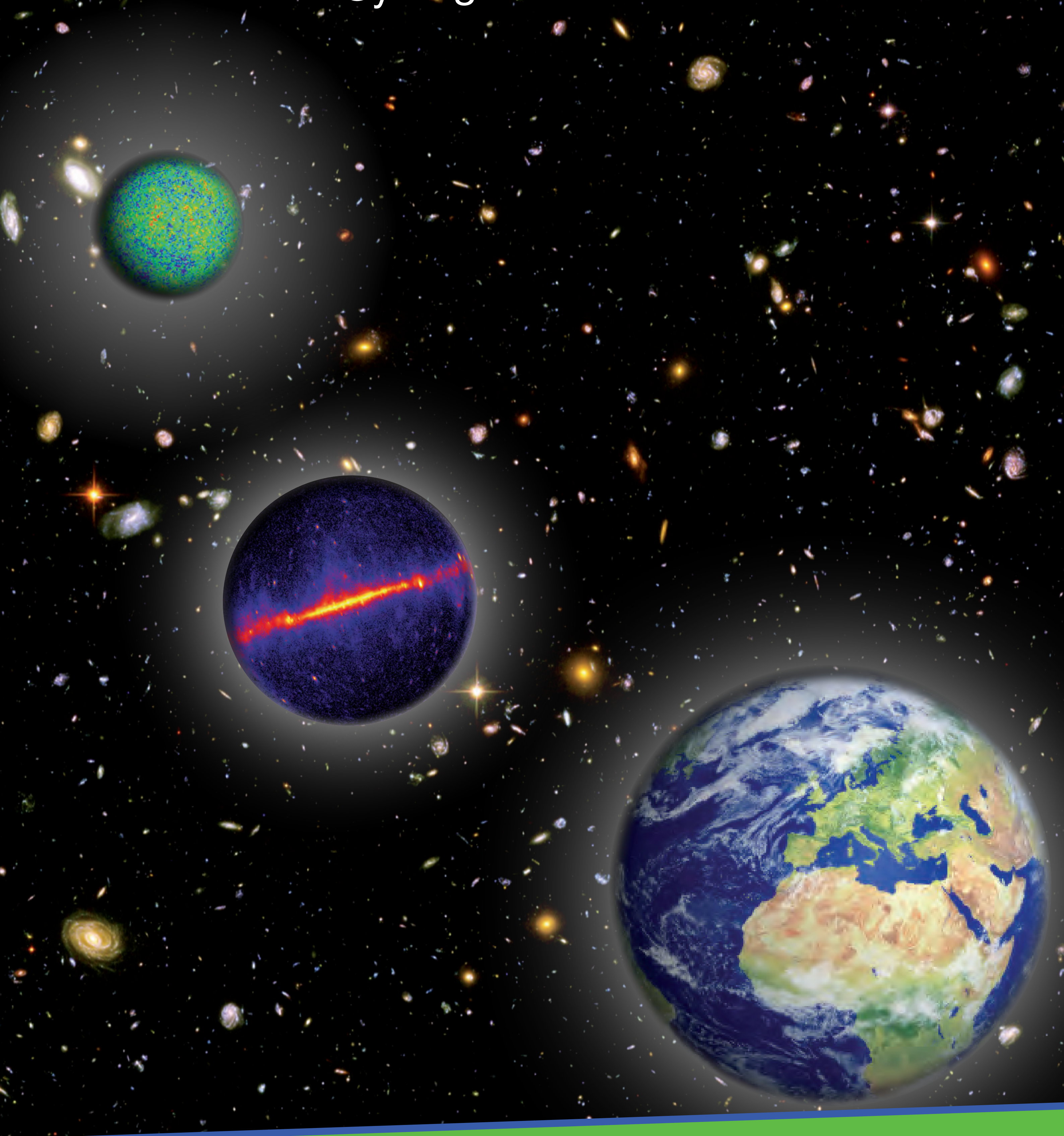
From the geosphere to the cosmos

Synergies with astroparticle physics



ASTROPARTICLE PHYSICS FOR EUROPE

www.aspera-eu.org

ASPERA

CREDITS

Written by:

Dr Ino Agrafioti (IN2P3/CNRS, France).

Editorial Committee (in alphabetical order):

Eugenio Coccia (INFN, Italy)

Paschal Coyle (CPPM/IN2P3/CNRS, France)

Karl-Heinz Kampert (Bergische Universität Wuppertal, Germany)

Stavros Katsanevas (IN2P3/CNRS, France)

Sean Paling (STFC / BUL, UK)

Fabrice Piquemal (LSM/IN2P3/CNRS, France)

Christian Spiering (DESY, GERMANY)

Special thanks to the following scientists:

Andre, Michel (UPC, Spain)
Arnaud, Fabien (EDYTEM/CNRS, France)
Autran, Jean-Luc(IM2NP/Aix-Marseille Univ, France)
Bay, Ryan (Univ California Berkeley, USA)
Bellini, Gianpaolo (INFN, Italy)
Crescentini, Luca (Univ of Salerno, Italy)
Pinto, Massimo (ENEA-INMRI, Italy)
Plastino, Wolfango (Roma Tre Univ, Italy)
Bellou, Nikoletta (HCMR, Greece)
Budnev, Nikolaj (Irkutsk State Univ, Russia)
Deschamps, Anne (CNRS/Nice-Sophia Antipolis Un., France)
D'Ettorre Piazzoli, Benedetto(INFN, Italy)
Draganov, Deyan (Delft Univ Technol., The Netherlands)
Gaffet, Stéphane (LSBB, CNRS, France)
Gaisser, Tom (Univ Delaware, USA)
Hubert, Philippe (CENBG, CNRS, France)
Keilhauer, Bianca (KIT, Germany)
Kirkby, Jasper (CERN, Switzerland)
Lefèvre, Dominique (CNRS,France)
Marteau, Jacques (CNRS, France)
Miele, Gennaro (Univ Napoli, Italy)
Morin, Dennis (CNRS/Université Toulouse le Mirail, France)
Price, Buford (Uni California Berkeley, USA)
Reyss, Jean-Louis (LSCE, CNRS, France)
Sabatier, Pierre (EDYTEM/Savoie Univ, France)
Tilav, Serap (Univ Delaware, USA)
Tonachini, Aurelio (INFN, Italy)
Van Haren, Hans (Royal NIOZ, Texel, the Netherlands)

Cover by:

Arnaud Marsollier (CERN)

Produced by:

ASPERA-2

TABLE OF CONTENTS

1. INTRODUCTION

Astroparticle physics (ApP) is the study of particles and radiation from outer space and of rare, cosmologically-significant elementary particle interactions. The scales of distances examined range from the realm of elementary particles to the outer reaches of the observable Universe, placing the field at the intersection of cosmology, astrophysics, particle physics and nuclear physics. Major fundamental research questions are within the scope of the field, notably, understanding the properties of dark matter, dark energy and gravitational radiation, and exploring the unification of the fundamental forces of nature. Furthermore, extreme astrophysical phenomena that produce *high-energy*[1] particles and *radiation* are of intrinsic interest since they have had, and continue to have, a major influence on the structure and evolution of the Universe.

ApP started as a specialised endeavour, pursued by a few charismatic pioneers who reached out beyond traditional disciplinary boundaries and used unconventional, innovative experimental techniques. Since then, the field has become a mature, globally-integrated research activity, involving approximately 4,000 researchers, with experiments being conducted underground, underwater, on the Earth's surface, in the atmosphere and in space. These are funded at the level of more than 300 million euros per year (excluding space launch costs). Today, ApP stands on the threshold of an era of discovery, with a new generation of proposed instruments that are likely to deliver major scientific breakthroughs based on enhanced sensitivity and resolution.

In addition, by taking the tools of particle physics from the confined environment of the laboratory into the natural environment to study the particles of the cosmos, this new field has developed interfaces with a remarkable number of other sciences: atmospheric physics and chemistry, climatology, geology, seismology, planetary sciences, volcanology, marine biology, oceanography, glaciology, space weather and biology in extreme conditions.

[1] When text is in italic, please refer to the Glossary at the end of the report.

The high quality of the research, the number of disciplines involved, and the impact of the research for questions of social concern motivated a proactive attitude by ASPERA (AStroparticle Physics European Research Area)[2] to foster and accompany these research activities in view of building active synergies between ApP researchers and other scientists. ASPERA has been stressing the strengthening of relations of ApP with other sciences since 2008 when its first Roadmap, the European Roadmap for Astroparticle Physics was published, presenting the future large infrastructures expected to address some of the most exciting questions about the Universe, such as the **Cherenkov Telescope Array (CTA), KM3NeT, EURECA, Einstein Telescope (ET), LAGUNA**, etc.

A workshop entitled "From the Geosphere to the Cosmos" was organised by ASPERA on the 1st and 2nd of December 2010 at the Palais de la Découverte in Paris, France. The speakers of the event presented existing synergies between Environmental Sciences and Astroparticle Physics. The success of the workshop is testified by the around hundred registered participants coming from all across Europe and by the articles published in leading journals and newspapers. The title of the Paris workshop was the same as that of this report, since we consider the latter to be continuation of the former.

The importance of multidisciplinary in content and interdisciplinary in execution research was also stressed in the update of the "European Roadmap for Astroparticle Physics" (2011): in all future research infrastructures, as in all existing ones, our environment is turned into an ally, a tool, a proxy, a detector medium or a target. The atmosphere is used as a target and a Cherenkov light detector medium in telescopes such as **CTA,** and as a fluorescence detector medium in telescopes as the **Pierre Auger Observatory** (see Section **2.1**). Mountains are turned into shields to protect experiments devoted to the detection of rare events in the underground labs (see Section **2.2**). Finally, ice or water are used as a shield and Cherenkov light detector mediums, for underwater/ice neutrino telescopes (see Section **2.3**).

[2] www.aspera-eu.org

Using the environment as a detecting medium implies that accurate knowledge and monitoring of its characteristics is essential for the determination of the properties of cosmic messenger particles, so that variation in environmental properties does not distort the data obtained by the ApP infrastructures.

In this respect, ApP is restoring the continuity between the study of the cosmos and the study of our environment. In particular, ApP infrastructures have four key characteristics that could also be of benefit to other sciences:

1) ApP infrastructures require **competence in complex sensing systems**, such as particle detectors.
2) ApP infrastructures require **technologies that allow the processing of large quantities of extremely pure and/or exotic materials**, such as those developed for the detection of rare events, dark mater, wimps etc.
3) ApP infrastructures require the development of advanced **systems for data acquisition**, **processing and dissemination**.
4) Even if we live in a world where sensors are more and more present and interconnected, **deploying sensors in remote or hostile environments** (ice, deep sea, deserts, caves, space) will always be, by definition, a difficult and costly task. ApP infrastructures are already or will be operating in such environments.

