of galaxies at these various scales provide important clues on the distribution and properties of dark matter halos. Halo statistics provides indirect constraints on the primordial density fluctuations, whose distribution is the signature of the parameters of the Universe and of the nature of the dark matter. One gains insight into the physics linking the primordial density fluctuations to present-day halos.

Because elliptical galaxies are thought to be the products of mergers of spirals, whose flat rotation curves indicate that dark matter halos surround them, they should also be surrounded by dark matter halos. If the mass distribution in elliptical galaxies were to follow the universal law found for dark matter halos in cosmological simulations, then their inner velocity dispersions would be much smaller than observed (Mamon & Lokas 2005a). Therefore, the inner regions of these galaxies must be dominated by stars (Mamon & Lokas 2005a,b). Also, the total mass of ellipticals is underestimated by a factor of two if one supposes: 1) the Navarro-Frenk-White (1997) density profile for dark matter halos instead of the more recent improvements; 2) isotropic velocities instead of the mildly radial orbits found in the cosmological simulations (Mamon & Lokas 2005b). An analysis of high resolution simulations of mergers of spiral galaxies containing gas and dark matter halos shows that the typical merger remnants have a stellar distribution that resembles that of observed ordinary ellipticals, both in space and in velocity space (Dekel et al. 2005). Therefore the very low velocities recently measured for the planetary nebulae surrounding ordinary elliptical galaxies are explained not with a lack of dark matter, but with the highly elongated stellar orbits found in these simulations.

With the aim of understanding the history of the formation and evolution of groups and clusters of galaxies, members of the team combine observations at all wavelengths. They have shown that clusters undergo mergers, and are therefore still forming. Preferential directions have been found, in agreement with the idea that clusters are located at the intersection of cosmic filaments

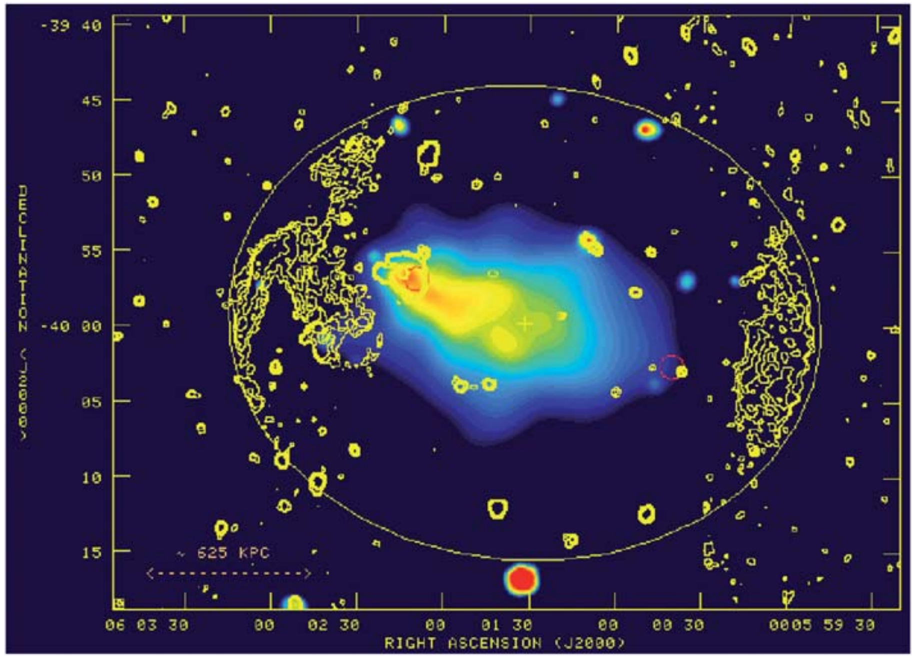


Figure 3.5: X-ray map of Abell 3376 obtained with ROSAT/PSPC, on which are superimposed 1.4 GHz VLA radio iso-intensity contours. The ellipse is a geometrical fit to the peripheral radio sources, whose centre is indicated by a cross (Bagchi et al. 2006).

and accrete matter along these filaments. Furthermore, X-ray observations have led to the discovery of two giant arcs of radio emitting material around Abell cluster 3376 (Bagchi et al. 2006), suggesting the existence of shock waves at very large scales (see Figure 3.5). Temperature and metallicity maps of the X-ray gas in clusters observed with XMM-Newton show that these objects are rarely in equilibrium, and provide insight into their formation (Durret et al. 2005).

A detailed optical analysis of the Coma cluster indicates that it is still accreting groups and that the two central galaxies have spent a different time span in the cluster centre. Several hundred low surface brightness galaxies were detected in Coma, as well as four sources of diffuse light (Adami et al. 2005a,b; Adami et al. 2006a,b; Adami et al. 2007), suggesting that galaxies may have been destroyed by mergers and tidal effects in dense environments (Covone et al. 2006). However, based on far ultraviolet observations with FUSE, clusters are confirmed to host smaller amounts of gas at 10^6 K than predicted in the nineties (Lecavelier des Etangs, Gopal-Krishna & Durret 2004).

Galaxies are found to be older in the central regions of cluster Cl 0048-2942 (Serote-Roos et al. 2005). This favours the idea that galaxies are continually

being accreted in the peripheral regions of clusters, where star formation is triggered. The analysis of the most distant fossil group at z=0.59 (Ulmer et al. 2005) has added evidence that such groups are formed by accretion of galaxies onto the central one. Nevertheless, the galaxy luminosity function of Abell 496, based on deep CFHT/MEGACAM images (Boué et al. 2007), shows a moderate number of faint galaxies (−1.4 slope), in contradiction with recent results claiming the existence of an important population of faint galaxies (−2.3 slope).

The observation of 13 spiral galaxies that are deficient in neutral hydrogen and *a priori* located far behind the Virgo cluster have led some to suggest that these galaxies lose their gas while penetrating the cluster, through ram pressure stripping by the intracluster hot gas. However, galaxies that penetrate clusters cannot bounce out beyond one or two cluster virial radii (Mamon et al. 2004). It was shown that among the 13 HI-deficient spirals, half are actually at the cluster distance and not behind (due to imprecise distances) and the other half lost their gas through tidal interactions with neighbouring galaxies (Sanchis et al. 2004).

In the core of the Shapley supercluster, spiral cluster galaxies are deficient in the ratio of continuum radio emission to near-infrared luminosity, a signature of active galactic nuclei and starbursts (Mauduit & Mamon 2007). This deficiency is caused by the destruction of cool cores of merging clusters, and by the enhanced ram pressure stripping in galaxies within merging clusters (Mauduit & Mamon 2007). Both mechanisms limit the gas supply for the active galactic nuclei, and ram pressure stripping limits the amount of star forming gas.

On larger scales, the large-scale clustering of galaxies along walls and filaments separated by large voids can be characterized quantitatively using correlation functions. Application to the ESO-Sculptor Survey (comprising BVR photometry of 13000 galaxies at R_c<23.5 and spectra and redshifts of 900 galaxies at R_c<21.5 and z<0.6), yields a bimodal behaviour analogous to that expected in the models of hierarchical collapse of dark matter halos: at small scales, the two-point correlation function is dominated by pairs of galaxies belonging to a same halo, and is thus determined by the profile of the dark halos; whereas at large scales, it is dominated by pairs of galaxies belonging to different halos, and thus match the matter correlation function. Moreover, the ESO-Sculptor analysis suggests that giant early-type galaxies tend to be preferentially located at the centres of the most massive halos, whereas the late spiral galaxies are rather located at their outskirts, or at the centre of less massive halos. Finally, dwarf galaxies are weakly correlated with the late spiral galaxies and tend to be satellites of early-type galaxies (de Lapparent & Slezak 2007). These results have extended to higher redshifts the local constraints on the dark matter halos, and have provided the first measurement of the dwarf galaxy correlation function.

3.4 CONCLUSIONS

Future observations from ground and space will provide large amounts of data, which the scientists of the "Origin and Evolution of Galaxies" group will be able to explore in depth using their expertise in observations and data reduction, in chemical and spectral modelling, and in kinematical and dynamical modelling. Large surveys in the visible (SDSS, 6dFGS, CFHTLS, Pan-STARRS, LSST) and the near infrared (DENIS, 2MASS, UKIDSS, WIRDS) will lead to imaging and/or spectroscopic follow-ups in gamma rays (SVOM/ECLAIR), X-rays (XMM-Newton, Chandra), ultraviolet (GALEX, HST/COS, WSO/UV), near-infrared (VISTA, VLT, CFHT, E-ELT), mid- and far-infrared (Spitzer, Herschel), and at sub-mm and radio wavelengths (APEX, ALMA, Planck, LOFAR, SKA). Virtual observatories will also play a crucial role in enabling access to the large databases. From these analyses, new breakthroughs are expected in the understanding of the starburst phenomenon and the effects of accretion and feedback in the formation of the galaxies.

The high quality of images acquired at CFHT/MEGACAM will allow astronomers to interpret the Hubble morphological sequence in terms of history of bulge and disk, and to determine the role and interplay of spiral arms, bars, rings, and dust. Comparison of the morphology and spectral properties of the various galaxy types, together with their relative spatial distribution within the dark matter halos, will provide crucial information on their history of star formation and mass accumulation. The analysis of clusters and groups of galaxies using X-ray, optical and mid-infrared archives will also considerably increase our understanding of the influence of local environment on mass profiles and velocity fields.

In parallel, our understanding of the local Universe will greatly improve. Using HST/ACS data combined with ground-based facilities will allow a better comprehension of how local Lyman α emitters are related to dust, a necessary step for making the link with the high redshift universe. ESA's GAIA satellite will open the way to a thorough study of the structure and evolution of the Milky Way, which will in turn serve as a benchmark for new full scale models of galactic disk formation in a cosmological framework. In cosmology, GAIA will allow one to resolve binary black hole systems in the nuclei of radio galaxies. GAIA observations will also enable studies of the "variable sky", from massive stars to active galactic nuclei and supernovae, the latter serving as standard candles for the distant Universe.

In the long term, the next generation of telescopes on the ground (E-ELT) and in space (James Webb Space Telescope) will allow astronomers to study the first generations of stars and galaxies (at z~10) with high spectral and spatial resolution. The next generation of integral field spectroscopy instruments on the VLT will complement these observations with unique kinematical and dynamical constraints.

4

HIGH ENERGY ASTROPHYSICS AND COSMOLOGY

The research team “High Energy Astrophysics and cosmology” is involved in the study of astrophysical sources of high energy radiation, especially gamma-ray bursts and quasars, and in the use of these bright objects as tracers of the distant Universe.

Theoretical activities in this group follow two main directions: modelling astrophysical sources of high-energy radiation, which aims at an understanding of the physics of different high-energy sources such as X-ray binaries and gamma-ray bursts; and the cosmic evolution of baryons. Big-bang nucleosynthesis is used in particular to test models of the primordial Universe involving new physics. A consistent description of the cosmic evolution of baryons from the first stars to the present epoch is also developed. Finally, cosmic rays are investigated in this cosmological context, and most notably their role in the origin of light elements. These various activities are related by the role of massive stars that are the source of metal enrichment, of ultraviolet photons for the reionization, and that are also probably the progenitors of gamma-ray bursts.

Team members are also involved in important observational programs, in particular the search and study of high redshift objects.

Several extensive surveys are used to search for new sources, both galaxies and quasars. Gamma-ray bursts however require a special observational strategy. To this end, the team has become involved in the preparation of the SVOM satellite mission, which is devoted to the multi-wavelength study of gamma-ray bursts and the use of their afterglows to probe the distant Universe. Another large observational program is absorption spectroscopy along the line of sight to distant sources, such as quasars and gamma-ray burst afterglows. The absorption lines are due to the interstellar medium of the host galaxy, the intervening structures along the line of sight, and the intergalactic medium. Their study allows one to measure the properties of the absorbing gas and its spatial distribution. The local interstellar medium is also analysed using stellar lines of sight. Spectroscopy is a powerful tool to probe low-density regions, structure formation (damped Lyman alpha systems) and the interstellar medium of evolved structures, and to understand their evolution. With current instrumentation, the attainable precision is sufficient to test possible variations of physical constants between the Universe at $z \sim 2$ and today, as discussed further below. ++++++++++++++++++++++++++++++++++

++

MODELLING ASTROPHYSICAL SOURCES OF HIGH-ENERGY RADIATION 4.1

The physical mechanism leading to the production of relativistic jets in active galactic nuclei, gamma-ray bursts and some X-ray binaries (micro-quasars) remains poorly understood. In particular, the role played by the spin of the central source is highly debated. Sikora, Starwarz & Lasota (2007) have recently investigated this problem. Studying the radio luminosity of active galactic nuclei, they observed two distinct sequences as a function of the bolometric luminosity, whereas only one sequence is found for X-ray binaries. For this reason, the radio activity in accreting black holes (which is related to the jet formation) cannot depend only on the accretion rate or the spectral state as in X-ray binaries. The accretion rate only fixes the slope of the sequence, whereas the normalization is determined by the spin of the central black hole. This suggests that the black hole spin plays an important role in relativistic ejections. In addition, as black holes in disk galaxies are found only in the "radio-quiet" sequence, their spins are probably low.

With respect to the physics of X-ray binaries, the study of Lasota & Hameury (2005) has recently provided strong arguments against the mechanism of gravitational resonance invoked to explain the "superhumps" observed in the light curves of low-mass X-ray binaries and cataclysmic variables. This study also shows that this popular model is in contradiction with both observations and models of accretion disks.

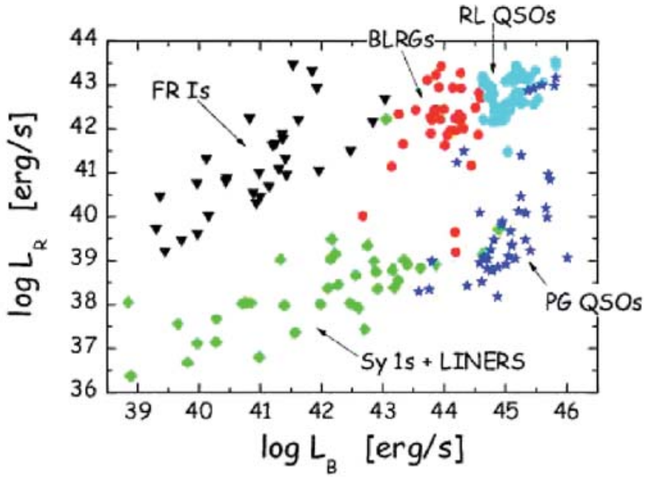


Figure 4.1: Active galactic nuclei radio luminosity as a function of the bolometric luminosity. Two sequences are found.

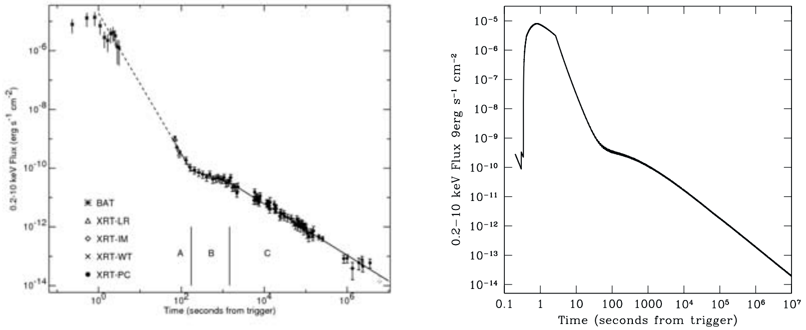


Figure 4.2: The X-ray afterglow of gamma-ray bursts. Left: an example of an early X-ray afterglow observed by Swift/XRT. Right: the result of the modelling of such an afterglow using the long-lived reverse shock model developed at the IAP.

Another long-term activity of the team aims at building a consistent description of all phenomena observed in gamma-ray bursts. In the most discussed scenario, it is proposed that a young stellar mass black hole produces a highly-relativistic ejecta. Because of the initial variability, internal shocks form and propagate within the ejecta. Due to the deceleration by the ambient medium, a reverse shock crosses the ejecta, and a strong ultra-relativistic external shock propagates in the circumstellar medium. Electrons accelerated in these shocks radiate to produce the observed emission. Studies conducted in the group have shown that the X- and gamma-ray prompt emission of some peculiar gamma-ray bursts (deemed “anemic” or X-ray flashes) can be explained by internal shocks, already known to reproduce well “classical” gamma-ray bursts (Barraud et al. 2005; Daigne & Mochkovitch 2007). Until 2004, the afterglow seemed to be well reproduced by the external shock model. However the results of the Swift mission have revealed a complex behaviour in the early phase that is not easily reproduced by this model. This is illustrated in the study of GRB 050820a reported in Genet, Daigne & Mochkovitch (2007a). As a first alternative, the afterglow has been modelled in the “electromagnetic” model of Blandford & Lyutikov (Genet, Daigne & Mochkovitch, 2006). More recently, a new paradigm has been proposed, in which the afterglow is due to a long-lived reverse shock. The first results are very promising, as shown in Genet, Daigne & Mochkovitch (2007b).

4.2 BIG-BANG NUCLEOSYNTHESIS AND THE COSMIC EVOLUTION OF BARYONS

Big-bang nucleosynthesis represents a very useful probe of the first instants of the Universe (Coc et al. 2004, Figure 4.3). In order to improve the accuracy of the theoretical calculations, the nuclear network has been updated

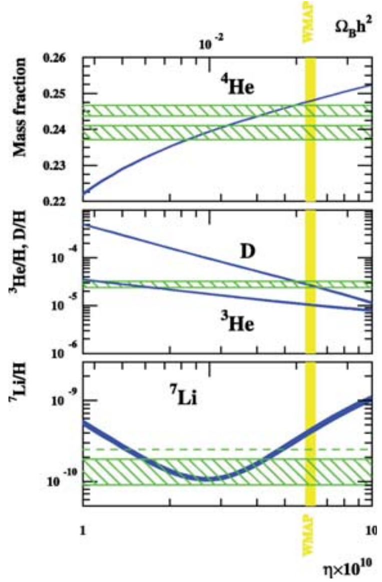


Figure 4.3: The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as a function of the baryon -- photon ratio. Dashed regions show the observed abundances. The vertical band indicates the WMAP value of $\Omega_b\ h^2$.

(Descouvemont et al. 2004, 2005; Coc et al. 2004). In particular, it can be shown that new measurements of the cross section ^{7}Be(d,p)2^{4}He cannot solve the discrepancy between observations of stars in the Galactic halo and the abundance of ^{7}Li predicted by big-bang nucleosynthesis for the value of Ω_b given by the WMAP results (Angulo et al 2005).

Predictions from big-bang nucleosynthesis are so sensitive that it now allows testing alternative models for gravity (Coc et al. 2006). The effect of the variations of fundamental nuclear parameters has also been studied at the epoch of the solar system formation (Olive et al. 2004) and during big-bang nucleosynthesis (Coc et al. 2007). To that effect, the relations between fundamental parameters that are predicted in unified theories have been considered. In particular, the production of ^{4}He is very sensitive to the neutron lifetime and the proton-neutron mass difference which are related to the Yukawa coupling constants and the fine structure constant. In the same context, it has been shown that the variation of the deuterium binding energy could reconcile the ^{7}Li primordial abundance with existing observations (Coc et al. 2007). Finally, the effect of the decay of unstable particles on the production/destruction of nuclei has also been investigated. This mechanism is strongly constrained by the ^{3}He/D ratio and cannot solve the problem of the abundance of ^{7}Li. This gives interesting constraints in the parameter space of supersymmetric theories where dark matter is made of neutralinos or gravitinos (Ellis, Olive & Vangioni 2005).