For all these reasons, the use of ApP infrastructures by other sciences is not just a wise and efficient use of resources, but is also likely to lead to great scientific advancements in other scientific fields.

In this report, multiple examples where current ApP infrastructures have been successfully used by other sciences are presented (Table 1). Only some of these synergies were presented in the "From the Geosphere to the Cosmos" workshop, proving that this is a growing field with a lot more potential than currently realised. Table 1 is of course not exhaustive, but merely meant to serve as a stimulus for the development of further successful collaborations between ApP and other scientific fields. It is for this reason that in Table 1, existing synergies are first categorised according to what scientists are trying to understand (Atmosphere, Earth, Ocean, Earthquakes, Biodiversity) and then according to the location of existing ApP infrastructures (Underwater/Ice, Underground, Atmospheric and Terrestrial).

It was also considered important to distinguish synergies where ApP infrastructures are used to

a) obtain high quality data or inspire the development of new instruments

or

b) test new theories.

Table 1 Existing Synergies between ApP and other sciences. Please note that in Section 3, the same colours will be used in the header of each page to indicate if the main infrastructure involved is Atmospheric and Terrestrial (green header), Underground (red header) or Underwater/ice (blue header).

	ATMOSPHERIC AND TERRESTRIAL	UNDERGROUND	UNDERWATER
UNDERSTANDING THE ATMOSPHERE	1. SPACE WEATHER (Section 3.1.1) 2. ATMOSPHERIC MONITORING (Section 3.1.2) 3. COSMOCLIMATOLOGY (Section 3.1.3) 4. THUNDERSTORMS and LIGHTNINGS (Section 3.1.5)	1. COSMOCLIMATOLOGY (Section 3.1.3)	1. ATMOSPHERIC TEMPERATURE VARIATION (Section 3.1.4)
UNDERSTANDING THE EARTH	1. EROSION RATE CALCULATION (Section 3.2.1) 2. VOLCANO TOMOGRAPHY (Section 3.2.5)	1. COASTAL ROCK CLIFF EROSION (Section 3.2.2) 2.CHRONOLOGY for THE PALEOENVIRONMENT (Section 3.2.3) 3. EARTH's INTERIOR - GEONEUTRINOS (Section 3.2.6)	1. PALEOCLIMATE (Section 3.2.4) 2. EARTH RADIOGRAPHY (Section 3.2.7)
UNDERSTANDING THE OCEANS		1. CORAL CHRONOLOGY (Section 3.3.6)	1. CONTINUOUS OCEANOGRAPHIC DATA (Section 3.3.1) 2. SEDIMENT TRANSPORT (Section 3.3.2) 3. OXYGEN DYNAMICS (Section 3.3.3) 4. RADIOACTIVITY (Section 3.3.4) 5. INTERNAL WAVES (Section 3.3.5)
UNDERSTANDING EARTHQUAKES	1. EARTHQUAKE MONITORING GRID (Section 3.4.1)	1. SEISMO-ELECTROMAGNETIC COUPLINGS (Section 3.4.4) 2. EARTHQUAKE PRECURSORS (Section 3.4.5) 3. SLOW EARTHQUAKE MONITORING (Section 3.4.6)	1. EARTHQUAKE AND TSUNAMI MONITORING (Section 3.4.2) 2. STUDYING THE LAKE ENVIRONMENT (Section 3.4.3)
UNDERSTANDING BIODIVERSITY		1. IMPACT OF RADIATION (Section 3.5.7) 2. EXTREMOPHILES (Section 3.5.8)	1. UNDERWATER SOUND MONITORING (Section 3.5.1) 2. DEEP SEA BIOLUMINESCENCE (Section 3.5.2) 3. BIODIVERSITY UNDER ICE (Section 3.5.3) 4. BIODEGRADATION (Section 3.5.4) 5. MICROBIOLOGY (Section 3.5.5) 6. BIOFOULING (Section 3.5.6)
APPLICATIONS		1. WINE DATATION (Section 3.6.1) 2. SALT CHARACTERISATION AOC (Section 3.6.2) 3. SOFT ERROR RATE IN ELECTRONICS (Section 3.6.3) 4. ROCK DEFORMATION (Section 3.6.4)	

2. ApP RESEARCH INFRASTRUCTURES

2.1. DETECTING THE COSMIC RAIN

High energy *gamma* and *cosmic rays* coming from space are mostly absorbed by the Earth's atmosphere, i.e. collide with nuclei, mainly oxygen and nitrogen, to produce a cascade of secondary particles called an *extensive air shower (EAS)*. Consequently, gamma- and cosmic-ray astronomy could not detect directly gamma and cosmic rays until it was possible to get the detectors above the whole or most of the atmosphere using balloons or spacecraft. Nowadays very energetic gamma and cosmic rays can also be detected indirectly by ground-based experiments measuring *Cherenkov* or *fluorescent light*.

Three experiments represent a new generation of devices capable of doing so with unprecedented precision. The European experiments **H.E.S.S.** and **MAGIC** have already opened a new and unique spectral window on the universe. In the Southern hemisphere, **H.E.S.S.** (High Energy Stereoscopic System)[3] is a system of Imaging Atmospheric Cherenkov Telescopes (IACTs) located in Namibia. It investigates gamma rays in the 100 *GeV* to 100 *TeV* energy range.

H.E.S.S is an array of four 13-metre Cherenkov telescopes, 120 meters apart in Namibia. (Credit: H.E.S.S collaboration / ASPERA)

In the Northern hemisphere, **MAGIC** (Major Atmospheric Gamma-ray Imaging Cherenkov Telescope)[4] is a system of two IACTs situated on La Palma, Canary Islands, at about 2,200 m above sea level. **MAGIC** detects particle showers released by gamma rays with energies between 50 GeV and 30 TeV.

H.E.S.S., **MAGIC** and the dominant US counterpart **VERITAS (Very Energetic Radiation Imaging Telescope Array System)**[5] have increased the number of known high energy sources by an order of magnitude in the last four years.

The Pierre Auger observatory consists of 1,660 detectors distributed on a 3,000 square kilometres area in Argentina (Credit: Pierre Auger collaboration / ASPERA) .

While much progress has been made in understanding cosmic rays with low to moderate energies, those with extremely high energies remain mysterious. The **Pierre Auger Observatory**[6] is a detector that spreads over an area of 3,000 m^2 that is studying these ultra-high energy cosmic rays, the most energetic and rarest of particles in the universe. Completed in 2008, the **Auger Observatory** has already collected more data on particles with energies above 10^{19} eV than any other experiment and is the largest instrument of its type currently in operation. Observatories of much larger area are essential for progress in the field.

All three of these experiments rely on an accurate understanding of atmospheric phenomena. As a consequence, it is of paramount importance that Astroparticle Physicists invest in the improvement of the precision of existing atmospheric monitoring techniques. For example, the Auger Observatory

[3] http://www.mpi-hd.mpg.de/hfm/H.E.S.S./
[4] http://magic.mppmu.mpg.de/
[5] http://veritas.sao.arizona.edu/
[6] http://www.auger.org/index.html

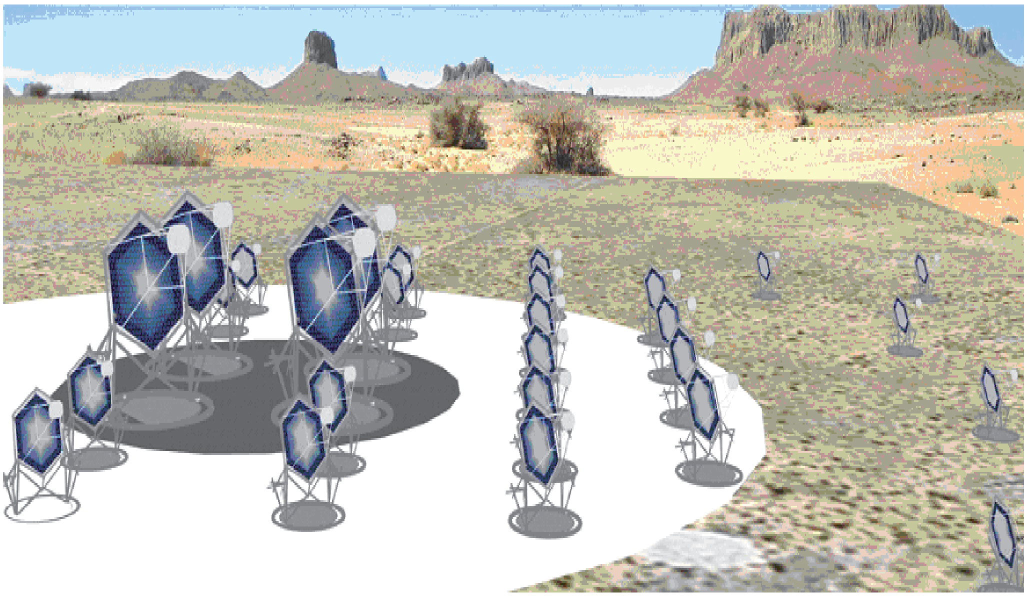
measures the chemical composition of very high energy cosmic rays from observations of the longitudinal development of the particle cascade in the atmosphere. These profiles differ between light and heavy primary particles and their differences have to be distinguished from those caused by seasonal and short-term variations of the atmospheric profile and/or by the rapidly changing atmospheric aerosol content (see Section 3.1.2).

Similar problems are encountered with the energy determination of cosmic rays at the **Auger Observatory** and with gamma rays detected by **H.E.S.S.** and **MAGIC**: the aerosol distribution and their attenuation properties are crucial factors in the energy determination of the detected gamma rays, which in turn affects scientific results such as the measurement of the extragalactic background light produced by the first stars.

The experience gained in atmospheric monitoring will be also used in the R&D for future projects such as the **Cherenkov Telescope Array (CTA)** [7], thereby maintaining the European lead in **ApP.** **CTA** will be a next generation ground-based very high-energy gamma-ray instrument, with an array of dozens of telescopes. It will serve as an open observatory to a wide astrophysics community and will provide a deep insight into the non-thermal high-energy universe. **CTA will offer an increase in sensitivity of between a factor** of five and ten over current instruments, and extend the energy range of the gamma rays observed. It is envisaged that **CTA** will consist of a southern hemisphere array, aimed at observations of Galactic sources, and a northern hemisphere array, optimised for extragalactic observations.

A second point of convergence with atmospheric science is located in the technologies developed for the purposes of the observatories. For instance, the **Pierre Auger Observatory** has deployed a relatively dense grid (step of 1.5 km) covering a very large area (3,000 km^2) with autonomous (solar powered), intelligent (local processing) and synchronised (GPS) sensors. Powerful data acquisition systems have been developed that are robust to the changes of geometry and number of nodes of the network. This system exhibits a series of technological solutions with large application potential to, for example, networks developed for ground and underwater seismic monitoring (see Section 3.4.1).

For both of these reasons, the opportunities that arise from the use of the infrastructures for gamma- and cosmic-ray exploration by scientists from other disciplines for the understanding of our atmosphere will have great societal implications: the effects of climate change, earthquakes, erosion, volcanoes and lightning will affect our future and that of our planet. Some of these opportunities are described in this report (first column of Table 1).



Artist's view of CTA. Large mirrors in the centre collect enough light to catch dim showers from low-energy gamma rays. To obtain large statistics at high energies where particles are rare but the associated showers are bright, smaller mirrors cover an area of a few square kilometres (Credit: ASPERA / D. Rouable)

[7] http://www.cta-observatory.org/

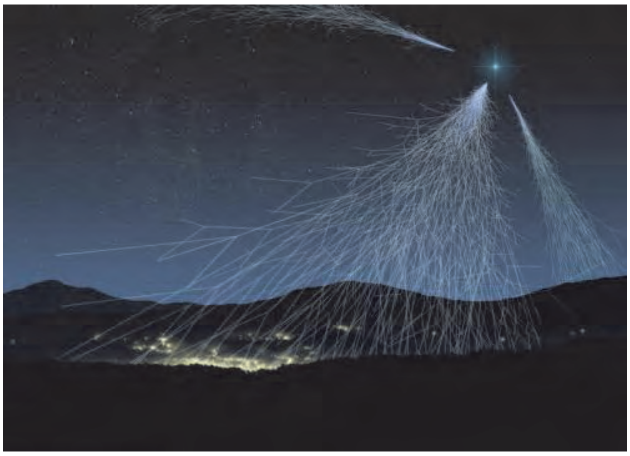
2.2. COSMIC SILENCE TO LISTEN TO THE PAST

"Master, while you are trying to pry into the mysteries of the sky, you overlook the common objects under your feet."

Remarked Thales's servant with a chuckle, when Thales had stepped majestically into a well.

In order for Astroparticle Physicists to detect the strange and illusive fundamental particles of our Universe, they need instruments shielded from the cosmic rays that constantly bombard us from stars, supernovae and distant galaxies, but also from the rest of the surrounding natural radiation, such as gamma-rays, X-rays, alpha particles, neutrons and photons. All these sources of noise can result in misleading signals or conceal the signals we are looking for. As a result, Astroparticle Physicists have been investing in accurately determining the characteristics of the coupled hydrological, mechanical, chemical and biological properties of the subsurface environment to assure that the background of their experiments is completely noise free.

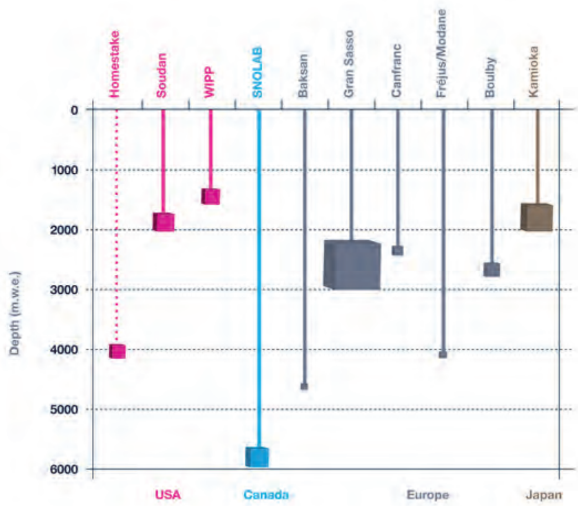
Hence, these instruments can provide unique opportunities to address central questions in modern earth science, geology, volcanology, hydrology, biology and engineering in an environment free of the background noise inherent to doing science at the Earth surface.



Before reaching the Earth's surface, cosmic ray messengers interact with the constituents of the atmosphere, changing their nature and energy. A large variety of secondary particles, which decay or make new collisions, is produced. (Credit: L.Bret / Novapix /ASPERA)

Interdisciplinary platforms have been developed in six European underground facilities that were developed for **ApP**, four of which (**Gran Sasso** , **Canfranc**, **Modane** , **Boulby** – see map below) can be regarded as fully operational scientific infrastructures. These infrastructures differ in depth[8], dimension and scope:

(a)



(b)

(a) Map of Europe showing the underground ApP laboratories. Operational infrastructures in red. (b) Diagram showing the depths (in terms of metre water equivalents – m w.e.) of the four operational underground laboratories as compared to other underground facilities in the rest of the world (Credit: (a) ASPERA (b) taken from the Deep Science (2006) report DUSEL)

[8] The Baksan Laboratory depth corresponds to the planned extension.

Digging the Gran Sasso Underground Laboratory (Credit: INFN / ASPERA).

The largest underground laboratory in the world is by far the **Gran Sasso Underground Laboratory**[9], in the North of Italy, with a total underground area 17,000 m^2 (volume: 180,000 m^3), on average 3,800 m w.e. underground. The laboratory encompasses three main halls plus ancillary tunnels, providing space for services, plants and smaller-scale experiments. The current ApP experimental program at **Gran Sasso Underground Laboratory** is very rich, including CERN to **Gran Sasso** beam experiments (**OPERA** and **ICARUS**), neutrinoless double beta decay searches (**CUORE**, **GERDA** and **COBRA**), dark matter searches (**DAMA/Libra**, **WArP**, **CRESST** and **XENON**) and solar and geo-neutrinos (**BOREXINO**). The laboratory is already supporting small-scale measurements on geology, biology and environmental issues.

The **Laboratorio Subterràneo de Canfranc**[10] (**LSC**) in the Spanish Pyrenees was created in early 1980s, but was recently expanded thanks to a new parallel road tunnel. The **LSC** now contains two main halls of surface area 600 m^2 and 150 m^2 respectively, plus ancillary tunnels and services (e.g. clean room), all of which at about 2,400 m w.e. depth. Six experiments have been approved by the International Scientific Committee, on neutrinoless beta decay (**BiPo** and **NEXT**), dark matter searches (**ANAIS** and **ROSEBUD**), low-background assays for liquid scintillators (**SuperK-Gd**) and geo-dynamics (**GEODYN**).

View of Hall A of LSC (Credit: LSC)

While the **Gran Sasso Underground Laboratory** is the largest in the world, the **Laboratoire Subterrain de Modane**[11] (**Underground Laboratory of Modane, LSM**) in South France is currently the deepest underground infrastructure, its minimum rock overburden being 4,000 m w.e. (average overburden: 4,800 m w.e.). Its total surface area is about 400 m^2 and it is composed of a Main Hall, a 70 m^2 Gamma Spectrometry Hall, and two secondary halls (18 m^2 and 21 m^2). At the moment, **EDELWEISS-II** for dark matter search and **NEMO3** for neutrinoless beta decay are both placed in the **LSM**. The low-radioactivity counting facility and the 13 HPGe low-background detectors hosted in the Gamma Spectrometry Hall are regularly used for radio-assay and qualification of materials, not just for the ApP experiments but also by other sciences. The **DOMUS** project, is the planned extension of the laboratory by 60,000 m^3 in coincidence with the excavation of a new safety tunnel.

The LSM Main hall (Credit: LSM)

Last but not least, the **Boulby Palmer Laboratory**[12] **(BUL)**, in North-East of England, is another underground laboratory increasingly used for interdisciplinary research. Established in the early 1990s and located in a working potash and rock-salt mine, **Boulby** has a total laboratory area of about 1,500 m^2, including the most recently opened 120 m long 'Palmer Laboratory' located at about 1,100 m depth (2.805 m w.e.). **Boulby** hosts the Dark Matter search experiments **ZEPLIN-III** and **DRIFT-II.** It also hosts many multidisciplinary studies including **SKY**, a cosmoclimatology project. The **DEEP CARBON**, muon tomography 3D structural survey project, studies in ultra-low-background radio-ecology, life in extreme environments (extremophiles) and various geology and rock engineering studies. A unique aspect of the

[9] http://www.lngs.infn.it/
[10] http://www.lsc-canfranc.es/
[11] http://www-lsm.in2p3.fr/
[12] http://www.hep.shef.ac.uk/research/dm/boulby/info.php

Boulby Underground Laboratory is the rare, symbiotic partnership the science facility has with the mine owners Cleveland Potash Ltd, who provide underground space and many support services to enable the science to be carried out.

Boulby potash mine, which houses the Deep Underground Science Facility (Credit: Dave Eagle).

Each underground ApP infrastructure has specific characteristics that are beneficial for some interdisciplinary experiments and disadvantageous for others: rock types, loading conditions, temperature and fluid regime. In order to gain the most valuable insights into the underground world, a number of engineering, geoscience, biological and environmental sciences experiments need to take place in the context of international collaborations and at many different underground laboratories. As demonstrated by the examples of this report, such insights have already been obtained (second column in Table 1).

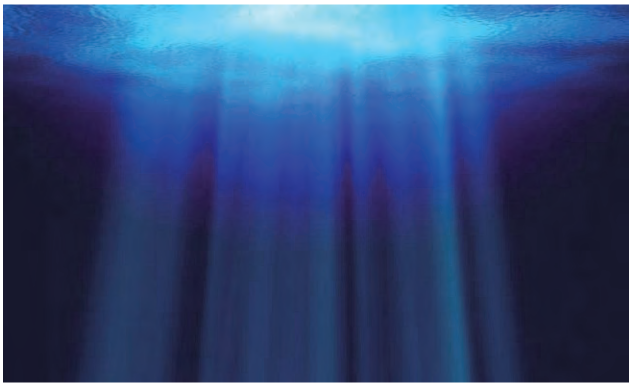
Finally, sharing of such exceptional infrastructures will lead to an efficient use of resources at many different levels: physical space (office space, computers and processors, conferencing facilities, housing, etc), personnel (not just scientific but also engineers and technical staff), services (internet access, specialised instruments etc), and dedicated experimental support (wet lab space, drilling equipment, etc), both above- and below-ground.