The variation of fundamental constants may also be tested experimentally using spectroscopy of quasars. Several studies by the group, using data from the VLT Large Program (340h with UVES), and the "multiple multiplets" method to constrain the variations of the fine structure constant have found the limit $\Delta\alpha/\alpha < 0.2\times10^{-5}$ between $z = 2$ and $z = 0$ (Srianand et al. 2004; Chand et al. 2004; Chand et al. 2005; Chand et al. 2006), see also Figure 4.4. Concerning the variation of the proton to electron mass ratio, the following limit has been obtained: $\Delta(mp/me)/(mp/me) < 2\times10^{-5}$ at $z \sim 2.5$ (Ivanchik et al. 2005; Reinhold et al. 2006).

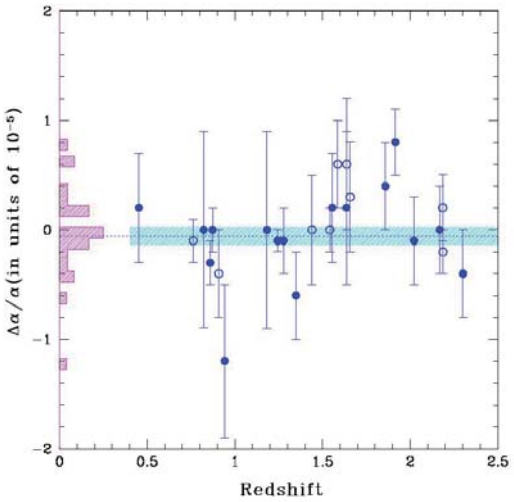


Figure 4.4: Observational constraints on the variation of the fine structure constant from VLT data.

The cosmic evolution of baryons has been studied in the framework of the hierarchical scenario for structure formation, using a large set of observational constraints: cosmic star formation rate, chemical abundances at different redshifts and in different astrophysical sites and type Ia/II supernova rates (Daigne et al. 2004; Daigne et al. 2006). These studies have led to interesting constraints on the mass range of the first stars. Furthermore, the same model allows one to compute the neutrino background produced by type II or pair-instability supernovae associated with population III stars and/or normal stars. Interestingly, the estimated flux is close to the detection limit of Super Kamiokande (Daigne et al. 2007). The corresponding gravitational wave background, which has also been calculated in Sandick et al. (2006) could be detected by LIGO III or future interferometers such as BBO and DECIGO.

Finally, VLT observations of lithium-6 in halo stars reveals abundances which are ~1000 times larger than the BBN prediction. It has been proposed that this isotope could be formed by spallation of nuclei in the intergalactic medium by cosmological cosmic rays. This mechanism produces lithium-6 without creating an excess of lithium-7 (Rollinde et al. 2005; Rollinde et al. 2006). In order to understand some of the physical processes related to Galactic cosmic rays, their sources and their composition have been studied in Taillet et al. (2004) and Combet et al. (2005).

DETECTION AND OBSERVATIONS OF SOURCES AT HIGH REDSHIFT 4.3

Ultra-luminous infrared galaxies correspond to phases of intense star formation in massive elliptical galaxies, which are a major contribution to star formation at $z > 1$. Their luminosity and star formation rate can be estimated from the dust emission in the millimetre range, while the detection of CO allows determining the mass of the interstellar medium, the dynamics and the total mass of the galaxy.

The group participates in several large ongoing programs at the IRAM Observatory. This has notably led to the detection of dust around quasars at redshifts as high as $z > 6$ (Wang et al. 2007; Wang et al. in preparation; Willott et al. in preparation). The CO content and the structure of a dozen of submillimeter galaxies have also been measured (Neri et al. 2003, Greve et al. 2005, Tacconi et al. 2006, Tacconi et al. in preparation), and the C^+ line at 157 μm has been detected for the first time at large redshifts (Maiolino et al. 2005). Recently, a new program has started with the MAMBO camera at IRAM which aims at measuring the millimetre emission of infrared sources at large redshift in the Spitzer/SWIRE survey. About 50 sources have already been detected at 1.2 mm (Lonsdale et al. in preparation; Polletta et al. in preparation; Omont et al. in preparation). These results characterize the far-infrared luminosity of an important class of SWIRE sources and show that they constitute the largest sample of high redshift ultra-luminous infrared galaxies known at present, which represent a key step in the formation process of massive elliptical galaxies. Such samples of massive galaxies are important to identify large-scale structures at $z \sim 1.5$-2.5 and are a complement to the search for proto-galactic clusters around active galactic nuclei with WIRCAM (Galametz et al. in preparation), or in the future with Spitzer, Herschel or using the Sunyaev-Zeldovich effect (Omont et al. 2007).

Data from the CFHT-LS (see Chapter 5) offer an optical complement to near-infrared Spitzer data. One ongoing project aims at studying simultaneously the variability and the mid-infrared emission of active galactic nuclei and to analyse the infrared emission of CFHT-LS galaxies at $z \sim 3$-4. The use of CFHT-LS data will also allow the identification of high redshift galaxies and quasars using color-color selection criteria defined on the basis of the synthetic populations models of Bruzual & Charlot. This allows one to measure the star formation rate in these galaxies and its evolution, to study their environment and clustering and to estimate their contribution to the extreme ultraviolet and X-ray backgrounds, in order to better constrain the sources of reionization at $z < 6$.

Recent deep surveys with Chandra and XMM-Newton allow the precise measurement of the contribution of quasars to the intergalactic X-ray flux, and to characterize two classes of quasars: one with a weak X-ray absorption associated with classical quasars and the second with a strong X-ray absorption which is obscured in the optical. They are easily distinguished in X- vs optical diagrams. However, they span the same range of hard X-ray luminosities and absolute K magnitudes and are therefore tracing the same level of accretion. The fraction of absorbed X-ray sources (~ 75 %) appears to be independent of redshift (Mainieri et al. 2002; Gilli et al. 2003; Szokoly et al. 2004; Gilli et al. 2005; Mainieri et al. 2005; Tozzi et al. 2006).

A new program to search for quasars at various redshifts in large imaging surveys has been initiated by members of the group. It will eventually lead to (i) finding sources adapted to the study of the intergalactic medium (see e.g. Scannapieco et al. 2006); (ii) studying non-biased samples of damped Lyman alpha systems (see e.g. Ledoux et al. 2003); and (iii) studying the active galactic nuclei luminosity function. Photometric methods to select quasar candidates have been developed and spectroscopic follow-up is underway at the AAT.

As mentioned in the introduction, the group is also involved in the SVOM project (Schanne et al. 2006), a Sino-French satellite funded by the two space agencies (phase A in 2007, launch in 2012). SVOM has gamma, X-ray and visible instruments on board and can detect, localize in real-time and observe gamma-ray bursts and their afterglows. The two main objectives are the physical study of gamma-ray bursts and their use for cosmology. The latter requires rapid follow-up from large telescopes, as illustrated by Vreeswiijk et al. (2007). In order to understand the role of gamma-ray bursts as tracers of the distant Universe, the redshift distribution of long gamma-ray bursts has been studied in some detail (Daigne, Rossi & Mochkovitch 2006). This study concludes that evolution is necessary to account for the Swift data. In particular, stars at high redshift seem more efficient in producing gamma-ray bursts than in the local Universe. This model is now used to test SVOM detection algorithms and to compute the expected rates for different classes of gamma-ray bursts.

SPECTROSCOPIC STUDIES OF THE INTERSTELLAR AND INTERGALACTIC MEDIUM 4.4

The only observational method to study the intergalactic medium and the interstellar medium of distant galaxies is to use the absorption lines from neutral hydrogen and metal ions in quasar spectra. The group actively participates in several ongoing programs using the VLT UVES and FORS instruments. In particular, a large collaboration of astronomers from ESO countries are carrying out a Large Program VLT-UVES (334 h, with the PI from IAP), which represents a spectroscopic survey of absorption lines in bright quasars. This programme has already led to the publication of 21 refereed papers and an invited review in an IAU colloquium (Bergeron & Herbert-Fort 2005). A large H_2 survey led by a group member has also obtained more than 50 nights at the VLT. Some particular subjects of interest are the evolution of the chemical enrichment of the intergalactic medium, the measurement of the ultraviolet intergalactic flux and the properties and the origin of the highly ionized phase.

Concerning the latter, two problems can be solved by the existence of a warm-hot phase with temperature $T \sim 10^5$-10^7 K in the intergalactic medium: the missing baryons (~50 %) at $z \sim 0$ and the missing metals (~60 %) at $z \sim 2.5$. This warm-hot intergalactic gas has been identified using absorption lines of the OVI doublet (1032, 1038 Å) associated with the Lyman-α forest in quasar spectra. The chemical enrichment turns out to be highly inhomogeneous and the distribution of oxygen bimodal (Bergeron et al. 2002; Bergeron & Herbert-Fort in preparation), see Figure 4.5.

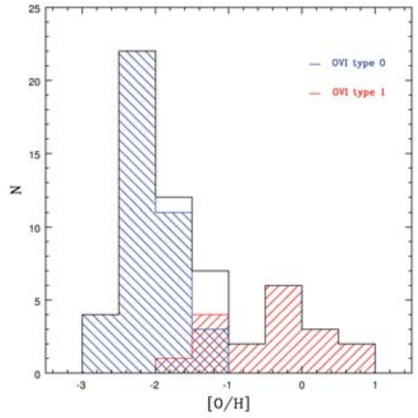


Figure 4.5: The abundance of OVI absorbers on 12 quasars lines of sight in the VLT-UVES Large Program. The distribution is clearly bimodal, which confirms the existence of two populations among OVI absorbers.

The first study of the OVI content in underdense regions in the intergalactic medium has also been completed. It has been shown that the OVI abundance increases with density, which suggests that a large fraction of this gas is associated with galactic winds (Aracil et al. 2004). Furthermore, all damped Lyman alpha systems appear to have an associated OVI absorption. This probably means that a hot phase ($T > 10^6$ K) exists in all galaxies at high redshift (Fox et al. 2007). The corresponding galactic winds could have powered the ejection of metals from the most massive halos up to distances larger than 2 Mpc (Scannapieco et al. 2006). Finally, a mass-metallicity relation has been observed in damped Lyman alpha systems (Ledoux et al. 2006), the most massive systems (in which the winds should be less efficient) having the largest metallicity (and then also the largest star formation rates).

The physical conditions in the hot ($T>10^6$ K) intergalactic medium have been determined and compared to models of large halos of gas heated by shocks in galactic winds. Observing time at the VLT has furthermore been obtained in order to identify these OVI systems spectroscopically at $z \sim 2.5$. In the hot IGM at $z \sim 0$, data from XMM-Newton and Chandra are used to detect very hot gas (OVII/OVIII absorptions).

High redshift damped Lyman alpha systems are absorbers with large column densities, and are therefore considered as the precursors of galactic disks. As the gas is neutral, metal abundances can be accurately measured and such systems can be used to constrain models of cosmic chemical evolution. The first systematic search for H_2 in these systems has been conducted by observing around 70 quasars with VLT-UVES. Molecular hydrogen has been detected in 15 systems and CO in one system. This survey led to the publication of about 15 papers. Among the results, it has been shown that the existence of molecules is highly correlated with the gas metallicity, H_2 being detected in 40 % of systems with a metallicity greater that $1/20\ Z_\odot$ (Petitjean et al. 2006). Furthermore, the gas in damped Lyman alpha systems, whose physical properties can be studied in detail (Noterdaeme et al. 2007), turns out to be homogeneous, except in molecular components where metal depletion on dust can be large (Rodriguez et al. 2006). A lot of information can thus be extracted from multi-wavelength studies of damped Lyman alpha systems. For instance, the observation of the Lyman alpha emission coupled with the measurement of absorption from the excited level of CII, which is a tracer of gas cooling allows one to place strong constraints on the star formation rate (Heinmüller et al. 2006). A large survey of absorption at 21 cm in damped Lyman alpha systems at intermediate and high redshifts has been initiated, with more that 300 h at GMRT awarded (Gupta et al. 2007; Srianand et al. 2007).

Turning to the spatial structure of the intergalactic medium, quasar pairs with an angular separation of around 1 to 3 arcmin have been observed in order to study the correlation of the absorption lines detected in each line of sight. This allows identifying structures with scales of the order of the separation, or greater. From the observation of 33 pairs of quasars with FORS-VLT (Coppolani et al. 2006a, b), it has been possible to demonstrate the existence of a high correlation, which is compatible with the formation of structures in the standard cosmological model. This is the largest sample of pairs that has ever been studied. These have also been used to conduct the first Alcock-Paczinsky test to measure the geometry of the Universe by comparing the transverse and the radial correlation. In a near future, this will constrain in an independent way the value of the cosmological constant Ω_Λ. One may further hope to observe groups of quasars in the same field, which would provide a new tool to reconstruct the 3D density field from the absorption lines detected in each line of sight. In order to constrain the topology of the intergalactic medium, specific inversion methods have been devised and statistical tools have been identified (Caucci et al. 2005). The simulations that are used must be normalized by the observation of the mean absorption in the intergalactic medium, and its evolution with redshift; this procedure introduces systematic errors, which have been estimated in Aghaee et al. (2005).

In the vicinity of a quasar, the strong ultraviolet flux decreases the Lyman absorption in the spectrum, as compared to the mean absorption. However an overdensity around the quasar would compensate for this proximity effect. The analysis of this proximity effect using data from the Large Program VLT-UVES at $z = 2\text{-}3$ (Rollinde et al. 2005), and quasars at $z>4$ obtained at Keck (Guimaraes et al. 2007) has confirmed the existence of a dense environment around quasars.

Finally, absorption spectroscopy of Galactic lines of sight is also an important tool to study the physical conditions of the interstellar medium of the Milky Way. For instance, the follow-up (started in 1999) of H_2 absorption lines observed with FUSE and other tracers like CH and CH^+ in the spectrum of the extincted runaway star HD34078 is underway to probe the small-scale (~1 AU) structure of the molecular interstellar medium (Rollinde et al. 2003). FUSE spectra do not show prominent structures in H_2 but indicate a high excitation level for the gas (Boissé et al. 2005), which is consistent with the fact that HD34078 is presently penetrating into the absorbing cloud. This was confirmed by direct observations of CO at IRAM. This is a unique situation that allows the exploration of the cloud structure crossed by the star, and also to study how the interstellar medium reacts after a dramatic increase of the ultraviolet flux. The origin of the observed strong time variations of CH and CH^+ lines, which may result from a clumpy structure of the cloud or perturbations due to the star, is also the subject of current investigations.

In order to study the problem of radiative transfer in a clumpy medium a two-phase random model developed in Boissé (1990) has been adapted to the case of an emitting medium to describe the internal extinction in galaxies. Analytical solutions can be obtained and it is possible to take into account opaque clouds, which are spatially correlated with newly formed stars. This model will be used in the near future to describe in a more realistic way the global energy budget within a galaxy, and the properties of the spectral continuum of distant galaxies. Similarly, by modelling the effect of the statistical mean over a whole stellar population, it is possible to model the formation of interstellar lines in the global spectrum of a galaxy. At present, these lines are well detected in the best spectra of distant galaxies, and ongoing work aims at extracting from such spectra some information about the metal content in these galaxies.

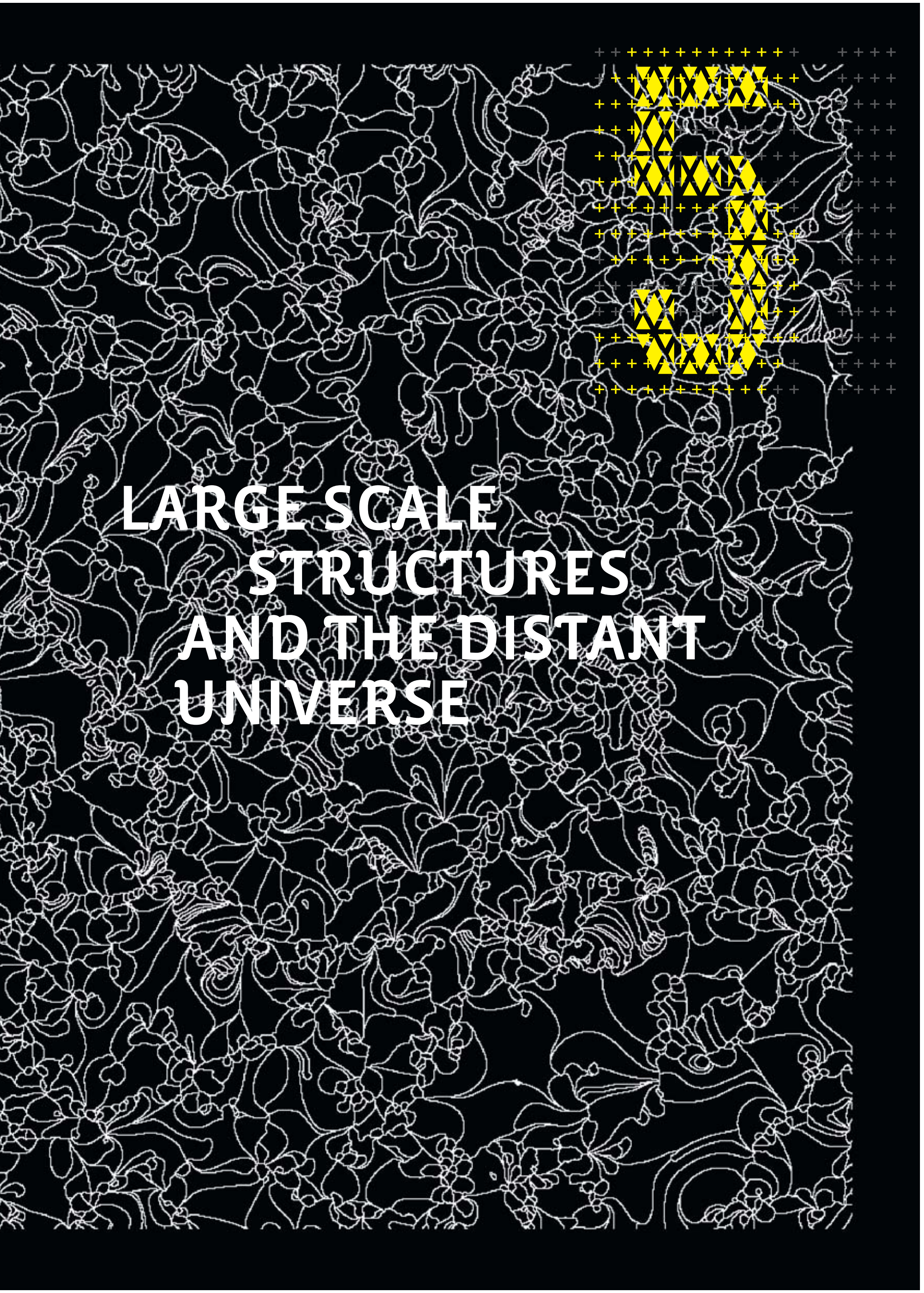
4.5 CONCLUSIONS

Observing gamma-ray bursts and quasars, measuring their properties, and interpreting the data in order to investigate the underlying physical processes will be the major objectives of research of this team in the coming years. The exceptional luminosity of these objects allows their detection up to very high redshifts, and using their spectrum as background light one can measure the properties of the intervening gas at various epochs. These constraints will in turn supply the models developed in the team to construct a realistic global description of the history of baryons in the Universe.

This project benefits from the developments of new instruments in different wavebands, such as HESS at very high energies and soon GLAST. These observatories will provide new constraints on the models of accretion and ejection processes developed in the team. Models of the high energy gamma-ray emission from relativistic jets are also being developed in the group, which will be compared to these data. In the more specific case of gamma-ray bursts, the “standard model” is currently experiencing various difficulties when compared to the recent Swift results. In particular it becomes impossible to model independently the prompt and the afterglow emission. The consistent model of these two phases that has been developed at IAP represents a real asset in this rich observational context, in particular with respect to interpreting data in different energy bands. Recall that Swift will be observing gamma-ray bursts for several years, their high-energy spectrum will be measured by GLAST, and after 2012, the prompt optical and X-ray spectrum will be studied by SVOM. The team is involved in this project not only at the scientific level, but also in

the development of the web site offering a full access to data for the SVOM collaboration and a restricted access for the gamma-ray burst community.

Furthermore, in 2008, XSHOOTER will be installed at the VLT. This instrument is designed for the rapid spectroscopy of gamma-ray burst afterglows, which opens many possibilities. Based on its expertise with quasars, the team will be strongly involved in these future observing programs. The multi-wavelength exploration of the distant Universe will moreover benefit in the coming years from several instruments (HST, IRAM, Spitzer, Herschel, APEX, Planck, CFHTLS, WIRCAM, VISTA), and the physical properties of an increasing number of objects at a wide range of redshifts will thus become available. This will provide new constraints for the model of the cosmic evolution of baryons from the first stars to the present Universe. The study of the cosmological evolution of cosmic rays will also benefit from an observing program aimed at investigating lithium-6 in halo stars at the VLT. The observational horizon will be pushed even farther in the long term thanks to the development of extremely large telescopes. Similarly, the project involving a test of models with new physics using constraints from big-bang nucleosynthesis is already quite successful and will continue in coming years.



LARGE SCALE STRUCTURES AND THE DISTANT UNIVERSE

The research topics of this team "Large scale-structures and the distant Universe" involves studying the distribution of matter in the Universe on the largest scales. Beyond an interest of a purely cartographic nature, it provides information on the nature of the Universe as a whole and raises the prospect of refining predictions of the cosmological model. For this reason research underway concerns both theory and observation: on the one hand, theoretical studies of the detailed properties of large scale structures according to various cosmological models, and on the other major observational programs, in particular Planck and TERAPIX. The group is also involved in state-of-the-art numerical simulations, which are used to simulate complex phenomena such as the formation and evolution of large scale structure and which, through the generation of virtual data, can help determine the best strategy for a given observational program. These numerical simulations are complemented by the development of mathematical methods dedicated to the statistical analysis of cosmological data sets.

5.1 LARGE COSMOLOGICAL SURVEYS

The preparation of large cosmological surveys involves predicting the signatures of different primordial cosmological models on large-scale structures in the Universe, in particular the impact of topological defects or dark energy. This activity is carried partly in collaboration with the team “Theoretical Physics, Gravitation and Cosmology”. In this field, investigations have focused on the signatures of statistically anisotropic universes, for instance with a multi-connected topology (Kunz et al. 2006; Cresswell et al. 2006, Kunz et al. 2007, Bielewicz & Riazuelo in preparation), the signatures of scalar tensor theories of gravity (Schimd et al. 2006), or the study of gravitational lensing effects on the detection of baryonic oscillations (Vallinotto et al. 2007).

A three year project funded by “Agence Nationale de la Recherche” (ANR) aims at producing numerical codes similar to **CMBFAST** and **CAMB** to process Planck microwave background fluctuation data, performing both small numerical simulations and a systematic scan of the relevant parameter sets. These data will provide a snapshot of unprecedented quality of the Universe 300,000 years after the big bang. The primordial fluctuations, which can be measured through tiny temperature or polarisation anisotropies are characterized by their power spectrum, which can notably be used to determine the parameters of the cosmological model. Figure 5.1 presents a comparison between WMAP and Planck efficiency at measuring the E mode polarization spectrum.

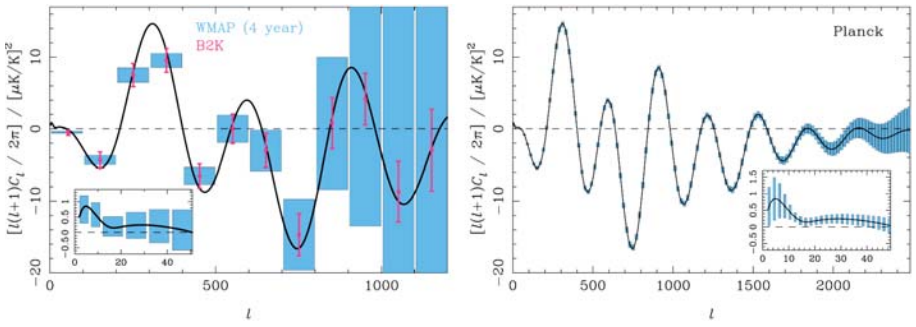


Figure 5.1: Simulation of the Planck data for the E-mode polarization with error bars (right panel) compared to the sensitivity of WMAP (left panel).

The IAP Planck team is responsible for timeline and frequency map data processing for the Planck HFI Planck satellite. Project-oriented activities concerning Planck are summarized in Section 7.2. Another ANR funded project is dedicated to preparing for the scientific exploitation of Planck data. At the

IAP, it supports a post-doctoral fellow whose work is primarily concerned with the detection of non-Gaussian features in the cosmic microwave background maps.

Finally, one member of the team is also involved in the BICEP/Robinson Gravitational Wave Background Telescope (http://bicep.caltech.edu/), which has been observing a small fraction of the sky from the South Pole since February 2006 and whose very high precision measurements should allow for a better determination of parameters related to the inflationary era of the Universe.

Another major observational program underway at the IAP is TERAPIX (“Traitement Elémentaire Réduction Automatique des PIXels”), which is a French national data centre dedicated to astronomical image processing. It was created in 1998 in order to provide astronomers with facilities to process and handle wide field imaging instruments, like MEGACAM (in the visible), or WIRCam (in the near infrared). TERAPIX is also in charge of processing the Canada-France-Hawaii-Telescope Legacy Survey (CFHTLS) and several other surveys. As discussed below, the data reduced by TERAPIX have led to a large number of published articles.

During 2004-2007, most of the work has focused on the cosmic shear analysis of the CFHTLS Deep and Wide data. Cosmic shear is a coherent gravitational deformation field, which corresponds to the gravitational deflections imparted on photons from the distant Universe. It can be detected through the correlation of shape properties between all lensed galaxies and its statistical properties allow measuring the normalisation (σ_8) of the dark matter power spectrum as well as the mass and dark energy density parameters, Ω_m and Ω_Λ, and the equation of state of dark energy (*w*). Results are reported in Tereno et al. (2005), Semboloni et al. (2006), Hoekstra et al. (2006), Schimd et al. (2007) and Benjamin et al. (2007), as well as in the following PhD theses: Semboloni (2006), Tereno (2007) and Fu (2007). Most noteworthy are the constraints obtained on *w* reported in Figure 5.2, which are the second ever published and the first that use the evolution of cosmic shear signal with redshift, or the constraints on quintessence (Schimd et al. 2007).

An investigation of the origin of a small discrepancy between the WMAP3 and the CFHTLS weak lensing analyses is underway (Fu et al. 2007 in preparation). However, by using the CFHTLS photometry from TERAPIX releases together with the spectroscopic redshifts from the VVDS, systematic errors on the redshift distribution of sources have been significantly reduced (Ilbert et al 2006). In parallel, better measurements of the weak lensing signal have been obtained using the STEP simulations to calibrate the shear-ellipticity relations (Heymans et al. 2006, Massey et al. 2007a). The discrepancy between WMAP3 and a joint CFHTLS, Virmos-DESCART, RCS and GaBoDS weak lensing

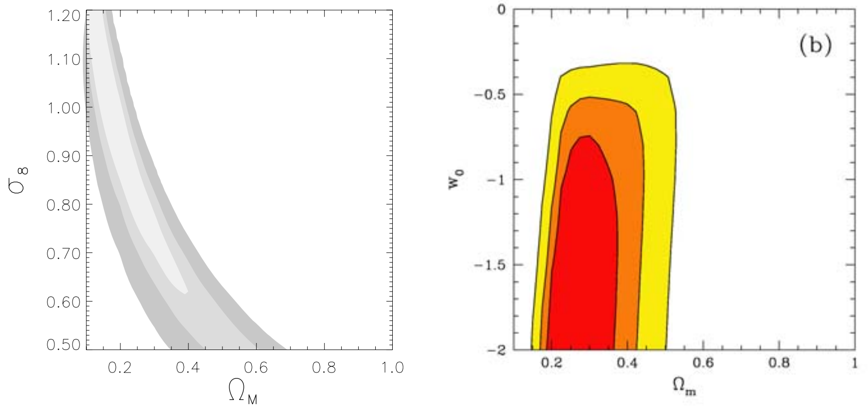


Figure 5.2: Constraints on σ_8-Ω_m and Ω_m-*w* , as derived from cosmic shear studies of early CFHTLS Deep and Wide data. Left: constraints from Benjamin et al (2007), showing no longer tension with WMAP3. Right: Constraints on *w* derived by Semboloni et al. (2006) and Hoekstra et al. (2006).

analysis then becomes negligible (Benjamin et al. 2007, see Figure 5.2). Though promising, the preliminary weak lensing analysis of the COSMOS Treasury Survey data still shows a discrepancy.

The Deep and Wide CFHTLS surveys are progressing well. The CFHTLS Wide is now four times larger and the Deep three times deeper since the second survey release. TERAPIX is also involved in the KIDS/VISTA survey that will cover 3000 deg^2 with the VST and VISTA, starting by 2008. Though shallower than CFHTLS, the survey will be done in 4 visible and 5 near infrared bands. It is led by a European consortium and supported by a European FP6 RTN Network, DUEL. On a longer term, TERAPIX is also involved in the fourth generation of imaging and weak lensing surveys. It is a partner in the DUNE consortium for the ESA Cosmic Vision AO. DUNE is a wide field space-based visible and near-infrared survey. TERAPIX will be involved in data processing, image simulation and weak lensing analysis for this project.

The Strong Lensing Legacy Survey (SL2S) searches for strong gravitational lenses in the CFHTLS Deep and Wide surveys. Analyses are made on the properties of each new lens configuration in order to provide spectroscopic and HST imaging follow-up for each lens. This allows one to determine the mass distribution and the properties of their dark matter halos. Eventually it will compare the results with predictions of numerical simulations of cosmological models. Its primary targets are rings around galaxies and arcs in groups and clusters of galaxies. The expected number of strong lenses in the CFHTLS will be large enough to derive robust statistical information on the mass profile and the triaxiality of halos. The SL2S project has been granted 130 HST orbits in snapshot mode for the CFHTLS lens follow-up. During the period

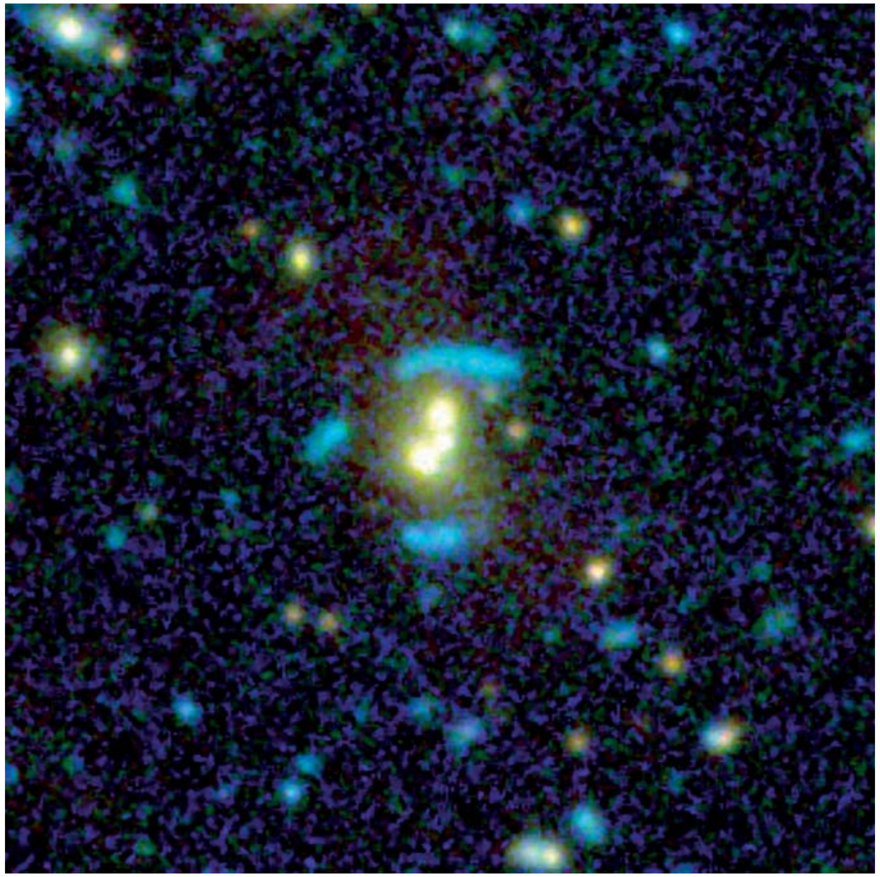


Figure 5.3: A composite image of a spectacular lens system found in the CFHTLS by the SL2S collaboration.

2006-2007, SL2S focused on the development of unbiased automated detection algorithms of rings and arcs. In particular, Alard (2007) developed new detection tools based on the local elongation of objects. This technique applied to the TERAPIX CFHTLS release T0002 has discovered several tens of very elongated objects. In parallel, another automated detection technique based on a panchromatic analysis of the same data set has been carried out. After multiple selections from these two samples, SL2S has derived a first catalogue of reliable rings and arcs candidates (Cabanac et al 2006). An HST imaging and a VLT spectroscopic follow-up of these lens candidates are underway.

The SL2S consortium is now modelling all lens candidates in order to derive the statistical distribution of lens configurations in the early SL2S catalogue. An immediate outcome of this study, the fraction of perturbed lens configurations, is of primary importance for cosmological models of halo formation.

In order to compare the observations with theoretical models, the SL2S consortium also uses the numerical simulations produced by the Horizon consortium, in which various members of the group play an active role.

The analyses of galaxy clustering in the CFHTLS and the COSMOS surveys have also been carried out by TERAPIX scientists. Concerning COSMOS, McCracken et al (2007, COSMOS special issue) measured the two-point angular correlation function of galaxies and compared this to predictions from the Millenium simulation (Springel et al. 2005). They found an excellent agreement with observations at bright magnitudes, even extending to details such as the change of slope predicted by the simulations. A similar study is under way on the four CFHTLS Deep fields in order to reduce the large cosmic variance of the COSMOS survey.

Using the TERAPIX CFHTLS T0003 release, Ilbert et al. (2006) constructed a unique catalogue of 550,000 galaxies with photometric redshifts to I_{AB}~24 calibrated using 3000 spectra from the VVDS surveys in the CFHTLS Deep fields. McCracken et al. (2007) used this catalogue to derive the evolution of galaxy clustering as function of redshift, of galaxy morphology and of intrinsic luminosity. They showed that the faintest elliptical galaxies are more strongly clustered at intermediate redshift, a result which is expected if most faint elliptical galaxies are hosted by the same dark matter halos as massive elliptical galaxies.

In order to trace the evolution history of massive galaxies and probe the relation between baryons and dark matter halos, TERAPIX is involved in the WIRDS and the COSMOS-NIR surveys (a deep near-infrared follow-up of CFHTLS Deep fields), and, soon, in the ULTRA-VISTA survey (starting next year). The first WIRDS data have been taken at CFHT and TERAPIX has produced first deep stacks and optical and near-infrared catalogues. The WIRDS consortium have used these catalogues to compute photometric redshifts, to derive the total stellar mass in galaxies (Ilbert et al. 2007) and the two point galaxy correlation function.

The visible and near infrared catalogues produced by TERAPIX are also used to select the "bright" and "deep" zCOSMOS spectroscopic samples for follow-up VLT observations. The project was granted 600 hrs of observing time on the VLT (Lilly et al. 2007). Pilot spectroscopic observations have demonstrated that the colour selection shown on Figure 5.5 is a reliable method to select z>1.5 galaxies (Figure 5.4).

While cosmic shear surveys can probe the distribution of dark matter using gravity, the EDELWEISS experiment (in which several members of the team participate) aims at the direct detection of non-baryonic Galactic dark matter particles using cryogenic detectors. These germanium bolometers are cooled

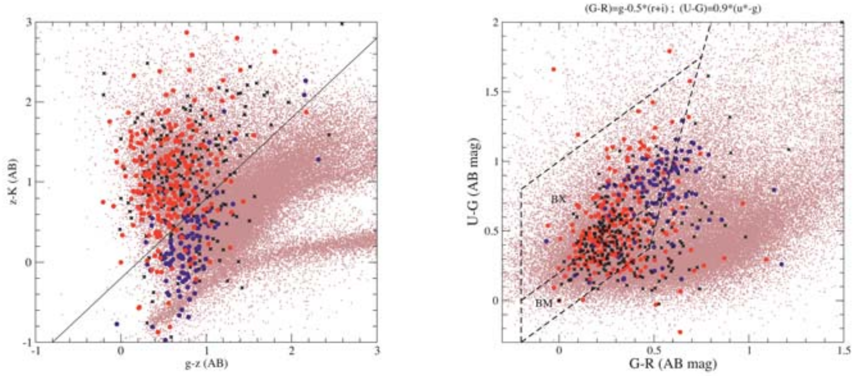


Figure 5.4: Galaxy colour-colour diagram constructed from visible and near-infrared CFHTLS and COSMOS photometric catalogues produced at TERAPIX. These diagrams are used to select high redshift galaxies from the whole sample of objects in the field (brown dots). The blue dots show z<1.5 galaxies with confirmed spectroscopic redshift. The red dots are those with z>1.5 . This spectroscopic follow-up is carried out by the zCOSMOS consortium.

down to about 20 mK and can simultaneously measure heat and ionization signals in events allowing one to discriminate between nuclear recoils (dark matter and neutron events) and electron recoils induced by the radioactive gamma and beta background. The first step of the experiment, EDELWEISS-I (a one kilogram detector mass comprising three modules of 320g) ended in March 2004 and has obtained between 2002 and 2004 the world's best limit to WIMP interactions (limit nucleon cross-section of about 10^{-6} picobarn for the spin independent interaction). EDELWEISS-II, the second phase of the experiment, is now running in the Laboratoire Souterrain de Modane with 28 detectors (with an active mass of Ge of about 9 kg, 40 detectors in the final version) with a sensitivity goal of 10^{-8} picobarn.

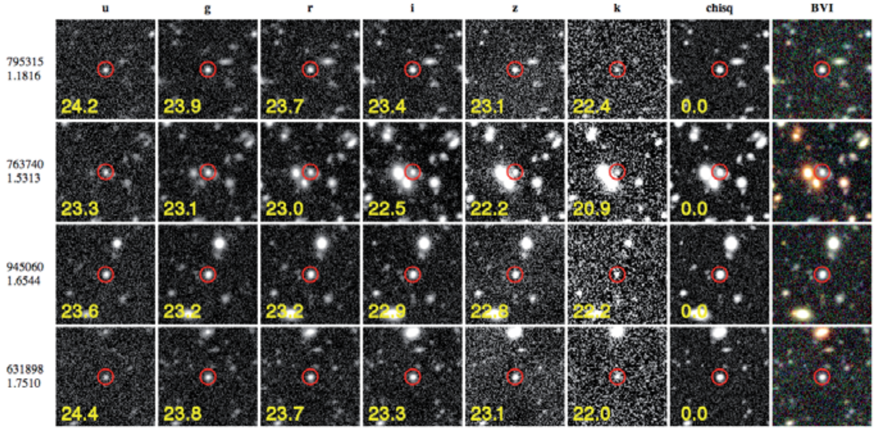


Figure 5.5: A sample of high redshift galaxies of the TERAPIX CFHTLS MEGACAM+WIRCam catalogue with spectroscopic redshifts and selected according to colour criteria (Figure 5.4). From left to right : ID number, redshift, MEGACAM/WIRCam images and magnitudes in u, g, r, i, z, K, chi2, and a composite colour image.

5.2 TOOLS FOR THE ANALYSIS OF COSMOLOGICAL DATA

Another research topic, in which scientists of the group invest a significant fraction of their time, involves improving data processing methods for large surveys. It often leads to the distribution of new more efficient tools to the scientific community.