2.3.JOURNEY INTO THE DEEP

"If I were to choose a single phrase to characterize the first (20th) century of modern oceanography, it would be a century of under-sampling."
Walter Munk

Our understanding of the underwater world has been relatively limited for two main reasons. First, as stated in the quote above, we are lacking appropriate data. Remote sensing via satellites only covers the upper layer of the sea. Ships can only carry out episodic surveys, are constrained by weather and costs, and are having difficulties in sampling the time and space scales relevant for understanding marine ecosystems. Finally, moorings can provide data in real- or near real-time, but not for long periods.

A second constraint is the lack of appropriate models to synthesize and understand the ever increasing data collected around the world. Models are vital for depiction and understanding of the ocean and climate system, and their predictive ability has serious consequences, not only for future ocean research, but also for policy making. A variety of models exist, but so far these have been poorly linked and there is little quantitative understanding of error growth in these models.

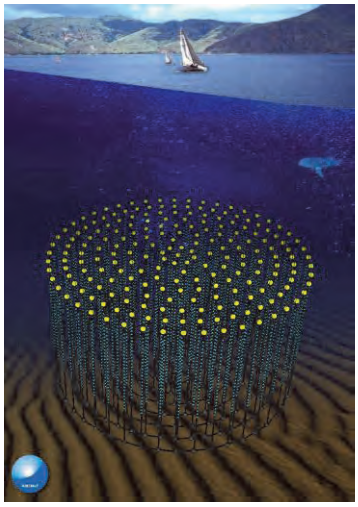


(Credit: Reactos Angelus Deepsea)

Thus, in order to achieve a safe, efficient, and environmentally sustainable use of the ocean, we need research infrastructures that are able to meet the global growing demands for scientific information, and share the knowledge between different disciplines on how to interpret the large amounts of data collected.

The current pilot *neutrino* telescopes in the Mediterranean Sea (**ANTARES**[13] in the Ligurian Sea, **NEMO**[14] in East Sicily and **NESTOR**[15] in the Hellenic Sea) are pioneering the development of permanent undersea observatories. Astroparticle Physicists needed to understand in detail the underwater environment of these detectors, so that these can be protected. They therefore developed high quality sensors that already provide real-time, high-bandwidth transmission of continuous measurements of oceanographic (current velocity and direction), geological (seismic), biological (optical and acoustic noise from sea organisms) and environmental (temperature, conductibility, salinity, pressure) parameters from sensors installed on the neutrino photomultiplier modules (PMTs).

The envisaged deep-sea (>2,000 m below sea level) neutrino telescope, **KM3NeT** [16], will be a next generation multidisciplinary observatory, offering a unique opportunity to explore a large range of properties of deep Mediterranean Sea over a period of many years.



Artist's conception of the KM3NeT telescope
(Credit: KM3NeT Consortium)

The installation of even more advanced specialised instrumentation on **KM3NeT**, will provide long-term measurements highly attractive to a wide field of sciences including biology, environmental sciences, engineering, geology, climatotology and oceanography.

[13] http://ANTARES.in2p3.fr/
[14] http://NEMOweb.lns.infn.it/index.php
[15] http://www.nestor.noa.gr/
[16] http://www.km3net.org

The modelling techniques already developed by Astroparticle Physicists in their *neutrino* detection quest will also be of value. Therefore, **KM3NeT** has the potential to play a key role in the multidisciplinary monitoring and assessment of the worldwide challenges of the 21st century, such as the effects of climate change. It is also important that **KM3NeT** and its pilot telescopes are all placed in the semi-enclosed Mediterranean Sea, a region that has been described as a "hotspot" for climate change, being highly reactive to variations in hydrodynamics, solar radiation, temperature, acidification, chemical contaminants, biodiversity, nutrient fluxes, stoichiometry, extreme events and biogeochemical fluxes.

Also in water but at the southeast corner of Siberia, at 1.1 km beneath the surface of the world's deepest and largest fresh-water lake, Baikal, lies the unique large telescope **Baikal NT-200**[17] - a neutrino telescope with 200 PMTs. The detector has a winter camp, from which they reach the PMTs by drilling through the winter ice cover. The objective of the Baikal Project is the creation of a kilometre-scale high-energy neutrino observatory, the **Gigaton Volume Detector (GVD)**. But Lake Baikal, surrounded by mountains, formed by converging rivers on a gaping continental rift created 25 million years ago, a 400-mile-long inland sea, has remained isolated from other water volumes. As a consequence unusual flora and fauna has evolved so independently that more than 65% of species living in the lake are thought to be found nowhere else on Earth. The neutrino detector, so deep beneath the lake surface, is a perfect instrument to measure the geological, biological among others properties of the lake and its surrounding areas.

The optical modules of the Baikal Neutrino Telescope. The main part of an optical module is a large (37 cm diameter) high sensitive QUASAR photo-tube. (Credit: the Baikal Project).

But it is not just water that has been used by Astroparticle Physicists as a Cherenkov light detector. Antarctic ice is both very thick and very transparent, so when a neutrino eventually interacts with an ice molecule, it will emit Cherenkov radiation that can be easily detected and its path be reconstructed. For these reasons, a cubic kilometre of pristine Antarctic ice is used as a lens in **IceCube**[18], an enormous observatory at the South Pole. Buried in this ice, to a depth of 2,452 meters, is an array of 5,160 detectors called DOMs (Digital Optical Modules) that look north, through the Earth, for neutrinos.

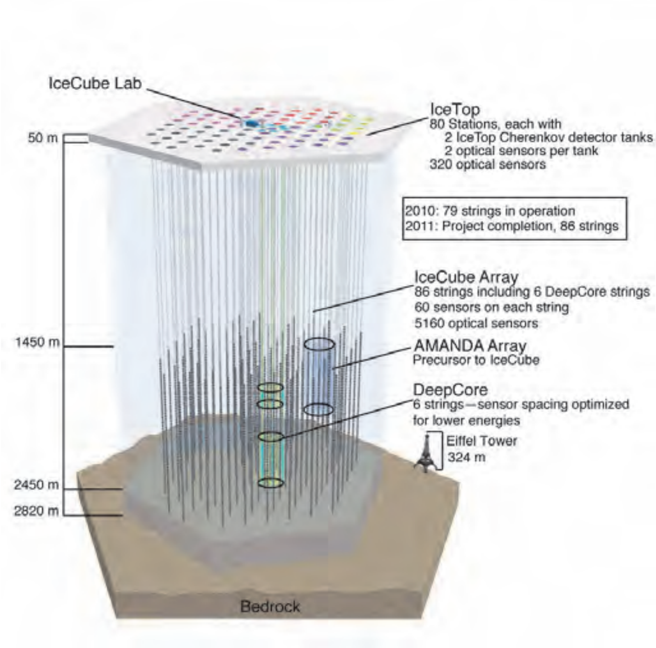


Diagram of the IceCube Neutrino Observatory
(Credit: IceCube Collaboration)

These and other underwater and under-ice synergies described in this report are listed in the third column of Table 1.

[17] http://baikalweb.jinr.ru/

[18] http://icecube.wisc.edu/

3. SYNERGIES

3.1. UNDERSTANDING THE ATMOSPHERE

The atmosphere protects life on Earth by absorbing solar radiation, by warming the surface and reducing temperature extremes between day and night. In order to anticipate atmospheric phenomena and events, it is essential to provide more accurate resolution of atmospheric processes. Enhanced understanding of the physical components of the atmospheric system, new predicting methodologies and powerful technologies have resulted in improved atmospheric simulations and predictions.

ApP infrastructures are contributing to these efforts. In Tibet, the **ARGO-YBJ** project studies gamma ray astronomy, but also investigates a way to foresee space magnetic storms (see Section 3.1.1). In Argentina, the **Pierre Auger Observatory** looks for high energy cosmic rays, but also measures continuously a variety of important atmospheric variables (temperature, pressure, humidity, clouds, aerosols, etc, see Section 3.1.2) and investigates lightning initiation (see Section 3.1.5). In Switzerland and the UK, the **CLOUD** and **SKY** experiments respectively, also study atmospheric aerosols and the effect of cosmic rays on them (see Section 3.1.3). Finally, in the South Pole, **IceCube** is used to measure atmospheric temperature variation (see Section 3.1.4).

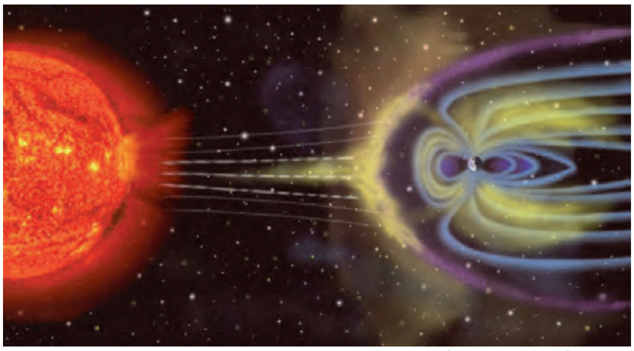
(Credit: Data: AVHRR, NDVI, Seawifs, MODIS, NCEP, DMSP and Sky2000 star catalog; AVHRR and Seawifs texture: Reto Stockli; Visualization: Marit Jentoft-Nilsen)

3.1.1. SPACE WEATHER

A different kind of weather

Our planet's magnetic field dominates the space environment near it, where blasts of solar wind, called Interplanetary Coronal Mass Ejections (ICMES), strike the magnetosphere causing disturbances or "magnetic storms". In this way, ICMEs drive massive currents in Earth's upper atmosphere, create brilliant auroras and cause fluctuations in the magnetic field. But what is the impact of these magnetic storms on our lives here on Earth?

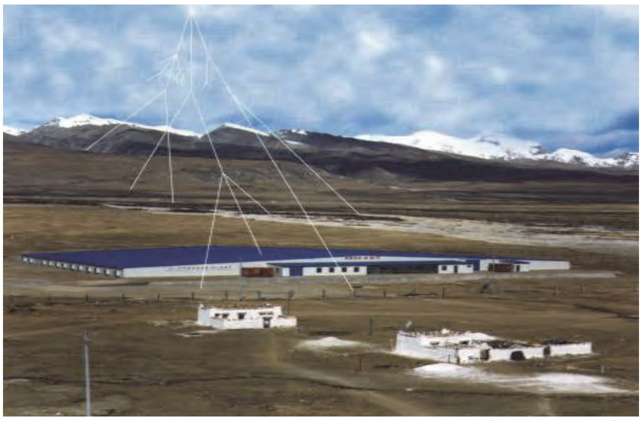
First, our dependence on satellites located in that same environment is increasing. By damaging our satellites, these storms can lead to loss of communication on the ground and large reparation bills. At the same time, magnetic storms can lead to electricity blackouts over large areas. These areas are going to become larger and larger as electrical power grids become more interconnected to improve efficiency.