For instance, **Healpix** is a hierarchical equi-surface and iso-latitude pixelisation of the sphere, presented in 1997 to analyse cosmic microwave background like data. The mathematical properties of this pixelisation yields a significant gain when computing the statistical properties of maps, while reducing numerical artefacts (Gorski et al., 2005). The code library is now available on sourceforge (http://sourceforge.net/projects/healpix/) in various languages; **Healpix** has become the de-facto the standard for cosmological microwave background analysis (Planck, WMAP, Boomerang amongst others) and is also used in other astrophysical domains (extra-solar planets, cosmic rays, weak lensing). The development and maintenance of the F90 and IDL versions of this library takes place at IAP.

Another project, EFIGI ("Extraction de Formes Idéalisées des Galaxies en Imagerie") addresses the question of the statistical analysis of galaxy shapes from an algorithmic and a practical measurement point of view. It aims at providing morphometric tools to extract detailed and reliable information on galaxy morphology in large imaging surveys. To explore novel techniques that go much further than simple statistics on basic shape parameters, EFIGI gather together experts in signal processing, computer programming and in astronomy. EFIGI follows the "open source" philosophy and it will publicly release all its software packages, all its catalogues of galaxies and provide a public web service. During 2006-2007, EFIGI developed a new tool to clean images using mathematical morphology, to compute a PSF model automatically and to derive shape of galaxies using PCA, ICA and shapelets. It can model object profiles using a non-linear fitting, can detect textures and it also comprises several automated machine learning tools. A set of fundamental galaxy attributes was created by the EFIGI team using a new complex interface. EFIGI eventually created a unique panchromatic database composed of 4000 galaxies with well defined set of attributes to each. The completion of this fundamental database is expected by 2007.

Software tools are also developed in the framework of TERAPIX. These tools are optimised for intensive processing of very large images. They consist of a series of programs for pixel processing, calibration, astronomical catalogue production, data handling and include also quality assessment tools and meta-data production. The codes are released under the free GNU GPL licenses to the astronomical community and are provided as documented, easily installable, portable, stand alone packages. During 2004-2007, TERAPIX released five new software products, and in total a dozen packages are now publicly available. The most recent are: **libVOTable** (access to VO format tables), **QualityFITS** (an image quality assessment overview tool), **SCAMP** (fully automated astrometric and photometric calibration of astronomical images), **PSFEx** (automated PSF measurement) and **MissFITS** (an image handling tool). In addition, most TERAPIX software has been updated in order to handle XML VOTable format as well as XSLT style sheets.

A further project concerns the implementation of regularised inverse methods to recover the star formation history and/or the kinematic properties of external galaxies from high resolution spectra (Ocvirk et al. 2006a,b). The non-parametric inversion allowed in particular to predict corresponding biases, and to identify the relevant regions within the spectra.

Similarly, the implementation of the automated image deconvolution tool **MAAD** (Multiscale Algorithm for Automatic Deblurring) has led to an online interactive deconvolution. Two specialized versions of **MAAD** have been developed, one involving a variable PSF in the field, the other involving multi-spectral deconvolution. This latter implementation has notably led to an analysis on the component separation of the physical fields of the Planck bands in the non stationary regime with polarisation.

This inversion technique was also applied to the tomography of the intergalactic medium from quasar spectra (Caucci et al. 2007) and to the non-linear multi scale recovery of convergence maps from all-sky (possibly partially masked) shear measurements (Pichon et al., in preparation). More recently, the group has investigated the possibility of tomographically reconstructing the magnetic field of the interstellar medium from spectral measurements of polarisation maps. This is a large non-linear inverse problem which allows one to probe the statistical properties of the field helicity (Pichon & Prunet in preparation).

Another ANR funded project, ECOSTAT ("Exploration du modèle COSmologique par fusion STATistique de grands relevés hétérogènes"), unites astrophysicists and mathematicians to develop advanced statistical methods to explore parameter sets of the cosmological model by using the largest possible amount of observations, in particular microwave background anisotropy data, deep galaxy surveys (VVDS, COSMOS) and weak lensing surveys (CFHTLS). Among the tools produced, one may mention a code for rapid computation of the likelihood of weak lensing effects. Several methods of statistical analysis (MCMC, HMC and PMC) have also been tested. Finally, the group is currently working on the likelihood computation for the WMAP and Planck data as well as the development of mathematical criteria to distinguish between favoured sets of parameters (using in particular Bayesian analysis).

5.3 NUMERICAL METHOD AND SIMULATIONS

The numerical simulations carried out in the group are generally devoted to the production of virtual data and development of analysis codes for preparing and interpreting the results of large scale surveys (see also section 7.4).

Concerning the tools developed for characterizing the properties of large scale structures, the "2D skeleton" has been investigated both numerically and theoretically. This skeleton corresponds to the crest line of the density field (see Figure 5.6) and provides a powerful tool to analyse the topology and the geometry of large scale structures (Novikov et al. 2006). The group has studied in particular the dynamical evolution of filaments and their relationship with the theory of random fields in order to make a non Gaussianity test (Colombi et al. in preparation). The "ND skeleton" corresponds to a generalisation of the two-dimensional case to three and more dimensions. A numerical investigation of the inner structure of filaments has been carried out, and a constraint on the content of dark matter and on the geometry of the universe could be thus derived using the Alcock-Paczynski test (Sousbie, Pichon & Colombi 2007; Pichon et al. in preparation).

The Vlasov-collisionless Bolzmann equation offers a powerful means to study the dynamics of dark matter. New algorithms which solve the non-collisional fluid equation directly in phase space have been implemented to avoid N-body relaxation and ensure symplecticity, in particular the cloud method (Alard & Colombi 2005), the waterbag method (Colombi & Touma 2007) and the local metric. A N-simplex Poisson solver was also developed in order to better model the dark matter caustics and to test the validity of the results from N-body simulations. It has been demonstrated (Mohayaee & Shandarin 2006) that caustics can be observed through strong gravitational lensing (Gavazzi et al. 2006) or gamma rays (Mohayaee et al. 2007). In the near future, these caustics could also be detected by electron/positron annihilation in the halo of the Galaxy. These caustic models will also be extended to non self-similar regimes without spherical symmetry.

Dark matter halos have been investigated from different perspectives. In particular, the diffusion process of orbits induced by stochastic perturbation of their environment has been examined in the context of an open system (Pichon & Aubert 2006). A detailed analysis of the statistical properties of dark matter accretion onto dark matter halos was carried out in a subsequent

Figure 5.6: The "skeleton" of large scale structure. Top: Temporal evolution of the skeleton of a LCDM simulation. Bottom: the distribution of clusters and filaments at z=0.

study (Aubert & Pichon 2007). In a related work, the anisotropic nature of accretion at small scales was investigated through the computation of the one- and two- points statistics of accretion using vector fluxes at the virial surface, and using the spatial distribution of satellites and detected substructures. The accretion occurs preferentially in the plane perpendicular

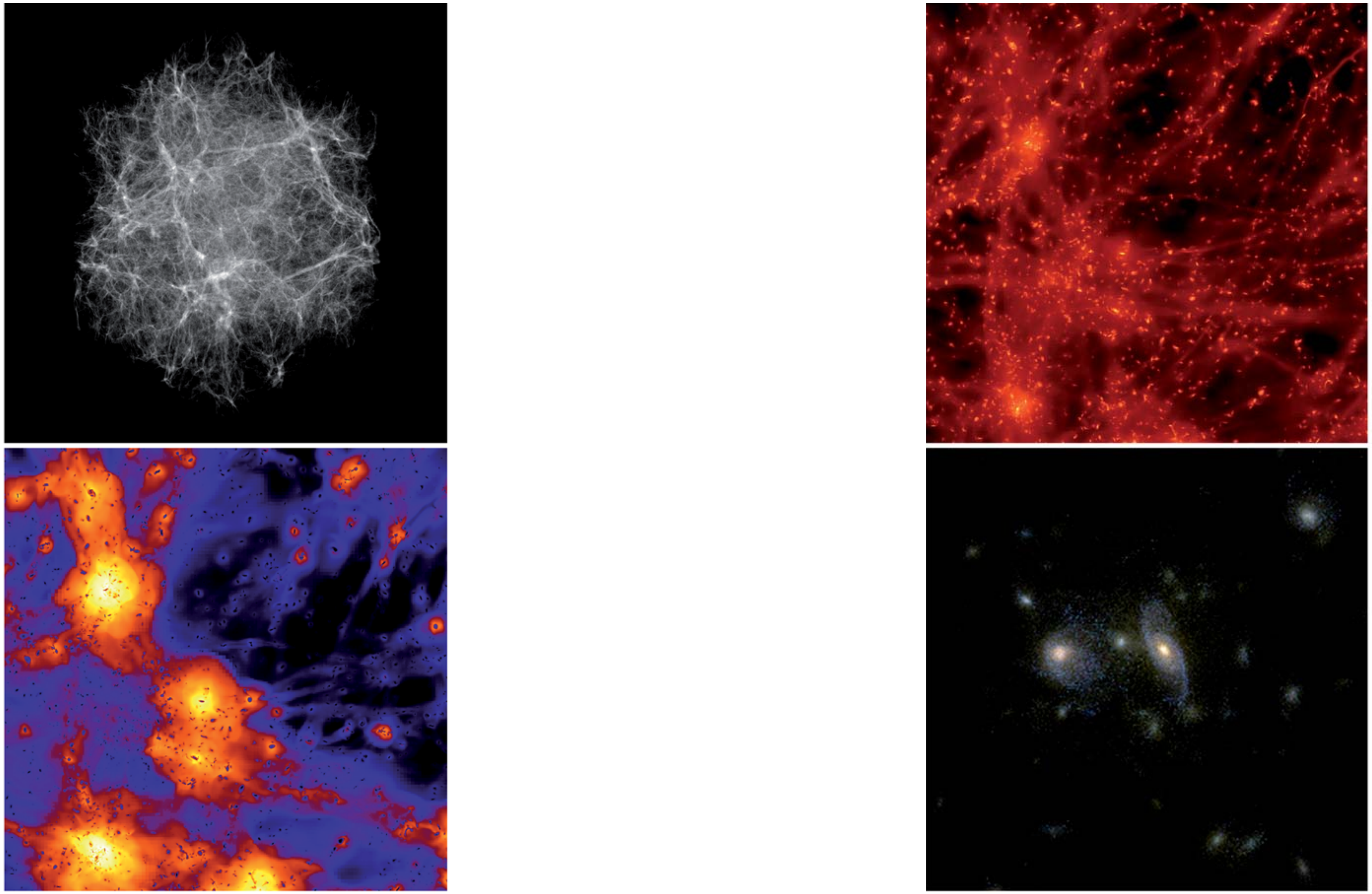


Figure 5.7: Dark matter in the Mare Nostrum simulation at z=2.5 on largest scales (top left); on some intermediate scale the gas density (top right), and the gas temperature (bottom left, same region) and on a smaller scale, galaxies in “true” colours in a cluster (bottom right).

to the direction corresponding to the spin of the halo. In the halo reference frame, the substructures have a proper spin orthogonal to their velocity, in agreement with the picture that the flow takes place along the filaments, a result confirmed using the skeleton (Aubert, Pichon & Colombi 2004; Sousbie et al. 2007).

Moreover, a simple and now commonly used analytical fit was adjusted to radial and anisotropy profiles of dark matter halos (Mamon & Łokas 2005). The radial velocity measurements show that the velocities are quasi-Gaussian within the virial radius, whereas their distribution becomes very peaked beyond the virial radius (Wojtak et al. 2005). A Jeans analysis was also carried out over 10 LCDM halos observed along three axes (Sanchis et al. 2004). This work has shown that the dispersion-kurtosis method yields accurate

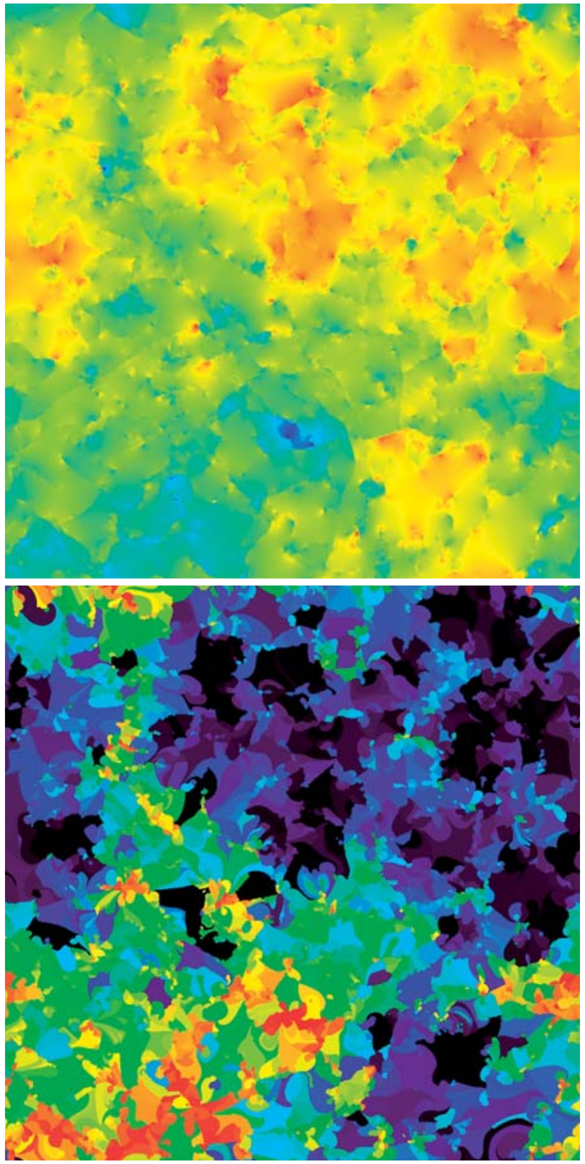
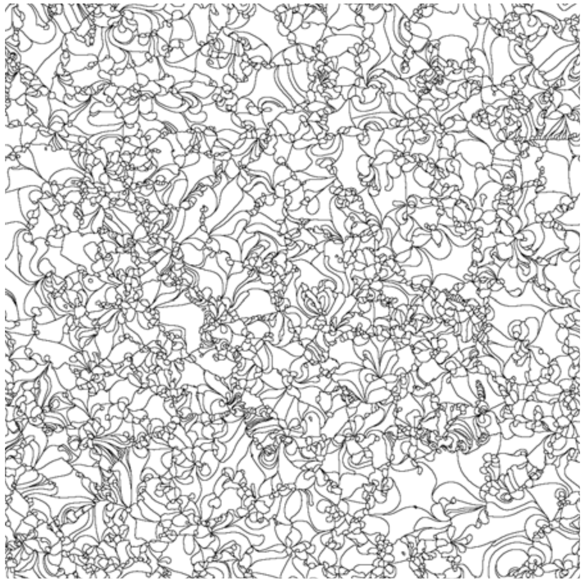


Figure 5.8: Simulation of the effect of strings in the CMB. From top to bottom and left to right, the field itself, its partition according to peak patches and the corresponding skeleton.

estimation of masses, velocity anisotropies and concentrations within these halos, which justifies its extension to observed galaxy clusters.

The "MAK" method can be used to reconstruct the initial conditions of large-scale structures in the local Universe. Its implementation in simulations on



scales larger than 5Mpc (Mohayaee et al. 2006) has allowed improvements in the analysis of galaxy catalogs and also the measurement of the mass of local clusters less than 10 Mpc distant (Mohayaee & Tully 2005). This method is currently being tested and will be used to build the initial conditions of the Universe for simulations in the context of the Horizon project.

Finally, a statistical gravity velocity relation has been derived in order to constrain the dark matter content directly in redshift space (Colombi et al. 2007). A dark matter sub-structure finder has also been developed and the identification of sub-structures and caustics using and the angle-action of the underlying system are underway (PhD of M. Maciejewski).

Concerning the realization of numerical simulations in itself, the group has played a significant part in the HORIZON project (http://www.projet-horizon.fr). The IAP contribution involved making and processing the full physical hydrodynamic simulation "Mare Nostrum" (1024^3 particles in a $50h^{-1}$ Mpc box with four levels of refinement) and the HORIZON 4π simulation (4096^3 particles in a 2Gpc box with six levels of refinement), which to date are both the largest simulations of their kind, see Figure 5.7. More specifically the group has invested effort in initial condition generation; in post-analysis algorithms, e.g. **adaptahop** for substructure detection (Aubert et al. 2004) and **powmes** (for the construction of the multi-scale power spectrum); and finally in the production of catalogues and synthetic data in VOtable format corresponding to the morphological and spectroscopic properties of virtual galaxies. This work has also led to the analysis of various physical fields

(Ocvirk, Pichon, Teyssier in preparation) and the accretion process at the virial radius; the luminosity function and its cosmic evolution (Devriendt et al. in preparation); or the generation of synthetic quasar spectra to probe the clustering of metals in the intergalactic medium (as in Scannapieco et al 2004).

Finally, methods to simulate the dynamics of topological defects networks were updated. From the knowledge of these simulated networks, it has become possible to compute numerically the impact of these strings on the cosmic microwave background (Figure 5.8) and the Kaiser-Stebbins effect. These simulations are used to gauge the possible influence of topological defects on the upcoming Planck data, and to calibrate tests of non-Gaussianity on the microwave background.

5.3 PROSPECTS

In the near future, the team will structure its research around the scientific interpretation of data from the distant Universe, the analysis and post processing of these data, and their production either through observational programs or via numerical simulations for their virtual counterparts.

In particular, team members are strongly involved in the Planck HFI instrument, and part of the data reduction is to take place at the IAP. Since the skills to interpret these data can be found within the team (and more generally speaking, within the IAP), one can look forward to the arrival of the first data and the exciting theoretical investigations that it will initiate.

Weak lensing analysis is a very successful cosmological tool, and IAP can be considered as one of the world leaders in this field. The significant investment of the team members in developing techniques of data reduction and analysis over the last few years will serve well in the near future, for instance for the upcoming space-based large surveys (e.g. DUNE/SNAP).

The success of HORIZON and the strong involvement of the team in this project warrant the continuation of this numerical effort. The knowledge acquired has clearly demonstrated that the availability of synthetic data led to greater flexibility in developing innovative techniques of data analysis and scientific interpretation. In the meantime, the production of larger and larger amounts of simulation data will require significant new resources in order to avoid restricting the team to a purely production role and to confirm the leading position worldwide of IAP in this discipline.

6

THEORETICAL PHYSICS: GRAVITATION AND COSMOLOGY

The GReCO (GRavitation & COsmology) team at the IAP, which comprises nine permanent theoretical physicists, moved to the IAP in 2000 first as an independent research group in the department of theoretical physics of the CNRS. It has since merged with the IAP. The research activities of these physicists are concentrated on the following topics: (1) the characterization of gravitational wave signals produced in cataclysmic events such as inspiralling compact binaries; (2) the study of extensions to the theory of general relativity (scalar-tensor theories, string theories) and their cosmological or astrophysical consequences; (3) aspects of astroparticle physics, with particular emphasis on the origin of ultra-high energy cosmic rays and the nature of dark matter; (4) early Universe cosmology, and most notably the nature of dark energy, models of cosmological inflation and the physics of cosmological perturbations. The association of GReCO with the IAP has been mostly motivated by the numerous points of contact between these themes of research and the ambitious observational programs conducted in other research teams. As the following will hopefully demonstrate, this strategy has proved successful.

6.1 GENERAL RELATIVITY AND POST-NEWTONIAN EXPANSIONS

The most promising sources of gravitational waves (which could be detected by the LIGO and VIRGO interferometers) are inspiralling compact binary systems shortly before their coalescence. Since thousands of such orbits will be observable by these detectors, one must predict as accurately as possible the motion of the two bodies. This requires calculations up to the 3 1/2th post-Newtonian order (written "3.5PN"), i.e. including general relativistic corrections of order $1/c^7$ beyond the Newtonian description. When the bodies are described as point particles, one has to regularize the calculations in order to obtain the equations of motion. Previous studies conducted in this research group had demonstrated that Hadamard regularization was sufficient up to order 2.5PN ($1/c^5$), and terms of order 3.5PN have recently been obtained using this technique (Nissanke & Blanchet 2006). However, order 3PN calculations reveal singularities of a nature that cannot be treated adequately in this way. In particular, one of the coefficients of the equations of motion remained undetermined to this order, in addition to three other coefficients in the resulting gravitational wave field. Using dimensional regularization, Blanchet et al. (2004, 2005) have been able to calculate these missing coefficients. In detail, the remaining logarithmic divergences emerge in this procedure as poles $\propto 1/\varepsilon$ (where $\varepsilon = d-3$, d denoting the spatial dimension), and it has been shown that such poles can be removed by a renormalization of the particles world-lines. One thus achieves an unambiguous determination of the equations of motion and the gravitational wave field up to order 3PN. The values of three coefficients have been confirmed using other methods. On a more formal level, a recent study by Blanchet, Faye & Nissanke (2005) has simplified the formalism that allows accounting for the effects of radiation backreaction on the gravitational field of an isolated system in the framework of the post-Newtonian expansion.

The studies reported in Blanchet, Damour & Esposito-Farèse (2004), Blanchet & Iyer (2005), Blanchet, Damour & Iyer (2005) and Blanchet et al. (2005) have thus solved a crucial part of the problem of the construction of templates of gravitational wave signals emitted by inspiralling compact binaries. One must recall that the use of these templates is mandatory to detect such signals in LIGO and VIRGO. Figure 6.1 shows these templates calculated using two different methods: in dashed red line, using the aforementioned post-Newtonian expansions, and in solid blue line, using full-blown general relativistic numerical simulations. Numerical relativity can probe the plunge phase but it must start shortly before the coalescence, unlike post-Newtonian expansions. The agreement between the numerical calculation and the post-Newtonian expansion in the intermediate phase between the inspiralling and the merger phases is remarkable.

In the case of black hole binary systems, the effects of the intrinsic spins of the two black holes must be taken into account in the signal analysis conducted by VIRGO/LIGO/LISA. Simulations of such analyses have moreover shown that the effects of spins up to order 2.5PN had to be included in the signal templates, their contribution being potentially more important than the spin-spin interaction at order 2PN. This relativistic correction of order 2.5PN has been calculated, first for the equations of motion and the conserved quantities (Faye, Blanchet & Buonanno 2006), then for the gravitational wave field and the orbital phase of the binary system (Blanchet, Buonanno & Faye 2006).

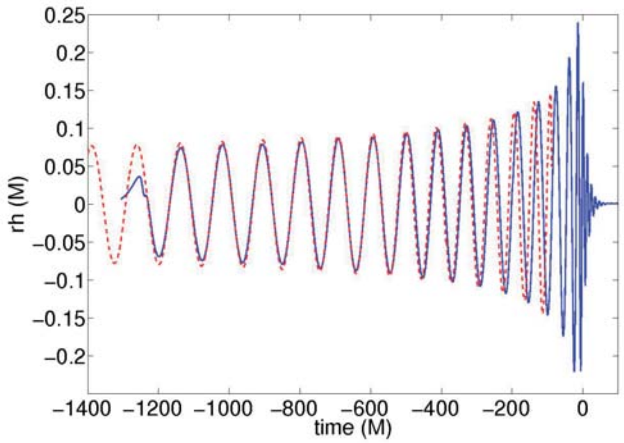


Figure 6.1: Template of the gravitational wave signal as a function of time, emitted by inspiralling compact binaries. The dashed red line indicates the template calculated through post-Newtonian expansions up to order 3.5PN, while the solid blue line shows the results of full-blown general relativistic numerical simulations. Time 0 corresponds to coalescence.

The study of Blanchet, Qusailah & Will (2005) has also calculated up to order 2PN the speed acquired by a binary black hole system as a consequence of recoil following gravitational wave emission. This effect is dominated by the plunge phase during which that coalescence takes place, leading to a recoil speed of order 250 km/s. Finally, several other aspects of gravitational wave physics have also been considered, such as the construction of templates for highly spinning binaries (Buonanno et al. 2005, Hartl & Buonanno 2005, Buonanno et al. 2004, Pan et al. 2004), the design of advanced ground-based gravitational detectors (Buonanno & Chen 2004) or the possible connection between gravitational waves and high energy photon or neutrino signals (Buonanno et al. 2005).

6.2 THEORIES OF GRAVITATION

Among the possible extensions to general relativity, scalar-tensor theories play a particular role since scalar partners to the graviton are generic predictions of unified and multi-dimensional theories, and because they may also play a crucial role in cosmology, in particular during eras of accelerated expansion. Various experimental constraints on these theories which had previously been derived by members of the GReCO group have been revisited recently following the publication of new precise solar system data (notably from the Cassini spacecraft) and the discovery of new highly relativistic binary pulsars (PSRs J1141–6545 and J0737–3039). In order to analyze the consequences of these new data, it has been necessary to recode the numerical calculations of the internal structure of neutron stars in scalar-tensor theories with an increased accuracy. Today's constraints are shown in Figure 6.2, for a generic class of scalar-tensor theories characterized by two coupling constants (Esposito-Farèse 2004; Esposito-Farèse 2005a, b; Damour & Esposito-Farèse 2007). Similar constraints on scalar-tensor theories have been obtained by studying their influence on primordial nucleosynthesis (Coc et al. 2006), see also Figure 6.2.

Finally Bruneton (2006) and Bruneton & Esposito-Farèse (2007) have shown that the pure scalar theory of Nordström, which is a limiting case of scalar-tensor theories, offers a well-suited framework in which to compare the behavior of post-Newtonian expansions with non-perturbative results.

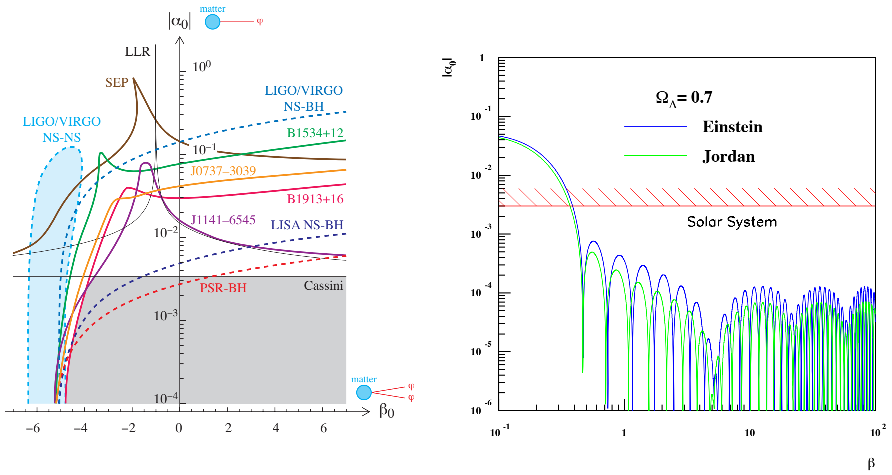


Figure 6.2: Experimental constraints on the two dimensional parameter space of scalar-tensor theories of gravitation. Standard general relativity corresponds to $\alpha_0 = \beta_0 = 0$. In the left panel, the allowed region is indicated in gray; the various labels indicate which data have been used. In the right panel, the constraints have been obtained by a study of the influence of these theories on primordial nucleosynthesis; the allowed region is located below the curves.

The GReCO has also actively pursued studies on the theoretical foundations of Modified Newtonian Dynamics (MOND), which has been introduced by Milgrom in 1983 as an alternative to dark matter. The general idea is to attribute the discrepancy between dynamical and luminous mass measurements of clusters of galaxies to a fundamental modification of the law of gravitation in the regime of small acceleration $a < a_0$, where $a_0 \approx 10^{-10}$ m s^{-2} and is a constant derived from observational data. One of these studies has led to a critical and detailed discussion of the various fundamental theories proposed to reproduce the MOND phenomenology (Bruneton & Esposito-Farèse 2007). In particular, it is shown that most of these theories are not consistent as field theories, either because they cannot result from a variational principle, or because their Hamiltonian is not bounded from below. This study has also brought to light new problems, such as the fine-tuning of certain functions necessary to remain compatible with solar system or binary pulsar constraints. Nevertheless, several no-go theorems of the literature rest on hypotheses that are not strictly necessary, hence the space of possible theories is a priori larger than expected. As a by-product of this study, a consistent field theory is demonstrated to reproduce the Pioneer anomaly without violating any other experimental test of general relativity.

Other studies by Blanchet (2007a, b) have shown how the MOND phenomenology could be understood not as a violation of the law of gravitation, but as the consequence of an effect of gravitational polarization in a medium made of gravitational dipoles. These dipoles would align themselves in the gravitational field produced by ordinary matter thereby enhancing the gravity of ordinary matter. In the models proposed in Blanchet (2007a), this dipole dark matter is "exotic", in the sense that it invokes negative gravitational masses, which leads to a violation of the equivalence principle. However, the model proposed in Blanchet (2007b) is fully relativistic, and in agreement with the equivalence principle.

In the same spirit of exploring theories beyond general relativity, other studies have addressed the problem of deconstruction of gravitational theories and models of multigravity (Deffayet & Mourad 2004a,b), the cosmological perturbations in brane universes (Deffayet 2005a), the problem of the van Dam-Veltman-Zakharov discontinuity in the brane induced gravity scenario (Deffayet 2005b), as well as the problem of the strong self-coupling in massive gravitation theories and the brane induced gravity scenario (Deffayet & Rombouts 2005).

In string theory, studies of the group have focused on its application to early Universe physics, both from a fundamental and a phenomenological point of view. One aspect of string cosmology is, for instance, related to the dynamics of branes in brane inflation models. In this context, the study of Israël (2007) has shown that the unstable mode that is responsible for brane/anti-brane annihilation can be interpreted geometrically when the curvature of space-time is sufficiently large. Another important aspect of the phenomenology of string theory is its relation to supersymmetry breaking. Various tools have been developed in order to build non-supersymmetric yet perturbatively stable string theories, a construction which proves to be notoriously difficult (Israël & Niarchos 2007).

6.3 ASTROPARTICLE PHYSICS

The origin of ultra-high energy cosmic rays, whose energy can reach the "astronomical" value of 10^{20} eV, remains unknown. At these extreme energies their flux is very low, around one particle per square kilometer per century above 10^{20} eV and only a handful of such events have been observed in large experiments. From a theoretical perspective, it is also notoriously difficult to understand which source (and by what means) could accelerate these particles to such extreme energies. The group has tackled this problem from different angles. In particular, one member of the group (now at SUBATECH) has been involved in the Pierre Auger Observatory, which will increase greatly the amount of available data thanks to its large aperture (see in particular Revenu 2005). Most studies of the group have nevertheless remained theoretical, focusing on the acceleration mechanisms in astrophysical objects and the propagation of these particles in extragalactic magnetic fields.

The study of Fermi acceleration around a shock wave has been the subject of several studies. In the relativistic regime, it has been shown that successful acceleration could only be achieved if the magnetic field has been amplified on small spatial scales upstream of the shock wave (Lemoine, Pelletier & Revenu 2006). The magnetohydrodynamic instability provoked by the streaming of a net cosmic ray charge upstream of the shock wave is an interesting candidate in this respect. Indeed, it has been shown that this instability could strongly amplify the magnetic field in the non-relativistic shock waves typical of supernovae remnants (Pelletier, Lemoine & Marcowith 2006; Marcowith, Lemoine & Pelletier 2006) and its generalization to the relativistic regime is underway.

Extragalactic magnetic fields can strongly influence the trajectories of ultra-high energy cosmic rays and consequently the source image observed by detectors. In order to characterize these effects, members of the GReCO group have developed Monte Carlo simulations of particle propagation from source to detector for various models of the intergalactic magnetic field. Some of these studies, using extensive numerical simulations of large scale structure formation, have in particular argued that even particles with energies as high as 10^{20} eV should suffer substantial angular deflection (Sigl, Miniati & Ensslin 2004, Sigl 2004, Armengaud, Sigl & Miniati 2005, Sigl & Armengaud 2005, Armengaud, Sigl & Miniati 2006). Other studies have shown that the extragalactic magnetic field could explain the shape of the all-particle energy spectrum in the region of the "second knee" at 10^{18} eV (Lemoine 2005, Kotera & Lemoine 2007). In this scenario, the role of the extragalactic magnetic field is to prevent particles of energies smaller than 10^{17} eV from reaching the detector since the propagation time from the closest source becomes longer than the age of the Universe. The latter study has used numerical simulations of large-scale structure formation performed by the "Numerical Simulation" group at IAP.

Finally, as mentioned above, the group has also been involved in research on the nature of dark matter and the prospects for its direct or indirect detection. For instance, the comparison between the event rates in different dark matter direct detection targets was shown to be a powerful tool for the identification of the nature of these particles (Bertone, Cerdeno & Collar Odom 2007), whilst the study of their effects on astrophysical objects was found to provide interesting constraints on the mass and coupling of dark matter particles (Bertone & Fairbairn 2007). It has also been argued that a gravitino with a mass of order 1MeV could be a natural candidate for dark matter in the framework of a gauge mediated supersymmetry breaking scenarios of particle physics with SO(10) grand unification (Lemoine, Moultaka & Jedamzik 2007; Jedamzik, Lemoine & Moultaka 2006a). In such scenarios the prospects for detection are non-existent since the cross-sections are too small by many orders of magnitude.

COSMOLOGY AND FUNDAMENTAL PHYSICS 6.4

The ever-increasing wealth of precision data in cosmology (some of which originates from other teams at the IAP) has led to a refined vision of the standard cosmological model and its parameters. It also allows conducting ever-more precise tests of the underlying fundamental physics. This line of research has been actively pursued at GReCO in most areas of modern theoretical cosmology, either concerning the nature of dark energy, the theory of inflation, cosmological perturbations and their signatures, or on higher-dimensional brane models of the Universe.

For instance, the acceleration of the expansion of the Universe now appears to be a well-established fact. Although this accelerating phase could be caused by a cosmological constant, the required magnitude of such a

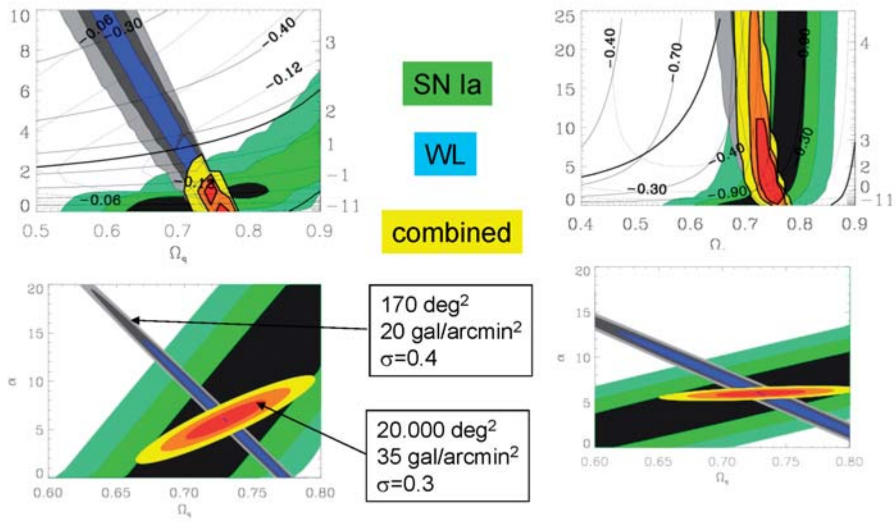


Figure 6.3: Top: constraints on the parameters of two quintessence potentials (left: power-law, right: SUGRA) obtained through the joint analysis of WMAP3, CFHTS and SNIa data. Bottom: expected constraints for SNIa (in green) and weak lensing (in blue) for two suveys: CFHTLS and DUNE/SNAP.

constant leads to a notorious problem of fine-tuning (also regarded as the coincidence problem). Quintessence models, in which the accelerated expansion is due to a dynamical scalar field, may solve this problem since they generically behave as attractors towards the current value of vacuum energy for a large class of initial conditions. However, one must understand the nature of this quintessence field and incorporate it into well-motivated scenarios of particle physics. Steps in this direction have been taken in Brax & Martin (2006), Brax & Martin (2007), Martin & Musso (2005). In these works the consequences on the variation of the fundamental constants of the implementation of this scalar field in supersymmetric theories have been discussed. As demonstrated in Schimd et al. (2007), the scalar field potential may be constrained by combining type Ia supernovae data with microwave background anisotropy data and weak lensing data from the CFHTLS as discussed in Chapter 5. These constraints are summarized in Figure 6.3. This work in fact provides a clear example of the benefit of joint collaborations between the GReCO and observational projects at the IAP. Baryon acoustic oscillations are another promising technique to investigate of the nature of dark energy (Vallinotto et al. 2007).

It could also be that cosmic acceleration indicates a departure from general relativity on cosmological scales. Several studies have therefore investigated tests of general relativity and of more general theories of gravitation, such as the scalar-tensor theories discussed above (see for instance Uzan 2007).

One tool to discriminate between these possibilities is provided by angular distance-luminosity relation (Uzan, Aghanim & Mellier 2004). Tests of the constancy of fundamental constants also offer a means of verifying the equivalence principle, as discussed in Ellis & Uzan (2005). In this respect, one may improve the constraint on the variation of the fine structure constant by an order of magnitude if one relates the fundamental couplings and constants to the nuclear parameters and incorporates these relationships in a code of primordial nucleosynthesis (Coc et al. 2007, see also Chapter 4). Finally, it has been shown how weak lensing data could provide a sensitive test of modified gravity (Schimd, Uzan & Riazuelo 2005). The relationship between scalar tensor theories with models having an equation of state parameter less than -1 and solar system constraints on general relativity has been characterized in Martin, Schimd & Uzan (2006).

Cosmological inflation is generally defined as a phase of accelerated expansion. As is well-known, such a phase can solve the problems of a hot big-bang. The prototype has a slow rolling scalar field, whose energy density is dominated by a potential term. Inflation may also provide the required density perturbations on cosmological scales through the amplification of vacuum fluctuations of the inflaton field (a mechanism reviewed in Martin 2004, 2007). The scale invariant spectrum of density fluctuations predicted by inflation is in such remarkable agreement with the observed microwave background anisotropies that one is now able to constrain the parameters of the scalar field potential, as discussed in detail in Martin & Ringeval (2006) and as illustrated in Figure 6.4. In this context, it becomes crucial to refine the calculations of the resulting scalar and tensor modes of perturbations. The study of Osano et al. (2007) has therefore calculated the spectrum of gravitational

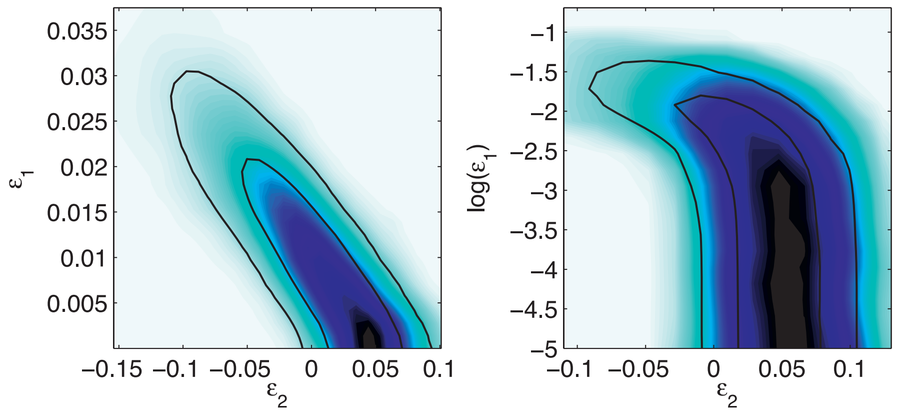


Figure 6.4: Present constraints on the slow-roll parameters (i.e. approximately the first and second derivative of the inflaton potential during inflation) obtained from an analysis of WMAP3 data.

waves (tensor modes) produced by the coupling of scalar and tensor modes at second order. Furthermore the quantization of the inflaton fluctuations has been generalized to anisotropic spacetimes in order to understand the robustness of the scenario with respect to the hypotheses (Pitrou & Uzan 2007) and a formalism for describing the cosmological perturbations beyond the linear order has been constructed (Langlois & Vernizzi 2005a,b). The latter case provides a generalization of the zeta variable (the curvature perturbation) to all orders and the exact equation of evolution for this variable. The effects of stochastic fluctuations of the inflaton have been addressed in Martin & Musso (2006a,b).