Artist's rendition of Earth's magnetosphere (Credit: NASA).

For all these reasons, it is essential to develop accurate forecasting capabilities not only for the weather in our atmosphere, but also for magnetic storms caused by solar events. The **ARGO-YBJ** [19] (Astrophysical Radiation with Ground-based Observatory) experiment and the future project **LHAASO** [20] (Large High Altitude Air Shower Observatory) at YangBaJing in Tibet are dedicated to gamma ray astronomy above 300 GeV and cosmic ray physics above 10TeV up to 100PeV. ARGO-YBJ and the future LHAASO also aim to measure environmental parameters such as radon in the air, electric field in the atmosphere and aerosol distribution. At the same time, they are discovering a possible new method for space weather monitoring.

ICMEs release huge quantities of matter and electromagnetic radiation into space above the sun's surface, into the planet system or beyond. Exploiting the shadow cast by the Sun on very energetic cosmic rays, **ARGO-YBJ** is able to monitor the Interplanetary Magnetic Field (IMF), the part of the Sun's magnetic field that is carried into interplanetary space by the solar wind. When ICMEs begin their journey towards the earth, the IMF is enhanced and induces unexpected displacements and deformations of the Sun shadow, which can be detected with precision using **ARGO-YBJ**.



The Yangbajing High Altitude Cosmic Ray Laboratory (4,300 m.a.s.l.). showing the ARGO-YBJ detector, an air shower detector array covering an area of about 6,700 square metres in Tibet. (Credit: INFN / ASPERA)

Since cosmic rays are propagating with a speed of light, i.e. they are much faster than ICME, one can foresee a magnetic storm on earth two days before it arrives. The ARGO-YBJ detector cannot measure the Sun shadow with the required precision in a single day, however the large area LHAASO detector will be able to measure the Sun shadow within one day or so. Thus, it would be practically useful in monitoring unexpectedly large shifts of the sun shadow to foresee magnetic storms due to solar events approximately two days ahead of their arrival to the Earth.

Similarly, the count-rates of low energy cosmic ray particles are continuously monitored by the **Pierre Auger Observatory** yielding a particle rate of about 40 MHz. These data are used to study solar activity and space weather effects, such as Forbush-decreases. The 15 minutes time-average rates are made public via a web interface. Similar data are available also from the **IceCube** air shower array located at the South Pole and they complement an international network of neutron monitors distributed all over the world.

REFERENCES

ARGO-YBJ Collaboration (2011) "Mean interplanetary magnetic field measurement using the ARGO-YBJ experiment" *The Astrophysical Journal* **729**:113.

Pierre Auger Collaboration (2011) "The Pierre Auger Observatory scaler mode for the study of solar activity modulation of galactic cosmic rays" *JINST* **6**:01003.

IceCube Collaboration (2010) "Solar Energetic Particle Spectrum on 2006 December 13 Determined by Icetop" *The Astrophysical Journal* **689**:L65.

[19] http://argo.na.infn.it/

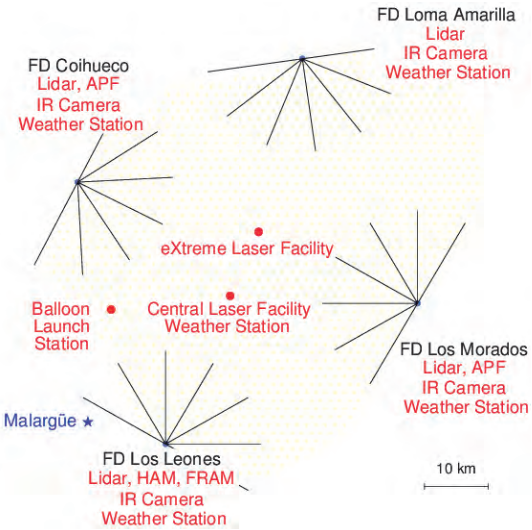
[20] http://english.ihep.cas.cn/ic/ip/LHAASO/

3.1.2. ATMOSPHERIC MONITORING

Atmospheric composition, structure, clouds, and aerosols

The **Pierre Auger Observatory** in Malargüe, Argentina is a facility for studying ultra-high energy cosmic rays using the atmosphere as the detector volume. The observatory consists of two major detector components: the Surface Detector (SD) – comprising an array of roughly 1650 water Cherenkov stations arranged in a triangular grid covering an area of 3000 km^2 – and the Fluorescence Detector (FD) – comprising 27 UV telescopes arranged to overlook the SD from four buildings at the edge of the array. The main component of each FD telescope is a spherical mirror that directs the collected UV light onto a camera of 440 hexagonal PMTs.

UV light (mostly within 290 - 420 nm) is emitted isotropically from atmospheric nitrogen molecules that have been excited by electrons of EASs. This faint light can only be observed at night when the signal from the air shower is not overwhelmed by moonlight. Additionally, strong wind and rainy conditions stop data taking in order to protect the FD telescopes. For guaranteeing an excellent reconstruction quality of the air shower observables, Astroparticle Physicists need to know as much as possible about their detector, with the atmosphere being its biggest part.



The SD stations (small grey dots) and the FD sites of the Pierre Auger Observatory close to the city of Malargüe. Also shown are the locations of the atmospheric monitoring instruments operated at the observatory (see text for details).(Credit: Pierre Auger Observatory)

Astroparticle Physicists installed a sophisticated atmospheric monitoring system supplementing the FD data acquisition to determine the atmospheric conditions during FD data taking. A list of monitors and their locations are shown in the figure above. Atmospheric state variables, like temperature, pressure, and humidity are mainly necessary for determining the fluorescence emission, but also for calculating the light transmission with respect to Rayleigh scattering. Atmospheric aerosol conditions are also measured, in order to describe the effect of Mie scattering in light transmission. Measurements of cloud coverage and height complete the set of atmospheric observables and are needed to identify absorption and reflections of fluorescence light by clouds.

The atmospheric monitoring system is composed of the following instruments:

- Meteorological radiosonde flights are regularly launched from the Balloon Launch Station and are used to measure the altitude profiles above the observatory of various atmospheric properties, such as air temperature, pressure and humidity. These properties affect the energy release of an air shower, the yield of nitrogen fluorescence emission and the light transmission towards the FD telescopes.

(Credit: Pierre Auger Observatory)

- Atmospheric conditions at the ground level (~ 1,400 m a.s.l.) are recorded every five minutes by a network of weather stations at each FD site and at the centre of the SD array. Since extensive meteorological data did not exist for the Malargüe site, members of the **Pierre Auger** collaboration started to perform their own measurements. Based on meteorological radio soundings ground-level measurements performed over several years, the collaboration created models of local seasonal variations of the atmosphere.

(Credit: Pierre Auger Collaboration)

– During FD data-taking, hourly aerosol depth profiles are derived by quarter-hourly shots of vertical UV laser tracks produced at the Central and eXtreme Laser Facilities (CLF and XLF) and observed by the FD telescopes. The aerosol optical depth profiles are a significant contribution to the air show reconstruction when determining the accurate primary energy of cosmic rays.

– In addition, aerosol and cloud measurements are performed by LIDAR stations (LIght Detection And Rangings, each consisting of an UV-laser and a PMT, and measuring aerosol content in the air backscatter) deployed at each FD telescope building. Currently the LIDAR data are mainly used for determining cloud coverage and cloud heights. At one FD site, a vertically-pointing Raman LIDAR test system has been installed to detect also the relative concentrations of N_2 and O_2.

– Two Aerosol Phase Function monitors (APFs) are installed at two FD sites. *A* collimated horizontal light beam from a Xenon flasher is shot in from of the FD telescopes. These detect the sideways-scattered light from which the phase function of the aerosol scattering process can be derived. The phase function for aerosols cannot be determined analytically since it strongly depends on the type, size, and shape of the aerosol content in air.

The LIDAR enclosure at Los Leones
(Credit: Pierre Auger Observatory)

– A Horizontal Attenuation Monitor (HAM) is used to determine the wavelength dependent attenuation of UV light caused by aerosols close to ground.
– A (F/ph)otometric Robotic Telescope for Atmospheric Monitoring (FRAM) was installed primarily to derive the wavelength dependence of the extinction caused by Rayleigh and Mie scattering by observing the brightness of stars.
– Furthermore, cloud coverage is measured by imaging the area above each FD station with Raytheon 2000B InfraRed Cloud Cameras (IRCC) being installed on the roof of each FD building. Every five minutes during data taking, the cloud coverage of the full field of view of each FD telescope is recorded.

Starting in spring 2009, the atmospheric monitoring of the **Pierre Auger Observatory** has been upgraded by a rapid atmospheric monitoring programme. Actual atmospheric profiles are measured shortly after the detection of particularly interesting air showers, such of very high energy or with unusual longitudinal developments. Three subsystems are participating in these observations: the meteorological radio soundings, the LIDARs, and the FRAM. The routinely observations by LIDARs and FRAM are temporarily discontinued after receiving a trigger for this rapid monitoring to allow dedicated scans of the atmosphere in the vicinity of the air shower within minutes after the event. For the radio soundings, a weather balloon used to be launched within about 3 hours after receiving a trigger. In particular, the data obtained by these radiosondes were used to test the suitability of a global atmospheric model for the application at the air shower reconstruction. Recently for example it has been found that the GDAS data (Global Data Assimilation System) from NOAA's National Centres for Environmental Prediction (NCEP) are a perfect replacement of local measurements since the GDAS data are freely available with a 3-hour resolution. Because of this, the rapid monitoring mode for radio soundings was terminated at the end of 2010.

It is not only high energy cosmic ray discovery that requires accurate monitoring of the atmospheric conditions. Gamma ray astronomy has been possible for many years now thanks to IACTs such as **H.E.S.S.** in Namibia, which also use the atmosphere as a detecting medium. Similarly to the **Auger Observatory**, **H.E.S.S.** is also monitoring the atmosphere, using radiosondes for the molecular profile (temperature, wind speed, etc) and LIDARs to investigate seasonality of the atmospheric aerosol loading.

Thanks to a collection of atmospheric monitoring data, the **Pierre Auger Observatory** and **H.E.S.S.** have accumulated large databases of atmospheric measurements. They have also developed new models for great-precision local atmospheric models. Both data and models will no doubt be useful to other disciplines, such as meteorology, climate science and atmospheric physics.

Aerosol and cloud monitoring research at **Auger Observatory** will be presented in more detail below.

REFERENCES

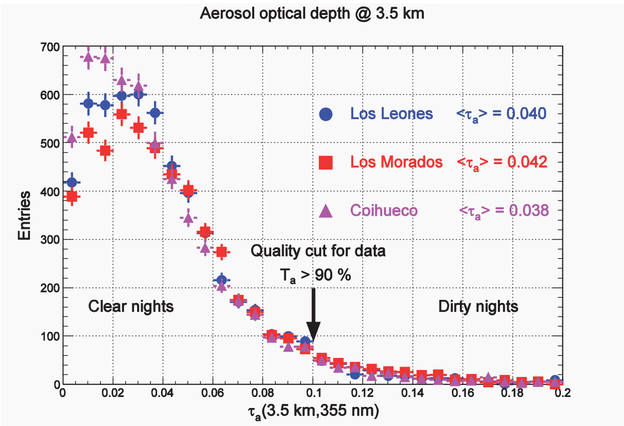
Keilhauer B for the Pierre Auger Collaboration (2010) "The Balloon-the-Shower programme of the Pierre Auger Observatory" *Astrophysics and Space Sciences Transactions* **6**:27–30.
Pierre Auger Collaboration (in press) "Description of Atmospheric Conditions at the Pierre Auger Observatory using the Global Data Assimilation System (GDAS)" *Astropart. Phys.*
Nolan SJ, Pühlhofer G and Rulten CB (2010) "Detailed studies of atmospheric calibration in imaging Cherenkov astronomy" *Astroparticle Physics* **34**(5): 304-313.

Measuring the sky's opacity: aerosols

In the late 19th and 20th century, attention turned from atmospheric chemical composition to the so-called trace gases and aerosol particles, since human actions and various natural feedback mechanisms were found to have substantial impacts on the complicated couplings amongst atmospheric aerosols, trace gases, air quality and climate.

Aerosols - tiny liquid or solid particles suspended in the atmosphere - in particular affect the quality of our life by influencing the Earth's radiation balance, directly through the scattering and absorption of solar radiation, and indirectly by acting as cloud condensation nuclei. In addition, aerosol particles modify the intensity and distribution of radiation that reaches the earth surface, in this way affecting the terrestrial carbon sink. So far, results have shown that natural aerosols are scarce with the exception of marine aerosols, but anthropogenic aerosols are not well-known or thoroughly measured, even if potentially they have high impact on the carbon cycle via the phytoplankton feed (greenhouse effect).

Better understanding and quantifying of the above aerosol effects require the development of advanced instrumentation and methodologies such as those developed by the **Pierre Auger Observatory** collaboration. An added advantage of measuring and validating atmospheric composition changes at this infrastructure is that it is located in the southern hemisphere, where there are relatively few aerosol profile instruments and measurements.

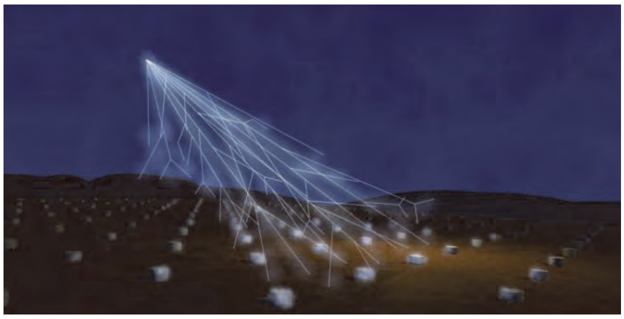


Aerosol measurements. Vertical aerosol optical depth at 3.5 km above the FD measured between January 2004 and December 2010 (from Louedec *et al.*, 2011).

The aerosol optical depth, i.e. the degree to which aerosols prevent the transmission of light, is deduced at the **Auger Observatory** by the CLF and the Raman LIDARs. In the case of CLF, a database for aerosol optical depth has been created that contains around 18,000 profiles at 3.5 km above ground. As shown in the graph above, the aerosol optical depth (using transmission τ_a as a proxy) is typically low above the **Pierre Auger Observatory** site, meaning that the majority of days are clear.

LIDARs (located at Los Leones, one of the four FD sites) also measure the vertical profile of the aerosol optical depth. A relative high content of aerosols was found in late winter and early spring, which could possibly be due to an increased occurrence of dust storms. Further data are needed to understand this regional seasonal pattern.

The data collected so far by both of these instruments have shown that variations in aerosol conditions have a greater effect on air shower measurements than variations in pressure, temperature or humidity. Furthermore, it has been shown that the density profiles of aerosols, as well as their size, shape and composition, vary quite strongly with location and in time. Moreover, depending on local particle sources (dust, smoke, etc.) and sinks (wind and rain), the density of aerosols can change substantially from hour to hour. Thus, if not properly measured, such dynamic conditions can bias cosmic ray shower reconstructions.



Artistic view of the Pierre Auger Observatory
(Credit: ASPERA/G.Toma/A.Saftoiu)

Finally, the sensitivity limits of the Raman LIDAR sampling can be studied at the **Pierre Auger Observatory** in order to improve the understanding of the technique. This is because the standard atmospheric Raman LIDARs are usually deployed where the aerosols are abundant, whereas at the Auger Observatory aerosol levels are low, as shown by the CSF data (see figure on the left).

REFERENCES

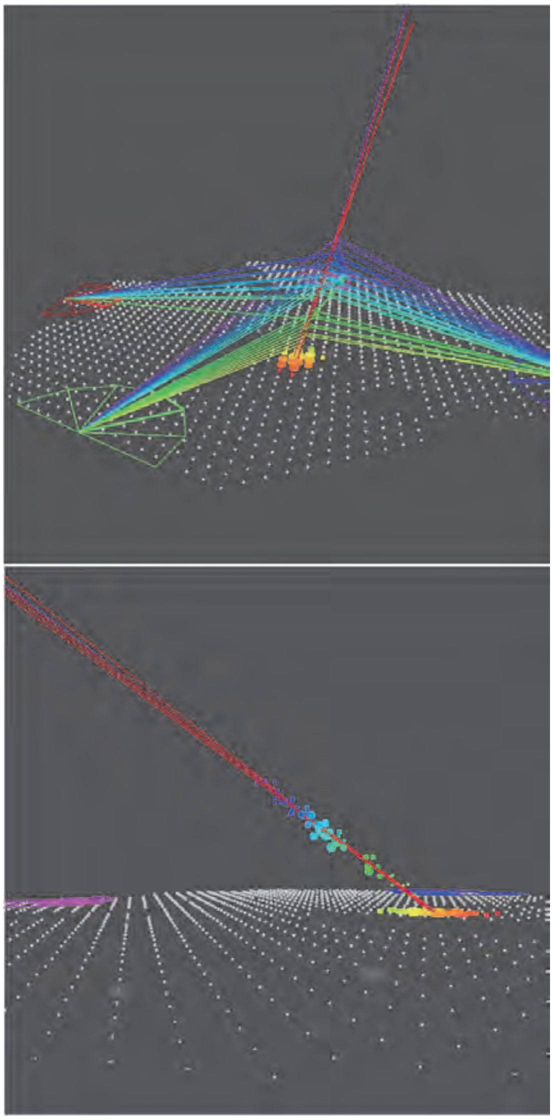
Pierre Auger Collaboration (2010) "A study of the effect of molecular and aerosol conditions in the atmosphere on air fluorescence measurements at the **Pierre Auger Observatory**" *Astroparticle Physics* **33**:108–129.

Louedec K for the Pierre Auger Collaboration (2011) "Atmospheric Monitoring at the Pierre Auger Observatory – Status and Update" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

Cloud micro-physics

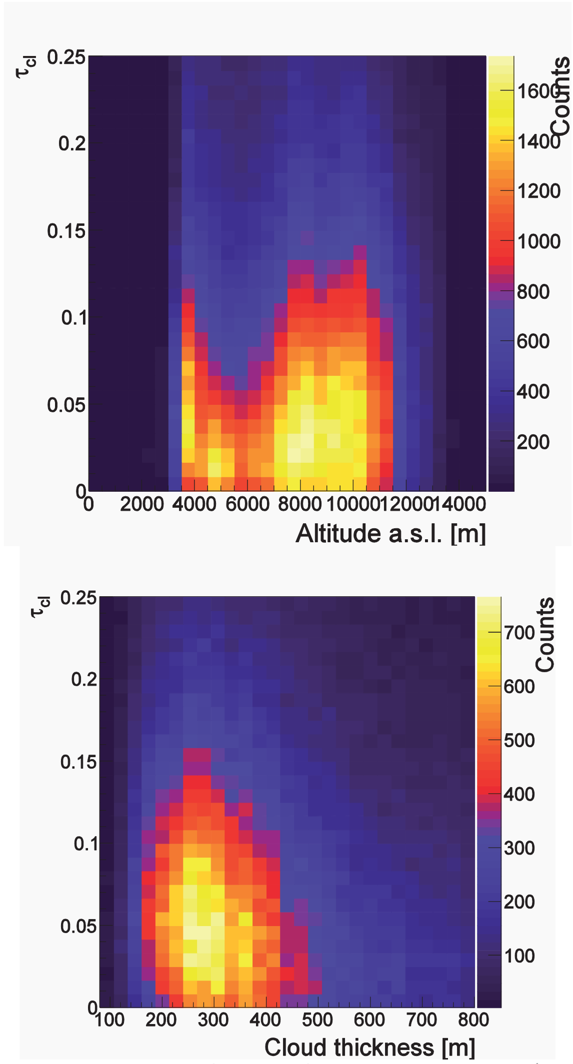
Both our uncertainty of what are the details of the relation between clouds and climate and the fact that the role of atmospheric electricity in solar variability and cloud processes have not been explored thoroughly, have lead to an increase in research in the field of cloud physics.

For Astroparticle Physicists, determination of the composition of clouds is essential since clouds are a major influence on the reconstruction of cosmic ray air showers by blocking the transmission of light, or enhancing the observed light flux due to multiple scattering of the intense Cherenkov light beam (see Figure below). Determination of cloud composition, however, is not trivial.



Shower light profile (seen by four FDs) with a large gap due to the presence of an intervening cloud.(Credit: Pierre Auger Collaboration)

In the **Pierre Auger Observatory** in Argentina, cloud coverage is recorded by Raytheon 2000B IRCCs located on the roof of each FD building. Since IRCCs cannot determine cloud heights, LIDAR stations are also used to observe clouds over each FD site producing hourly two-dimensional scans of the atmosphere such as the ones below, where cloud optical depth is plotted as a function of cloud layer altitude and thickness.