Multi-field models of inflation share a rich phenomenology. For instance, light fields during inflation may induce a modulation of metric fluctuations during the preheating phase (Bernardeau, Kofman & Uzan 2004), leading to a different consistency relation. Curvaton models, in which the cosmological perturbations stem from the fluctuations of both the inflaton and a curvaton field have also been studied in Langlois & Vernizzi (2004) and in Lemoine & Martin (2007). In particular, it has been shown that a curvaton could lead to the production of large isocurvature perturbations even if the energy density of this field is small as compared to others at the time of its decay.

Other studies, concerned with the possible deviations from Gaussianity, have addressed the quantization of interacting scalar fields in de Sitter space (Brunier, Bernardeau & Uzan 2005), the link between the quantized and the classical stochastic formalisms (Brunier, Bernardeau & Uzan 2004), the effects of finite size (Bernardeau & Uzan 2004), or the correlation between modes in the microwave background temperature fluctuations (Prunet et al. 2005).

In spite of all its successes, inflation presents several problems (see Brandenberger & Martin 2005). For one, this model has yet to be embedded in a realistic model of high energy physics. Indeed it is notoriously difficult to implement inflation in supersymmetry, supergravity or superstring theories without having to deal with a severe fine-tuning issue regarding the flatness of the potential, as discussed recently in Brax & Martin (2005). Furthermore, several models seem to lead inevitably to the appearance of cosmic strings, in particular hybrid D-term inflation in minimal supergravity, even if the contribution of these cosmic strings may remain compatible with the microwave background anisotropies (Sakellariadou & Rocher 2005a). This work has been refined and extended to F-term hybrid inflation in Sakellariadou & Rocher (2005b), Rocher (2006), Rocher (2004a,b). Finally, wavelengths of the inflaton fluctuations are initially smaller than the Planck scale, which raises the problem of consistency of the underlying physical theory. In particular, should the effects of quantum gravity be taken into account? However this trans-Planckian problem may also be seen as a window opened by microwave background

anisotropies on physics beyond the Planck scale and it has been shown how to interpret the apparent oscillations in the existing data in this respect (Martin & Ringeval 2004a, 2004b, 2005).

Bouncing Universe models, in which the scale factor goes through a minimum, may provide an interesting alternative to inflation. However in these models the Universe must either possess spherical spatial sections or one must invoke a fluid with negative energy. In the former case, one must explain why the present curvature is so small, which may require a phase of inflation posterior to the bounce, while in the latter case, instabilities arise which are difficult to contain. The evolution of fluctuations during the bounce phase in a positively curved Universe has been studied, and it has been shown that in contrast to inflation, one cannot find a generic case (Martin & Peter 2004).

In order to implement the effects of quantum gravity in the framework of the Wheeler-de Witt equation, the method of Hawking-Halliwell has been simplified by performing canonical transformations in order to write the Hamiltonian of fluctuations in a canonical form with uncoupled modes (Peter, Pinho & Pinto-Neto 2005). The equations for these modes, which are simple enough to be solved in a variety of cases, may be obtained without using the equations for the underlying metric. In the framework of the Bohm interpretation of quantum mechanics, it has then been possible to derive bouncing solutions for a spatially flat Universe, in which a scale invariant spectrum of gravitational waves could be produced if the energy density is dominated by dust (Peter, Pinho & Pinto-Neto 2006). It thus appears possible (although non-trivial) to provide an alternative to inflation as far as the spectrum of perturbations is concerned.

Finally, several other studies have constructed tools to constrain a possible non-trivial topology of the Universe from microwave background data (Riazuelo et al. 2004a; Riazuelo 2004b, Uzan et al. 2004, Kunz et al. 2006). The available constraints seem to exclude the possibility of detecting any such topology. Nevertheless the maps that have been constructed in these studies remain of use worldwide as they serve to develop and test estimators of large scale anisotropy.

CONCLUSIONS 6.5

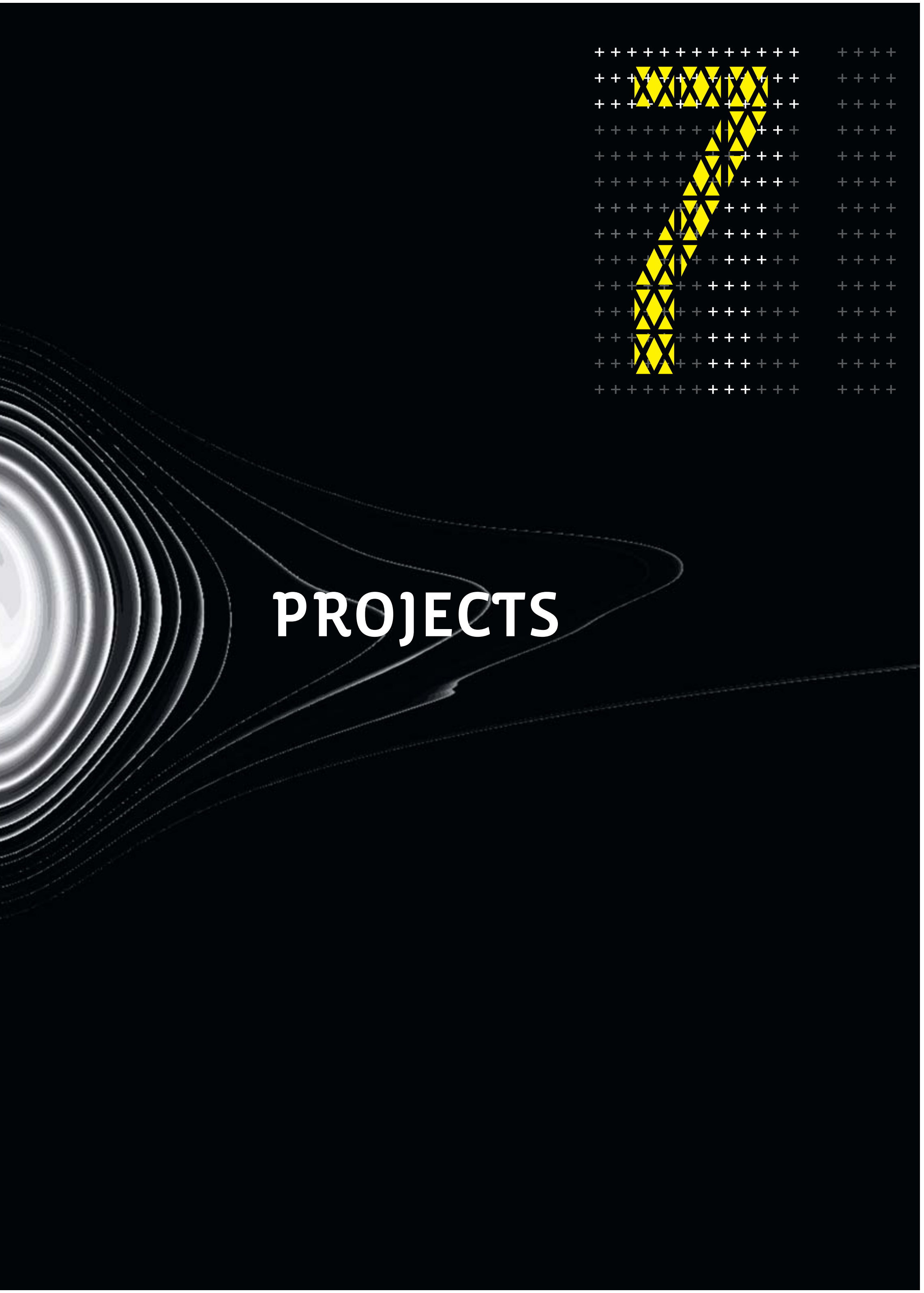
In the field of general relativity and its theoretical extensions, future research will focus in particular on data analysis by reinforcing the existing ties with the VIRGO and LISA experiments. A post-doctoral fellow has been hired on a joint project with the VIRGO experimental group at LAL. Furthermore, a new axis of research has emerged recently on the theme of extended theories of gravitation, in particular through the funding of an ANR project in collaboration with the theory group of APC.

Concerning astroparticle physics, the recent hiring of an expert in dark matter phenomenology as well as the hiring of a post-doctoral fellow in the field of particle acceleration in astrophysical sources (funded by ANR) have helped increase the size of the group. Future research directions will focus on theoretical aspects, and will benefit from the numerous experiments under development, both for ultra-high cosmic ray detection and for dark matter searches.

Finally, forthcoming large cosmological surveys which will probe the evolution and the nature of dark energy as well as the microwave background anisotropies with an unprecedented degree of accuracy will allow the group members to test and refine their theoretical models. Numerical tools in particular are being developed in the framework of an ANR-funded project to prepare the interpretation of these forthcoming datasets. One should also note that the recent hiring of an expert in superstring theories has enlarged the spectrum of activities in this area at GReCO, and several projects at the interface of superstring phenomenology and cosmology have already been initiated within the group.

7

PROJECTS



Scientists, engineers and technical staff of the IAP participate in various large scale projects of observational astronomy and cosmology. The science oriented activities of these projects have been described in the previous chapters of this report; the present chapter focusses on the technical tasks and the organization of these projects. Over the past decades, the IAP's involvement has moved from instrument design to the processing and the analysis of observational data. As of today, the IAP hosts TERAPIX, the data processing centre for the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS), the FUSE (Far Ultraviolet Spectroscopic Explorer) French data centre, and the Planck Data Processing Center for the Planck HFI instrument. IAP scientists are also actively involved in massive numerical simulations in the various domains of expertise of the scientific teams. As discussed at the end of this chapter, IAP has also taken part in other smaller sized projects: PLANET, EDELWEISS, DENIS, EROS and INSPIRE, whose science objectives span just as well the different themes of research of IAP.

7.1 FUSE

FUSE (Far Ultraviolet Spectroscopic Explorer) is a space telescope for high-resolution spectroscopy in the wavelength range 905-1087Å. Launched in June 1999, its spectral domain includes numerous atomic, ionic and molecular transitions, in particular deuterium, molecular hydrogen and oxygen VI. FUSE is a joint project between USA (NASA), Canada (CSA) and France (CNES), led by the Johns Hopkins University at Baltimore. Initially a 3-year mission, FUSE operations were extended twice, up to 2007. On July 12th, 2007, however, the FUSE spacecraft experienced a serious reaction wheel anomaly, making pointing impossible. The efforts to restart the wheel were unsuccessful, and it was decided to halt FUSE operations, despite the good shape of the instruments.

About sixty French scientists from a dozen laboratories have been working on FUSE observational programs. About 400 FUSE papers have appeared in peer-reviewed journals, more than 10% of which have a French first author and 25% at least a French co-author. FUSE studies in France are related to the Solar System, circumstellar disks, stellar physics and interstellar and extra-galactic media. Since 1998, six post-doctoral fellows and ten PhD theses were involved with FUSE data in France.

In 2007, the core of the FUSE team at IAP consists of four researchers, an engineer, a post-doctoral fellow and a PhD student. A dozen other IAP researchers are also involved in FUSE studies. The IAP FUSE team supports French users of the satellite, helping in preparing observations and their analyses and providing tools. A database of the FUSE observations is hosted at IAP. Available online (http://fuse.iap.fr), it is linked with the "Virtual Observatories" projects. The FUSE archive will remain a reference in the far-ultraviolet domain for decades.

7.2 PLANCK

The Planck team at the IAP is in charge of the IAP contribution to the ESA Planck satellite which aims at mapping the temperature and polarization anisotropies of the cosmological microwave background with enough sensitivity, resolution, and control of systematic effects so that all cosmological information within the temperature fluctuations can be extracted (see Figure 7.1).

The Planck project started with the ESA proposal in November 1992 to identify the third medium-class mission for the Horizon 2000+ program. It was selected for a phase-A study which started in November 1994, and which

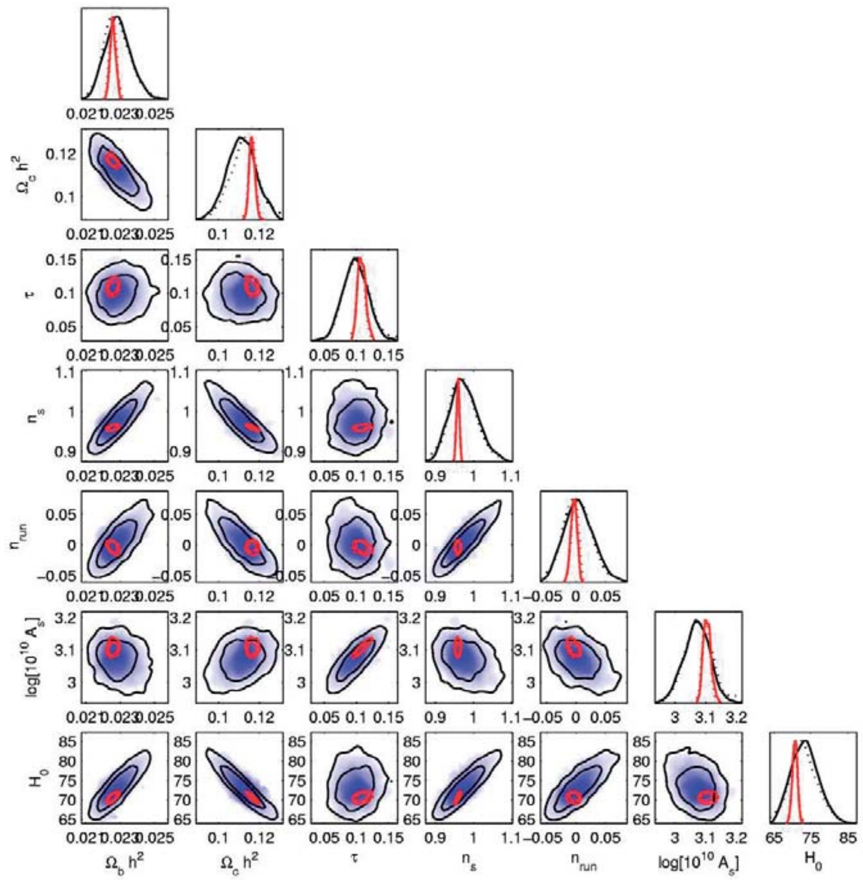


Figure 7.1: Estimate of the gain in accuracy on cosmological parameter estimation with Planck (red contours), as compared to WMAP (blue contours)..

was successfully concluded by the project selection by the SSAC in May 1996 (which followed the selection by CNES as a small mission of an earlier, smaller form of the project). The construction phase of the HFI consortium as candidate to build a part of the payload began in February 1997, and was concluded in early 1999 by the selection confirmation of the Herschel-Planck payload. The instruments are now delivered and the launch should take place around September 2008.

The IAP team leader is also Deputy PI of the HFI consortium and the HFI Data Processing Center manager. The task of the data processing centre is to transform the temporal flow of information from the satellite, with the help of ground calibration data, into an early release compact source catalogue in 2009, for follow-up by Herschel, and by 2011:

- Clean calibrated temporal flows from detectors
- Produce full sky maps at 6 different frequencies (between 100 and 850 GHz)
- Produce full sky maps of the identified astrophysical components, in particular that of the cosmic microwave background.
- Make a full statistical characterization of the anisotropies (in particular the angular power spectra).

Figure 7.2: the MAGIQUE cluster used for developing the Planck data processing pipeline.

A second data delivery is expected in 2012. Mission products, comprising processed data, codes and documents delivered by the Planck collaboration, will be made available worldwide by the "Planck Legacy Archive" which will be maintained by ESA. Earlier versions of some of these products will also be produced for scientific exploitation by the Planck collaboration during operations (1 year nominal) data analysis and the proprietary period (1+1 year), approximately each 6 months. This data processing centre effort was initially estimated at 300 years of a full time job.

The Planck data processing centre is geographically distributed and developments are shared between a number of countries (France, UK, USA, Germany, Canada) and, within France, between several laboratories (APC, CESR, IAP, IAS, LAL, SAp, LERMA, LPSC). France is responsible for roughly half of the total effort, as is the case for the instrument. The IAP team is in charge of coordinating the overall analysis effort of the acquired data (SGS2 part), while IAS leads acquisition and operations (SGS1 part). The IAP also coordinates the

French contribution, which concerns the transformation of the temporal flow into sky maps by frequency. This part of the data analysis is the most difficult, in particular in terms of the large data volume. The IAP team has invested a lot of effort into designing, developing and implementing a hardware and software infrastructure permitting an efficient and traceable data analysis. This infrastructure is deployed in other centres (CCALI, CPAC, IPAC) which allows a significant increase of the data processing capability of the data processing centre.

Concerning hardware, the team has driven the procurement and deployment, and operates a cluster with 280 processing cores, 740 gigabytes of memory and about 30 terabytes of fast disks which allows a first-cut analysis of all the data. In 2008, the team will design, procure, receive and deploy the flight machine which will be about three times more powerful, with 200 terabytes of disks. A dedicated computer room (specifically dimensioned thermally and electrically) has been designed and installed thanks to the support of the IAP technical and administrative staff. Concerning software, the team has developed an optimized input/output system which relies on a database and permits an exhaustive tracking of all operations carried out within the data analysis pipelines, while still being able to cope with very large data volumes.

The team has also deployed and operates collaborative infrastructures (e.g. CVS, CMT, lists server, web, cf. http://www.planck.fr) with the help of APC and LAL engineers.

Additionally, the IAP team has developed and implemented a number of essential data analysis tasks for Planck, in particular algorithms for the statistical characterisation of the detector noise properties, map-making and satellite pointing reconstruction. In all cases, these algorithms have been parallelised to make optimal use of the computing hardware infrastructure so that all data can be dealt with locally. A number of algorithms have been tested on real data in the framework of experiments such as ARCHEOPS, BOOMERANG and BICEP, in particular for polarization measurements.

The team has currently eighteen members, six researchers and 12 software engineers, six of which are on temporary contracts.

TERAPIX 7.3

TERAPIX ("Traitement Elémentaire Réduction Automatique des PIXels", http://terapix.iap.fr) is a French national data centre dedicated to astronomical image processing. It was created in 1998 to provide astronomers with facilities to process a new generation of wide-field imaging instruments, such as MEGACAM (in the visible), or WIRCam (in the near infrared). In particular, TERAPIX is in charge of the processing and the production of data releases for the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS). In practice, the three main tasks of TERAPIX are:

• the development of fast and user-friendly software tools, optimised for panoramic astronomical detectors which can be easily integrated into any image processing pipelines, and capable of handling large astronomical imaging surveys,

• the production of calibrated data ready for immediate scientific usage. These data are of two kinds, Legacy (like the CFHTLS) or dedicated, with specific requirements ("PI" data), and involve both MEGACAM and WIRCam. TERAPIX products include calibrated individual, stacked and chi-squared images, weight- and flag maps images, catalogues and a series of quality assessment and meta-data. TERAPIX output products and output meta-data are archived and distributed either by the CADC (CFHTLS) or at TERAPIX (PI),

• technical assistance to astronomers who are using TERAPIX products or who are willing to process visible or near infrared images on their own. These images are not necessarily from MECAGAM or WIRCam.