Cloud optical depth as a function of altitude and thickness. (Credit: Aurelio Tonachini)

REFERENCE

Pierre Auger Collaboration (2010) "A study of the effect of molecular and aerosol conditions in the atmosphere on air fluorescence measurements at the **Pierre Auger Observatory**" *Astroparticle Physics* **33**:108–129.

3.1.3. COSMOCLIMATOLOGY

Do cosmic rays influence cloud formation?

The **CLOUD** experiment at CERN and the **SKY** experiment at **Boulby Underground Laboratory (BUL)**, have been designed to study the effect of cosmic rays on the formation of atmospheric aerosols under controlled laboratory conditions. Increases in atmospheric aerosol particles cool the climate by reflecting more sunlight and by forming additional cloud drops, thereby making clouds brighter.

The increased amount of aerosol in the atmosphere caused by human activities is thought to have offset a large fraction of the warming caused by greenhouse gases. By current estimates, about half of all cloud drops are formed on aerosol particles that were "nucleated". Nucleation, i.e. the process of producing aerosol particles from the clustering of trace atmospheric molecules (rather than direct emission into the atmosphere) is therefore likely to be an important determinant of climate. However, the physical mechanisms of nucleation are not understood, so global models have been based on theoretical calculations or have been adjusted to match observations. **CLOUD** and **SKY** aim to understand the nucleation process and therefore provide reliable aerosol physics to reduce the uncertainty in climate forcings and projections.

The **CLOUD** experiment consists of a state-of-the-art chamber in which any part of the troposphere can be simulated under highly-controlled conditions, including unprecedented suppression of contaminants and precise control of the trace vapours that drive aerosol formation. A beam of particles from CERN's Proton Synchrotron accelerator provides an artificial and adjustable source of cosmic radiation.

The first published **CLOUD** results show that trace vapours assumed until now to account for aerosol formation in the lower atmosphere can explain only a tiny fraction of the observed atmospheric aerosol production, and that ionisation from cosmic rays significantly enhances aerosol formation under all conditions studied so far. Cosmic rays significantly enhance the formation of aerosol particles in the mid troposphere and above, and some of these new particles will eventually grow large enough to be seeds for clouds.

Trace sulphuric acid and ammonia vapours are thought to be important in the nucleation process and are used in all atmospheric models, but the mechanism and rate by which they form clusters together with water molecules have remained poorly understood until now. The **CLOUD** results show that a few kilometres up in the atmosphere sulphuric acid and water vapour can rapidly form clusters. They also show that cosmic rays enhance the formation rate by up to ten-fold or more. However, in the lowest layer of the atmosphere, within about a kilometre of Earth's surface, the **CLOUD** results show that additional vapours such as ammonia are required.

Crucially, however, the **CLOUD** results show that sulphuric acid, water and ammonia alone – even with the enhancement of cosmic rays – are not sufficient to explain atmospheric observations of aerosol formation. Additional vapours must therefore be involved, and finding out their identity will be the next step for **CLOUD**.

Precise measurements such as these are important in achieving a quantitative understanding of cloud formation, and will contribute to a better assessment of the effects of aerosol and clouds in climate models, as well as settling the open question of a possible influence of galactic cosmic rays.

REFERENCE

Kirkby J *et al.* (2011) "Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation" *Nature* 476: 429–433.
VIDEO: http://www.youtube.com/watch?v=63AbaX1dE7I

Fisheye view inside the 3-m CLOUD chamber through the lower manhole showing the UV fibre optic illumination and transparent HV electrodes (Credit: Maximilien Brice, CERN)

The **SKY** experiment at the **BUL**, UK, is also designed to explore the link between ionisation, aerosol growth and cloud formation. It too uses a chamber containing air and traces representing conditions in the earth's atmosphere, and uses external sources of radiation to simulate the effect of varying cosmic ray levels on aerosol nucleation and growth. The difference with **SKY** however is that is operates in a deep underground, low-background environment at the Boulby mine where ionisation from cosmic rays and other sources can be reduced to negligible levels so that ion-induced and 'neutral' aerosol nucleation and growth mechanisms can be studied separately and without the use of a 'clearing field'. The first **SKY** experiment 'SKY-ZERO' completed operation at **BUL** in 2010 and, as with **CLOUD**, confirmed the positive correlation between ionisation and aerosol nucleation. The next generation experiment 'SKY-II' designed to study the processes in more detail is now under construction and planned for installation at **BUL** in 2013.

SKY experiment at Boulby (Credit: Boulby Underground Laboratory)

3.1.4. ATMOSPHERIC TEMPERATURE VARIATION

A giant thermometer for the ozone layer

The **IceCube** *neutrino* observatory in Antarctica aims to detect high-energy neutrinos from astrophysical sources. It is also a cosmic-ray observatory, detecting more than 50 billion cosmic-ray *muons* per year. These downward muons produced by interactions of cosmic rays in the atmosphere above **IceCube** are a million times more numerous than the neutrino-induced muons from below, but the latter can be identified because the Earth is opaque to muons but not to neutrinos.

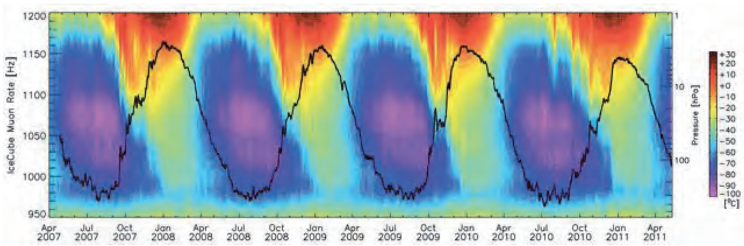
The observatory consists of a large array of optical modules in the ice at depths between 1,450 and 2,450 meters below the surface. Muon tracks are reconstructed by the arrival times of Cherenkov photons generated along the track, both for atmospheric muons from above and for neutrino-induced muons from below. Muons in the TeV energy range have sufficient energy to penetrate into and through the **IceCube** array from above. At these energies, the charged pions (subatomic particles) whose decay gives rise to the atmospheric muons more often interact once again in the atmosphere rather than decaying.

Because of this, TeV muons are produced primarily in the upper atmosphere, where the density is low. Moreover the probability of neutrino interaction is inversely proportional to the density and thus inversely proportional to the temperature, i.e. the warmer the atmosphere is, the less its density, the smaller the probability of pion interaction and the higher that of pion decay and muon generation. This temperature shows a strong seasonal variation over Antarctica, so variation in muon rates is ±10% between austral summer (November-March) and winter (April-October), and the relevant altitude region includes the ozone layer. The muon counting rate of 2.5 kilohertz is so high that the muon rate can track small changes in temperature on time scales of hours. For example, the motion of the polar vortex can be tracked: polar vortex is a persistent, large-scale cyclone in the stratosphere where temperatures drop, causing the formation of Polar Stratospheric Clouds that chemically alter the normally inert chlorofluorocarbons in forms that destroy the ozone layer.

IceCube also includes an array of detectors on the surface, which detect atmospheric muons in the GeV range. The re-interaction of TeV pions increases the number of low energy pions available to produce GeV muons. As a result, the collaboration found that the counting rate of the surface detectors has an opposite (and smaller) correlation with temperature.

In the summertime the Antarctic atmosphere is monitored by the NOAA Polar Orbiting Environmental Satellites and by the radiosonde balloon launches of the South Pole Meteorology Office. In the winter however, it is not possible to launch radiosondes and the temperature data are thus only estimates. Instead, **IceCube** background muon rates can be used from now on as a proxy of atmospheric temperature since when their data was compared to NOAA's measurements of atmospheric temperature, there was an extraordinarily high correlation.

The **IceCube** team has therefore a fascinating future in climate science ahead of them.



The daily atmospheric temperature profiles over the South Pole produced by NASA AIRS instrument on board the Aqua satellite[21] are shown from 2007 to 2011 (in colour code), along with the relative modulation in the measured muon event rate (black line) by IceCube. It displays the outstanding correlation of the high energy muon rate with the stratospheric temperatures.

REFERENCE

Tilav S *et al.* for the **IceCube** Collaboration (2010) "Atmospheric Variations as Observed by **IceCube**" Contribution to the 31st International Cosmic Ray Conference, Łódź, Poland, arXiv:1001.0776.

[21] http://disc.sci.gsfc.nasa.gov/AIRS/data-holdings

3.1.5. THUNDERSTORMS AND LIGHTNING

How is a lightning initiated?

Thunderstorms and lightning are some of the most extreme weather phenomena one can think of: there are 16 million lightning storms in the world every year, lightning strokes cause more deaths per year than any other weather phenomenon and commercial aircraft are struck by lightning once every 5-10 thousands hours of flight time. Although these figures are known for a very long time and have been the focus of many studies, the mechanism that leads to the final electric breakdown, i.e. lightning initiation, is still not well known.

Years of balloon, aircraft and rocket observations have shown thunderstorms never seem to make big enough electric fields to actually make a spark. One mechanism that could explain how a breakdown could happen with smaller electric field strengths are cosmic rays: cosmic rays could provide the seed electrons for a relativistic runaway electron avalanches. When cosmic rays strike the atmosphere they produce large showers containing millions of high-energy particles, mostly electrons, positrons and gamma-rays. If correct, then EASs should produce measurable radio frequency emissions. The flux of high energy cosmic rays is consistent with lightning frequency, but this theory is not yet proven.

A new project has recently started at the **Pierre Auger Observatory**, a large ground based detection array in Argentina. The Lightning Air Shower Study (LASS) uses an initial set of two Lightning Mapping Array (LMA) stations – with more being installed in 2012 – to search for time and spatial correlations between lightning and EASs. LMAs locate sources of impulsive very high frequency radiation events from time-of-arrival, measured at multiple ground locations and provide 3-dimensional images of lightning strokes inside storms. Using LMAs, LASS will therefore study the effect of strong electric fields on air showers but will also provide real-time data on storm and lightning activity over and around **Pierre Auger** for operational purposes.

It is interesting that cosmic-ray EASs may play a role, either by initiating lightning or as a tool for studying it. The LASS research is also important for the ApP infrastructure, since their sensitive electronics needed to observe the weak radio signals from cosmic-ray air showers are saturated by the strong signals from lightning strokes. LASS will thus be a study whose results will have wider implications beyond **ApP.**

Elves, discovered only in 1994, are another interesting and only partially understood phenomenon of the atmosphere. These are transient luminous events of about 1 ms duration and more than 600 km lateral extension, originating in the D-layer of the ionosphere, high above thunderstorm clouds, at an altitude of approximately 90 km. It has been demonstrated that elves, besides being detectable as optical and UV light emissions, also cause an increase of free electrons in the lower ionosphere. This increase in the local electron density, which has been estimated to be of the order of 5%, could have significant consequences on the chemical equilibrium over the elve hot zones. As a serendipity observation, the FDs of the **Pierre Auger Observatory** have provided accurate 3D measurements of elves at distances of about 800 km from the observatory. With an image sampling frequency of 100 ns the FD data will allow studying the elve evolution with an unprecedented time resolution thereby improving the understanding of the phenomenon.