TERAPIX aims at serving astronomers worldwide. All (fully tested) released software products developed at TERAPIX are available freely under an "open source" licence. Technical assistance or advice is available to any users on request. All software tools are designed, written and documented in order to work as stand alone applications on all standard platforms and by any user, even those with limited experience in astronomical image processing.

TERAPIX is funded by INSU, the French Programme National de Cosmology, the European AVO and AstroWise contracts, the CNRS EFIGI and MDA projects, and the IAP. In addition to manpower, most TERAPIX resources are used to purchase computing hardware: the TERAPIX computing facility is composed of a Gigabit network with 69 CPUs and 100 TB of RAID-5 disk storage. The TERAPIX centre is hosted by the IAP.

During 2004-2007, the main activies of TERAPIX were (1) software development for large astronomical detectors and wide field processing and data handling, (2) the development of a new pipeline dedicated to WIRcam and near-infrared data, (3) the operation of TERAPIX pipelines to produce CFHTLS releases as well as MEGACAM and WIRCam PI data and (4) the scientific exploitation of surveys produced (at least partly) by TERAPIX, like CFHTLS, COSMOS or WIRDS. These surveys are part of national and international scientific collaborations in which TERAPIX scientists are involved.

The TERAPIX pipeline dedicated to MEGACAM images is called **SPICA**. Its implementation, testing and validation took place during 2003 to 2007. It uses TERAPIX software (developed in-house), and starts from the data transfer from CADC and finishes with the quality assessment of final images and catalogues and the delivery of output products to CADC. It generates automatically the processing command lines, runs automatically each process and handles the queries and updates of the data base.

In detail, the processing is composed of three steps: (1) a preliminary quality assessment and grading of each input image, (2) an automated calibration and image stacking process followed by the catalogue production, a quality assessment step, similar to (1), and a delivery of products to CADC, and (3) a panchromatic analysis of stacks observed in several filters to produce colour-colour plots and additional quality assessment data. The database keeps tracks of all processing history as well as all relevant information on the stacked image and catalogue productions. All data and meta-data are either archived at CADC or at TERAPIX.

TERAPIX began processing WIRCam images in August 2005, but its involvement with this camera started earlier, during the data and processing definition phase at CFHT. From a computing resources or processing point of view there are many points in common between MEGACAM and WIRCam, so that many software tools or computing facilities can be reused. Some processing steps specific to near-infrared data were more critical and demanded additional software development and tests on real WIRCam images during several months. The TERAPIX WIRCam activities over the past two years have been concerned primarily with processing near infrared images and technical assistance to PIs as well as the development of new software tools and a WIRCam-dedicated pipeline.

Unlike MEGACAM PI data, the diversity of astronomical targets and scientific goals demand a flexible pipeline that permits a very broad set of functioning and processing parameters. The WIRCam pipeline is therefore not fully automated in order to keep all processing options open. WIRCam documentation is available at the TERAPIX[1] web site.

On the software side, most of the new developments for near infrared processing done at TERAPIX focussed on **EyE**, a tool to detect and correct bad pixels, **PSFEx**, an automated image quality analysis tool, and on updates of **MissFITS** and **WeightWatcher**.

Email (or, increasingly) the TERAPIX forum[2] is used to maintain contact with users.

1 http://terapix.iap.fr/wircam
2 http://terapix.iap.fr/forum

The PI WIRCAm and MEGACAM processing, together with the CFHTLS release production, form more than 70% of TERAPIX activities. For MEGACAM, the PI processing activity concerns about 40% of the amount of MEGACAM data, while the CFHTLS is about 80% of the amount of the production activity. This unbalanced ratio is a consequence of the "Legacy" nature of CHTLS products that demand more careful quality control and demand an extensive and broad set of meta-data, for single stacks as well as for the survey as a whole.

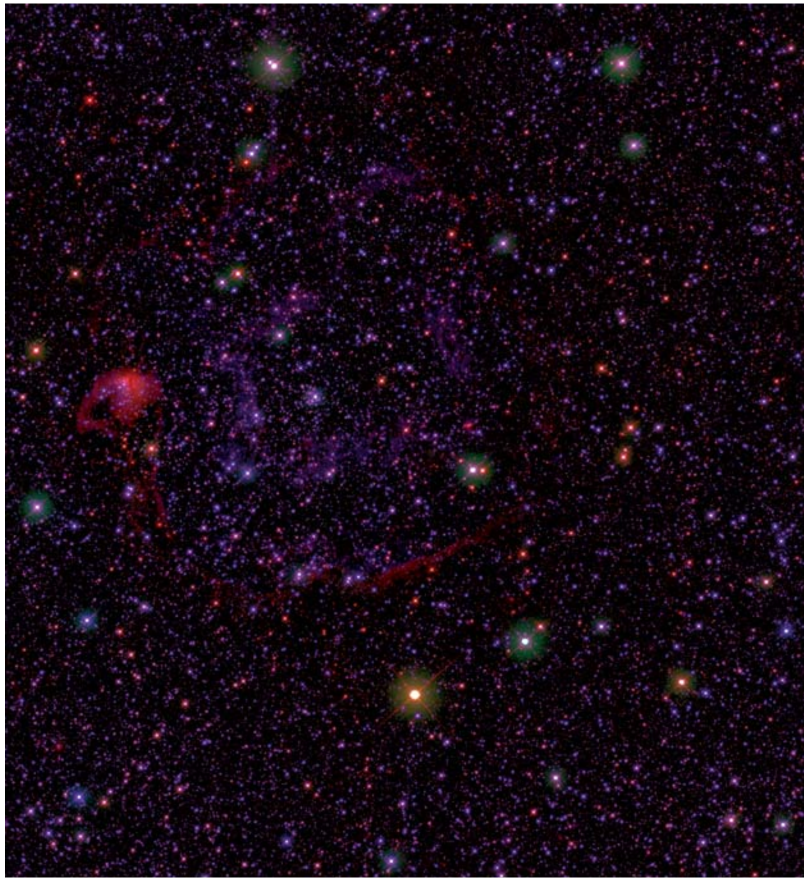


Figure 7.3: A composite WIRCam J, H, K image of a stellar field produced by the TERAPIX-WIRCam pipeline. The field size is 12x13 arcmin². It is composed of 105 single image in H, 172 in J and 73 in K bands, totalising 525, 3020 and 73 seconds, respectively.

To date, TERAPIX has processed 22 WIRCam-PI runs from 14 different PIs, and 49 MEGACAM-PI from 22 different PIs. Most PIs are from French, Canadian and Hawaiian institutes, or CFHT (Discretionary), but also come from from Taiwan, UK, Italy and USA.

During the period 2004-2007, TERAPIX released the CFHTLS T0001 (November 2004), T0002, T0003 and T0004 (May 2007). The current goal, as agreed by the CFHTLS Steering Group, is one release per year. The releases consist principally of the Deep (D1 to D4) and the Wide (W1 to W4) surveys and selected areas of the Very Wide survey. In total, the four releases represent more than 100 000 single MEGACAM images (including the production of 50000 weight map images), and the production of more than 10 000 stacked images and of more than 3 million meta-data files. All these data are archived either at CADC or at TERAPIX (see for example http://terapix.iap.fr/cplt/tab_t03ym.html for T0003).

The impact of TERAPIX servicing tasks and of TERAPIX data products is measured using the acknowledgment metrics on the page: http://terapix.iap.fr/article.php?id_article=597. To date (November 2007), 85 published refereed acknowledged TERAPIX (these metrics excludes papers that did not include acknowledgements, or those that only use TERAPIX software or refer to TERAPIX in a footnote). About 50% are survey data (CFHTLS, XMM-LSS, COSMOS, Virmos-DESCART) and the remaining 50% are PI targeted fields.

NUMERICAL SIMULATIONS AT IAP 7.4

The strength of IAP in computer science comes partly from its multidisciplinary approach in two principal fields: cosmology and (exo)planets. Initiated in the past by individual projects, simulation activity at IAP is now mature enough to compete at the highest international level. The IAP has access to national computer resources (IDRIS, CINES), as well as the HORIZON infrastructure (a meso-machine and a grid), and more importantly to one of the most powerful computers in the world (Mare Nostrum, Barcelona). Additionally, it is worth mentioning a local hardware configuration comprising four quad-core machines, a computer dedicated to visualization and large disk capacity (about 50To). At present, there are no less than eight codes under development or in use at IAP: **RAMSES**, the public tree-code **GADGET**, three Vlasov-Poisson solvers, a 3D code of hot Jupiter evaporation, a plasma PM code and a MHD code.

In cosmology, the IAP participates actively to the improvement of the adaptive mesh refinement cosmological hydrodynamic code **RAMSES** by developing specific modules: a cooling module (chemical evolution of primordial elements), a real time light-cone generator, and especially a MHD module using high order Godunov schemes (Teyssier, Fromang & Dormy, 2006; Fromang, Hennebelle & Teyssier 2006). The **Graphic** software (developed by E. Bertschinger) was parallelized under MPI to generate initial conditions for “extreme” simulations. This essential tool is used to generate the principal initial conditions of the HORIZON simulations, e.g. the hydrodynamical simulation “Mare Nostrum” (1024^3 particles in a $50h^{-1}$ Mpc box) and the 4π dark matter simulation performed at the CEA computing center (4096^3 particles). As discussed in Section 5.3, these two simulations are the largest ever of their kind.

The Vlasov-Poisson equations, used to simulate the dynamics of dark matter, are usually solved with N-body techniques, which are very noisy in phase-space. One objective is to develop new schemes which work directly in phase-space. In particular, Alard & Colombi (2004) developed a new method, tested extensively in 1D, which decomposes the distribution function on a basis of small “clouds” with elliptic support. Colombi & Touma (2007) have examined the traditional “waterbag” method in 1D, spherical systems and disks by following isocontours of the phase-space distribution function using oriented, adaptive polygons, see Figure 7.4. Finally a general scheme is being developed in 6D, using an adaptive local metric approach, similar to the “cloud” method (PhD thesis of G. Lavaux).

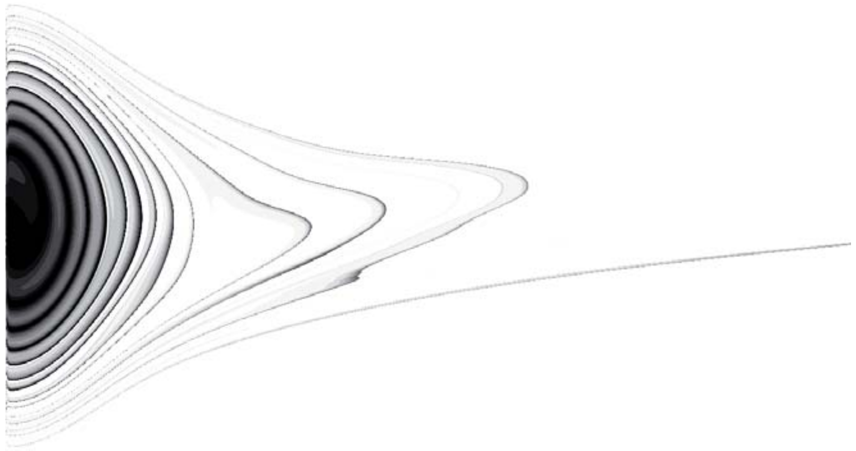


Figure 7.4: Collapse of a Hénon sphere, initially homogeneous with a Maxwellian kinetic dispersion. The phase-space distribution function is shown after ~10 dynamical times. Filamentation of dynamical origin is clearly visible and perfectly captured by the waterbag method employed here.

The previously-developed code for simulating the evolution of cosmic strings has also been improved and parallelised. This has led to the most accurate simulations of cosmic string networks of the past few years. Using this code, Ringeval et al. (2007) established for the first time the existence of a scaling relation for loops.

Tools for the statistical analysis and the detection of structure and substructures in cosmological simulations are also actively developed by the team. Works in this field include the development of the **adaptahop** code of halo and sub-halo detection (Aubert, Pichon & Colombi 2004), which is widely used within the HORIZON project (e.g. Cattaneo et al. 2005; Weinberg et al. 2006; Colombi, Chodorowski & Teyssier 2007); a phase-space sub-structure and structure finder, that might turn to be the best code of its kind to date (developed in the framework of the PhD of M. Maciejewski); the **powmes** code which uses a Taylor expansion approach to extract rapidly and with great accuracy the power-spectrum from an N-body simulation over all the available dynamic range (Colombi et al., in preparation); finally, a filament detection code in 2D, **FasToCh** (Novikov, Colombi & Dore 2006), and in 3D (Sousbie et al. 2006). A special effort is currently underway to improve these two codes by using a probabilistic approach combined with a standard percolation algorithm (Colombi, Sousbie & Pichon, in preparation). To this list, one can add numerous useful programs that address a large range of analyses (adaptive smoothing, percolation theory, angular structure of halos, count-in-cells and so forth). As a result the HORIZON component of IAP presents a worldwide level of expertise for the post-treatment of cosmological numerical simulations.

IAP has also developed a unique expertise in the generation of virtual observations, which represents one of the cornerstones of the HORIZON project. These mock observations are obtained from a sophisticated post-treatment of numerical simulations. Their applications are numerous: deep galaxy surveys, gravitational lenses in the strong or in the weak regime (e.g., Semboloni et al. 2007), the Lyman-α forest (e.g., Coppolani et al. 2006), cosmic microwave background secondary anisotropies among others. To mention only the most important aspects, the pipeline **GalICS** (developed at IAP, now based in Lyon) uses the results of dark matter simulations to extract a halo merging tree and to derive, using a semi-analytic modelling, the history of galaxy formation. The final result is a complete catalogue with spectral and morphological properties of the galaxies, as well as their positions in the simulation. Such a catalogue can be “observed” with the code **MoMaF** (developed at IAP during the PhD of J. Blaizot, then further developed at MPA Garching; Blaizot et al. 2005, 2006) to generate for example mock redshift surveys for the VVDS collaboration. **MoMaF** extracts a light-cone from the galaxy catalog generated by **GalICS** and applies instrumental selection. Finally, the code **SkyMaker** from TERAPIX (Bertin & Fouquet) allows one to generate realistic synthetic photometric images taking into account telecope and CCD camera properties, see Figure 7.5 for an illustration.

The IAP also invests a lot of efforts in visualization techniques for output from numerical simulations. For instance, a code was developed to visualise

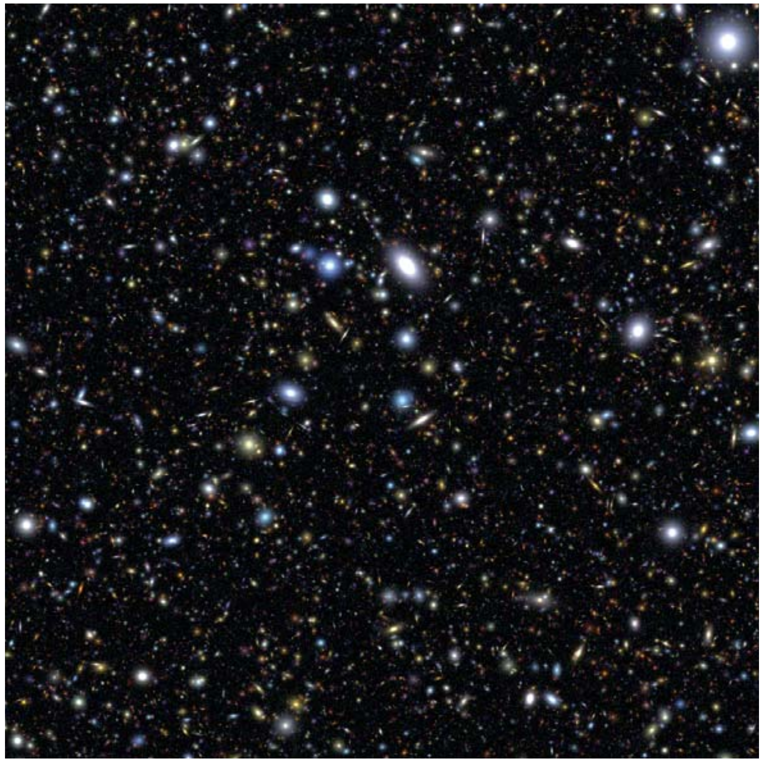


Figure 7.5: composit optical image of the deep sky simulated by **SkyMaker** in the framework of DUNE project.

in real time the particle distribution of an N-body simulation, using video card acceleration with the OpenGL library. Similarly, the **RealGal** code allows one to create movies of galaxies or distributions of galaxies by relying in a transparent way on public domain softwares (**pov-ray**, **mpeg_encode**, **yorick**). A ray-tracing code based on the tree structure of **RAMSES** allows one to compute the integral of any scalar observable accurately (for instance to generate Sunyaev-Zeldovich maps) along any line of sight. This code can treat part of the sky or the full sky, using various projection techniques (Figure 7.6).

Turning to exoplanetary dynamics, three codes (particle-in-cell, MHD, kinetic) have been developed to explore the evolution of magnetospheres of extra-solar planets and their interactions with their parent star. This project is the outcome of an international collaboration (IAP, LMC Grenoble, ESS at Seattle, CBK in Warsaw, LPL in Tucson). A 3D relativistic electromagnetic particle-in-cell code has been developed, which accounts for planetary and stellar magnetic fields, the presence of natural satellites (magnetized or not), and gravity. It offers direct access to microscopic plasma information such as the 3D velocity distribution function, as well as the general 3D topology of

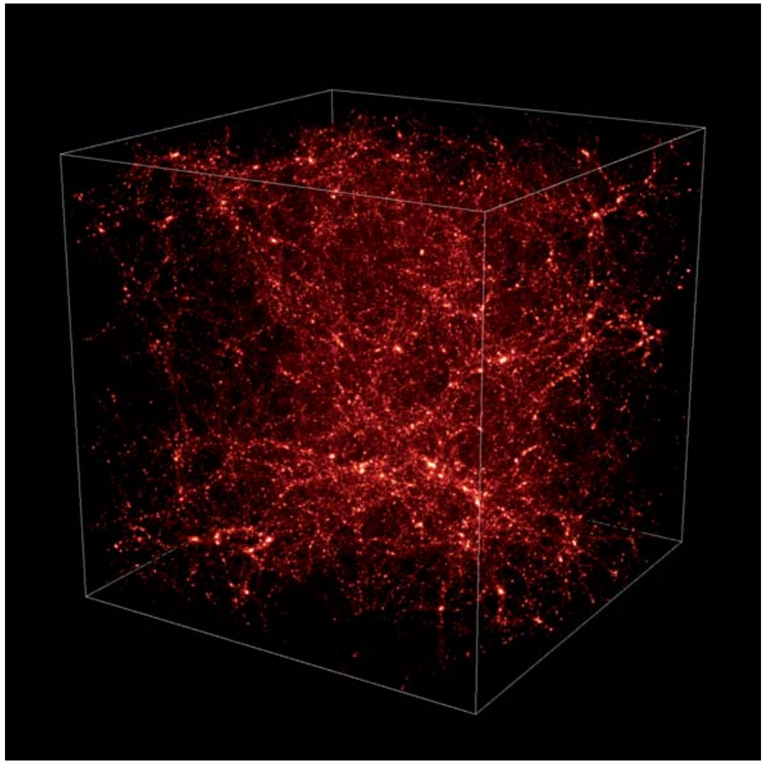


Figure 7.6: Ray-tracing through a **RAMSES** simulation : the dark matter density is represented in a logarithmic color scale.

magnetic fields and electric currents. A first application has been the study of the terrestrial magnetosphere (Baraka & Ben-Jaffel 2007). A second application concerns the magnetosphere of Jupiter, including Io's plasma, the intrinsic magnetic field of Ganymede, the rotation of the planet and the inclination of the dipole with respect to the spin axis (Ben-Jaffel et al., in preparation).

In addition, a 3D MHD code describing the interaction of the stellar wind with the interstellar medium is used to simulate the interstellar environment. This code accounts for stellar and interstellar magnetic fields as well as the presence of neutrals (Ratkiewics et al. 2004). A kinetic 3D code based on an exact treatment describing the interaction between neutrals and the local plasma is under construction. This code will provide access in a self-consistent way to each population, namely neutrals, ions and anomalous cosmic rays. A hybrid code coupling the MHD and the kinetic codes will then be developed to obtain iteratively the equilibrium between ions and neutrals. To compare the results of these simulations to the observational data of Voyager and HST, a 2D radiative transfer code was developed; it is applicable to both planetary atmospheres and the interplanetary medium (Ben-Jaffel et al., 2007). As

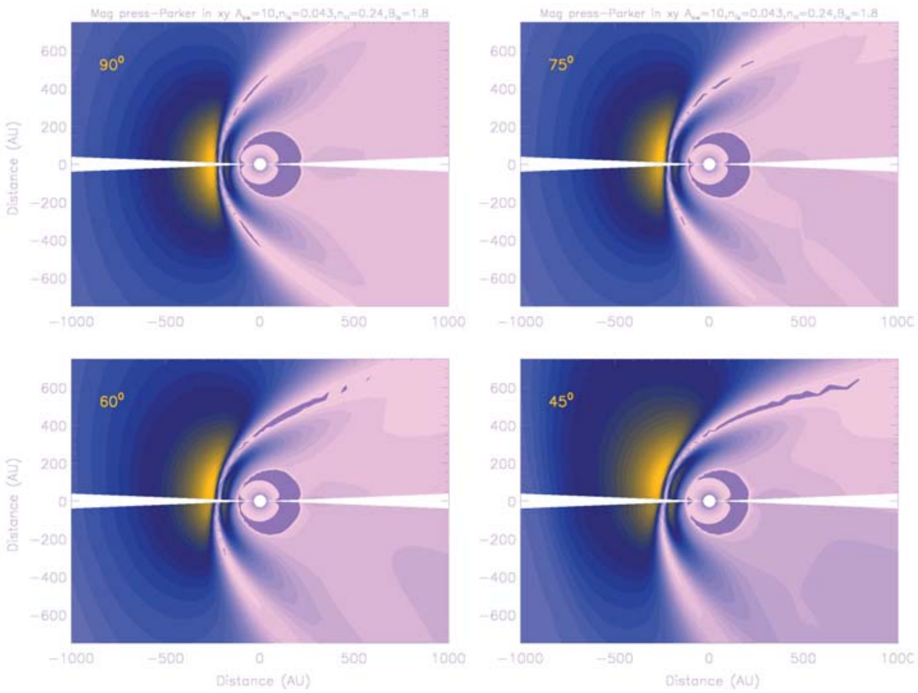


Figure 7.7: 3D MHD simulation of the interaction between stellar wind and local interstellar medium in the presence of interplanetary and interstellar magnetic fields. The figure shows isocontours of the magnetic pressure in a plane orthogonal to the ecliptic containing the solar axis and the direction of arrival of the interstellar wind, for various orientations of the interstellar magnetic field.

discussed in Section 1.3, the distortion of the heliopause, the terminal shock and of the interstellar shock had been predicted in 2002 (Ratkiewicz & Ben-Jaffel, 2002) and has just been confirmed by measurements in situ of the magnetic field by Voyager at a distance more than 100 AU from Earth (Opher et al. 2007).

The ESINPLE project is developing numerical simulations of exoplanetary magnetospheres and plasma environments using 3D MHD and 3D N-body electromagnetic and relativistic codes. Simulations performed in this framework currently use at best 256^3 resolution, but should reach the 512^3 level in a near future. It is now possible to cover extensively the problem parameter space, such as the total number of particles, grid resolution, relative mass of particles of different species, boundary conditions and so forth. Several groups of ions of various masses can be followed independently to generate observables such as various moments of the distribution function or the properties of the scatter of particles with respect to the local magnetic field lines. Furthermore, the inclusion of collision effects between particles in the particle-in-cell code is currently under study: this would allow one to simulate processes such as charge exchange, ionization/recombination. An

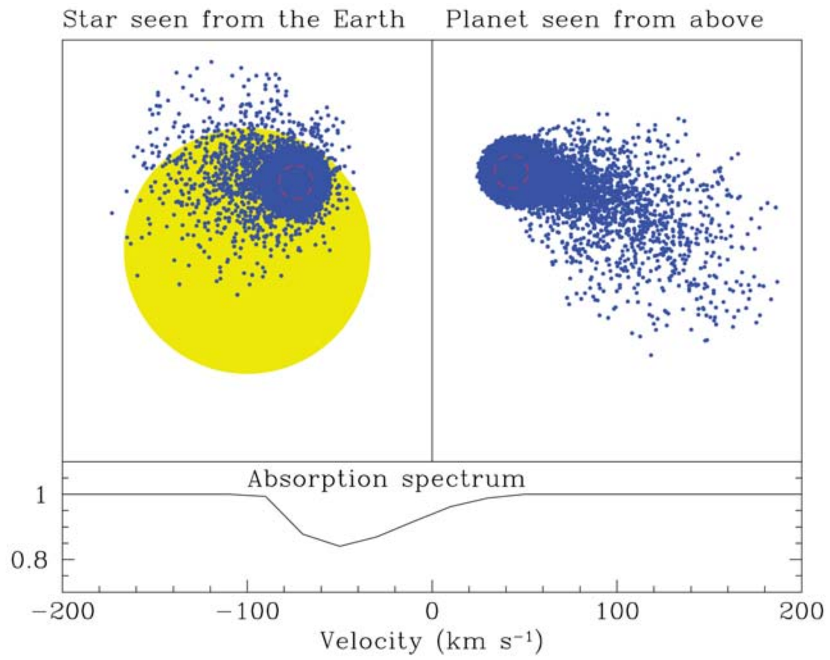


Figure 7.8: Numerical simulation of the escape of hydrogen atoms above an altitude corresponding to 0.5 times the Roche radius. The simulation shows the atom distribution in a comet like tail.

ongoing analysis aims at introducing an adaptive grid in the particle-in-cell code in order to optimize the diagnostics independently of the grid and the spatial resolution initially imposed. Finally, the ESINPLE project also involves the construction of visualization tools using the package IDL. The project has now at its disposal various packages (using widgets) optimised to explore in 3D various moments of the distribution function, to draw in 3D the magnetic field lines with a point-and-click interface, and to represent the local distribution function of velocities parallel and perpendicular to the field lines.

Concerning the dynamics of protoplanetary disks, the influence of the magnetic field has been studied for the first time thanks to the modification of the **GLOBAL** hydrodynamic code. This work showed in particular that the turbulence induced by the magnetic field alters significantly the disc dynamics by increasing its life duration and by modifying fragmentation processes (Fromang et al. 2004a, b, c, Fromang 2005, Fromang, Terquem & Nelson 2005).

Observations of extrasolar hot Jupiter transits have shown that these planets (which are very close to their host stars) can have an extended atmosphere, which induces significant mass loss (Vidal-Madjar et al. 2003). However, in order to compare these observations to dynamical models of hot Jupiter

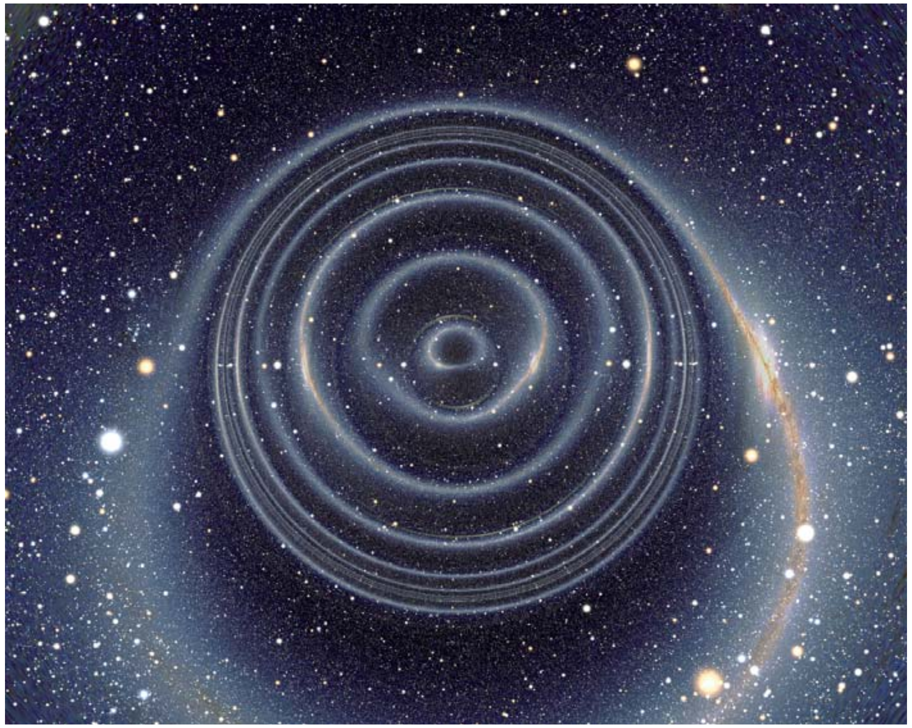


Figure 7.9: Visualisation of the effects of a naked singularity in a Reissner-Nordström metric.

atmospheres (e.g., Lecavelier des Etangs et al. 2004), it is necessary to convert the transit depth measurement in terms of loss rate. Only 3D numerical approaches can address this issue, and to date, the only such simulation was performed at the IAP. This N-body simulation takes into account gravitational forces, radiation pressure, radiative transfer inside the evaporating hydrogen cloud in the high atmosphere of the planet and allows one to interpret the transit depth of HD209458 (15%) as well as the spectroscopic profile of the absorption, and leads to an estimate of 10^{10} g/s for the hydrogen escape rate of de HD209458b (Lecavelier des Etangs et al., 2007, in preparation).

Finally, it is worth mentioning a program of visualization of the metric around black holes, which takes into account of the full range of relativistic effects produced by these objects (aberration, Doppler shift, intensity, gravitational distortions, image amplification and multiple images). The visual translation of these otherwise well-known effects had never been performed to such a high level of detail. This ray tracing program allows one to visualize what a spectator would see on a circular, elliptic, parabolic or hyperbolic orbit around a black hole, as well as the ephemeral spectacle that one would experience when entering the black hole horizon. With a few days of calcula-

tion on today's computers (3.0 GHz CPU and 1 Gb memory and a few gigabytes of disk space), one can perform high-resolution animations (1280x1024 pixels) of a few minutes in length. From a theoretical point of view, it can also give an impression of how a white hole singularity would seem, or a worm hole, or a naked singularity if such objects were to exist in Nature.

OTHER PROJECTS 7.5

The IAP is also involved in several other smaller-scale experimental projects. One of these, EDELWEISS, aims at the direct detection of non-baryonic Galactic dark matter particles using germanium cryogenic detectors cooled down to about 20 mK. These detectors can simultaneously measure heat and ionization signals in events allowing one to discriminate between nuclear recoils (dark matter and neutron events) and electron recoils induced by the radioactive gamma and beta background. The first step of the experiment, EDELWEISS-I (a one kilogram detector mass comprising three modules of 320g) finished in March 2004 and has determined between 2002 and 2004 the best limit to WIMP interactions (giving a nucleon cross-section limit of around 10^{-6} picobarn for the spin independent interaction). EDELWEISS-II, the second phase of the experiment, is now running in the Laboratoire Souterrain de Modane with 28 detectors (with an active mass of Ge of about 9 kg, 40 detectors in the final version) with a sensitivity goal of 10^{-8} picobarn.

The PLANET collaboration, whose PI is a member of IAP, searches for extrasolar planets using microlensing techniques, i.e. it searches for the light amplification of a background star caused by the passage of the planet close to the line of sight. This international collaboration brings together more than thirty scientists from twelve different countries.

EROS ("Expérience de Recherche d'Objets Sombres") used the same microlensing technique to search candidate baryonic dark matter concentrated in sub-stellar mass objects, except that it monitored background stars in the Magellanic clouds rather than in the Galactic centre as in PLANET. The EROS collaboration has joined dozens of scientists from the CEA, the INSU and IN2P3 of CNRS. Data collection (which took place on a 1m telescope at ESO) ended in March 2003. The subsequent analysis excluded sub-stellar mass objects as forming the bulk of the mass concentrated in the Galactic halo. Current analysis at the IAP now focuses on variable stars (see Section 1.1).

DENIS (Deep Near-Infrared Southern Sky Survey) has observed most of the Southern sky (21000 deg^2) in the I, J and K near-infrared bands. Three million images (about 2 Tb of data) were analyzed at IAP until 2001, then at "Observatoire de Paris". Several hundred millions stars have been extracted and the

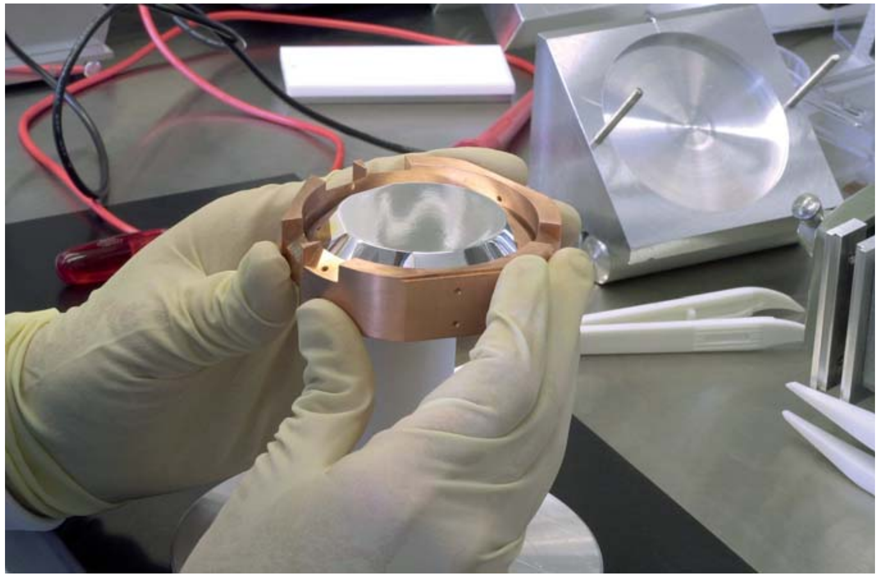
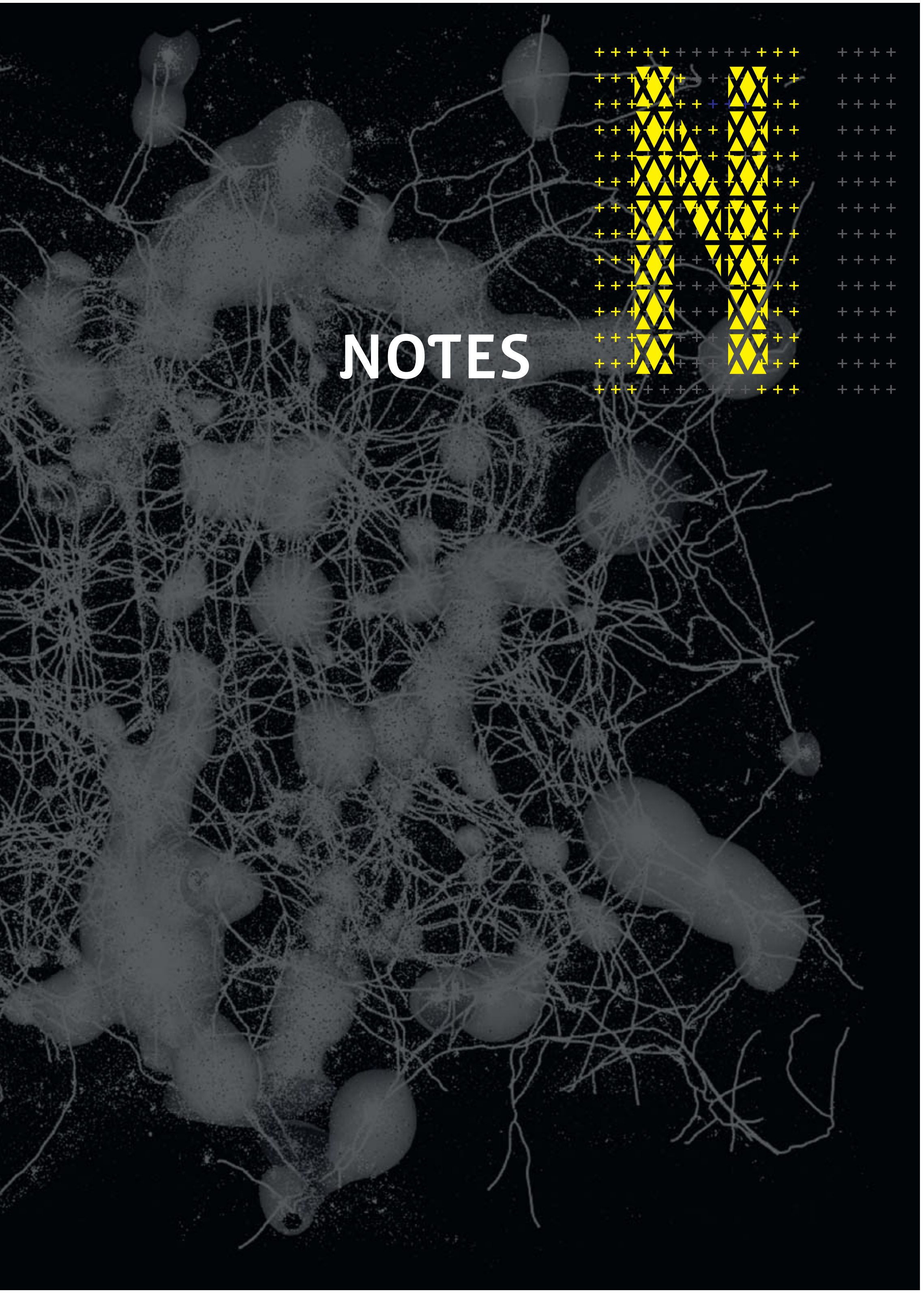


Figure 7.10: A detector of the EDELWEISS experiment.

associated databases are now freely available through the Strasbourg CDS web service. Furthermore, a pipeline dedicated to the extraction of galaxies has been developed at IAP; a preliminary source list served as a catalogue for the Australian 6dFGS. Current work concentrates on the final photometric calibration of the survey and the complete automatic extraction of around three million galaxies.

Finally, INSPIRE is a joint NASA-CNES rocket-borne ultraviolet spectropolarimeter which will measure the magnetic field on the surface of Jupiter. It will launch in 2008 (Harris, Roesler & Ben Jaffel 2005). INSPIRE will study Jovian auroras and their interaction with the interplanetary medium as well as testing new observational techniques in space. The French team (three members), whose PI is at IAP, is responsible for the delivery of a radiative transfer code to interpret the data and a kinetic code which simulates the interaction of the solar wind with the magnetosphere of Jupiter. INSPIRE benefits from an Alpha cluster with four processors and 8Gb RAM, an IBM machine with 6Tb for data storage, an AMD dual-core processor for calculations with 16Gb RAM and 6Tb of storage, a second machine dedicated to calculations with 32Gb RAM and 6Tb storage available in the near future. The gratings have been delivered in Spring of 2007, and the numerical tools for data interpretation have been developed.

NOTES



N › NOTES

C › CREDITS / PHOTO-BOOK

Art direction, graphic design and conception: Pete Jeffs Design Studio, Paris, 2007.
Printing and Fabrication: STIPA, Montreuil.

The Director of the IAP wishes to thank the anonymous worker who triggered the fire alarm by mistake. The entire IAP staff consequently moved to the sunny courtyard, offering ideal conditions for a group picture (by J. Mouette, IAP).