Lightning, photographed by William Biscorner of Memphis, Michigan. (Taken from NASA website)

REFERENCES

Krehbiel PR *et al.* (2008) "Upward Electrical Discharges from Thunderstorms" *Nature Geoscience* **1**:233 – 237.

Tonachini AS for the Pierre Auger Collaboration (2011) "Observation of Elves with the Fluorescence Detectors of **the Pierre Auger Observatory**" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

3.2. UNDERSTANDING THE EARTH FROM THE SURFACE TO THE DEEP

The environmental conditions of earth are determined by physical, chemical, biological and human interactions that transform and transport materials and energy.
This is the "earth system": a highly complex entity characterized by multiple nonlinear responses and thresholds, with linkages between disparate components.
TD Jickells (2005)

Only 30 years ago, geoscience was principally occupied with plate tectonics. Great advances have been made since then, including a paradigm shift, a consequence of an increasing number of global environmental issues, such as climate change, sustainability and energy. Hence, geoscience currently heavily focuses on threats associated amongst others with the increasing CO_2 concentrations in the atmosphere (and the associated changes in climate and sea level), the reducing availability of oil and gas reserves at a time when demand is increasing rapidly, and the increasing scarcity of natural resources, such as metals and fertilisers, manifested as rapid increases in commodity prices.

To understand the challenges of geological origin we need to investigate the underground world. At present, this kind of research is hugely constrained by the lack of appropriate underground research facilities that can host experiments for monitoring of earthquakes and other natural hazards and for research on the extraction of energy sources and materials, on carbon dioxide storage, on mining technologies etc.

Geoscientists in collaboration with Astroparticle Physicists have attempted to answer a variety of questions. Members of the **CRONUS** collaborations study cosmogenic nuclides, in order to determine cosmic ray distribution on the surface of Earth as a means to study erosion rates (see Section 3.2.1). At the **Boulby Underground Laboratory**, located just next to the cliffs of North East England, scientists are studying the processes that shape cliff evolution (see Section 3.2.2). In another underground laboratory, the **Underground Laboratory of Modane** (**LSM**), it is investigated how sedimentary records be dated precisely (see Section 3.2.3). In the South Pole, **IceCube** is used for paleoclimate research (see Section 3.2.4) but also to carry out earth tomography (see Section 3.2.7). The Earth's interior is also studied in the **Gran Sasso Underground Laboratory**, specifically researchers are trying to understand the origins of mantle heating and heat convection (see Section 3.2.6). Finally, in Italy, the Lesser Antilles and France, the **MU-RAY**, **DIAPHANE** and **TOMUVOL** collaborations respectively are producing tomographies of volcanoes using muons (see Section 3.2.5).

In fact, geosciences are more similar to ApP than one might think at first. Both sciences are working from the nanoscale to universal scales. In addition, similarly to Astroparticle Physicists geoscientists develop new and unique subsurface probes, use advanced instrumentation for characterizing pore structure, fluid composition, mineral assemblages and microfluidics, and use physics instruments to determine molecular structure and composition. And since the earth is a complex system, geoscientists are challenging the existing computational methodologies in order to interpret their huge and complex data sets in order to predict impacts of various artificial and natural events before they occur.

An Alaskan Volcano Erupts (Credit: J. N. Williams/International Space Station 13 Crew/NASA)

3.2.1. EROSION RATE CALCULATION

Timing the history of the Earth's surface

Geomorphology, paleoseismology, paleoglaciology, volcanology, hydrology, paleoclimatology and many other sciences all need an improved understanding of geochronology at the Earth's surface. Cosmogenic nuclides – produced in near-surface rocks by secondary cosmic ray neutrons and muons from the atmospheric reaction cascade – offer many new possibilities for unravelling surficial histories and processes, through allowing the determination of surface exposure ages of rocks as well as modes of soil production.

One can measure radionuclides produced *in situ* from major target elements (e.g. ^{39}Ar, ^{14}C, ^{36}Cl, ^{26}Al, ^{10}Be) that penetrate near-surface rocks down to underground depths of ~300 m. Deeper rocks are shielded from the build-up of cosmic-ray transmutations. In fact, nuclide production decreases quickly with depth in rock, so it is possible to date changes in landscapes, i.e. the amount of time that has passed since geological events such as earthquakes, landslides and glaciers occurred.

Cosmogenic nuclides have already revealed how fast Earth's surface changes from such forces as erosion. Thus, for the first time quantitative investigations of long-standing first-order problems in the above fields are possible.

The ApP community helped to generate the present methodological framework for cosmogenic nuclides for geoscientists as a by-product of their research. Astroparticle Physicists are required to know exactly how cosmic rays are distributed on the surface of Earth, taking into account variables like longitude, latitude, and elevation, as well as changes occurring over geologic time scales, such as periodic shifts in Earth's magnetic field. Accelerator Mass Spectrometry (AMS) allows direct identification and measurement of the number of atoms of a nuclide in a sample, for several nuclides of interest. This new methodology has also lead to a reduction in the size of samples (resulting in both economy and simpler chemical processing), and in the time it takes for the measurements to be obtained.

Data taking in the context of CRONUS-Earth (Credit: CRONUS-Earth)

The methodology is continuously refined, recently by two international research consortia **CRONUS-EU**[22] (Cosmic-Ray Produced Nuclide Systematics-EU) and **CRONUS-Earth**[23]. Over a dozen new calibration sites have helped to improve our knowledge of nuclide production rates over the past 2,000 years, tests of previous and new (altitudinal and latitudinal) spatial scaling of production rates have been completed, and an empirical correction to previous estimates of muonic interactions is being realized. Their aim is to achieve the accuracy needed for pertinent research questions on the Earth's past climate cycles, changes in soil erosion, frequency of floods and landslides, and how weathering of rocks affects global warming and cooling.

The **CRONUS** collaborations work together sampling rocks from key sites around the world, exposing elements to nuclear beams in high-energy accelerators, and counting cosmic-ray impacts with detectors aboard high-altitude aircraft. The ApP community has the infrastructure as well as the expertise to help realize these efforts.

REFERENCES

Stuart FM and Dunai TJ (2009) "Advances in cosmogenic isotope research from CRONUS-EU" *Quaternary Geochronology* **4**: 435.
Lal D (2011) "Using Cosmogenic Radionuclides for the Determination of Effective Surface Exposure Age and Time-Averaged Erosion Rates" in Handbook of Environmental Isotope Geochemistry (ed. M. Baskaran), Advances in Isotope Geochemistry, Springer-Verlag, Berlin Heidelberg.
Gosse JC (2011) "Terrestrial cosmogenic nuclide methods: taming elephants in the room" *GSA Annual Meeting*.

[22] http://www.cronus-eu.net/
[23] http://www.physics.purdue.edu/primelab/CronusProject/cronus/Main/what.html

3.2.2. COASTAL ROCK CLIFF EROSION

Towards a protection of the endangered cliffs

Although cliffs form approximately 75% of the world's coastline, the understanding of the processes through which they evolve remains limited because of a lack of quantitative data on the morphological changes they undergo. This is partly due their evolution representing undoubtedly one of the most complex areas of geomorphology due to a combination of marine, subaerial and anthropogenic processes. In addition, coastal geomorphology is currently buoyed by the implied threats of climate change and sea-level rise, and by the conceptual and technical challenges of predicting morphodynamic behaviour at the all-important `engineering' scales.

(Credit: Boulby Underground Laboratory)

Durham University, Cleveland Potash Ltd. and One Northeast recently formed a collaboration in order to develop a geoscience facility in the Astroparticle Physics underground laboratory at the Boulby mine, in North-East Coast of England. The depth and location of the mine offer an experimental environment that is ideal for geological studies that demand isolated low-background conditions; high *in situ* stress states; well established geochemistry; and logistical support in an otherwise impossible-to-reach location.

The **BUL** Geoscience Group has been monitoring and modelling the processes and mechanisms of hard rock sea cliff evolution along the North Yorkshire coastline since 2002. The influence of waves and tides on cliff development has long been recognised as important contributor to coastline evolution. Moreover, the erosion of coastal rock cliffs poses significant challenges to shoreline management and hazard mitigation plans, requiring significant public financial expenditure. Nevertheless the relationship between waves and the resistance afforded by foreshore and cliff material remains inadequately quantified and poorly understood.

For all these reasons, the **BUL** Geoscience Group has developed innovative, high resolution methods to monitor rockfall volume. The installation of a novel cliff-face monitoring system and an array of cliff-top microseismic sensors has provided further insights into the effects of microclimate and wave energy delivery on rockfall behaviour. This approach uses a combination of terrestrial time-of-flight laser scanning with high-resolution terrestrial digital photogrammetry to generate high-quality data-sets.

The research findings have allowed the development of new models of coastal rock cliff change. The link between relative sea level and geomorphological work done by wave action is both spatially heterogeneous and tightly constrained by foreshore topography. These data highlight the need for a greater understanding of cliff behaviour if, in the context of sea-level rise, future coastal evolution is to be predicted.

View of the Boulby Cliff (Credit: Gordon Hatton)

REFERENCES

Lim M, Rosser NJ, Allison RJ, Petley DN and Keen M (2010) "Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire" *Geomorphology* **114**(1-2):12-21.

Lim M, Rosser NJ, Petley DN and Keen M (2011) "Quantifying the Controls and Influence of Tide and Wave Impacts on Coastal Rock Cliff Erosion" *Journal of Coastal Research* **27**(1):46-56.

3.2.3. CHRONOLOGY for PALEOENVIRONMENTAL RESEARCH

Fixing the clocks

Loss of biodiversity, disequilibria in nutrient cycles (Nitrogen and Phosphorus) and climatic change are together described by the now-well-known term of “global change”. “Global change” is a concept challenging to the scientific community since it implies knowledge of the undisturbed conditions of the environment prior to human destabilisation, in order to assess the intensity of the “change” and to evaluate the reaction of ecosystems.

Lake sediment, naturally accumulating at the bottom of lake basins, can help in addressing this challenge as they are made of biological and mineral particles marking the evolution of environment. This however requires the establishment of reliable chronological methodologies. In most cases, sedimentary records are homogeneous precluding a direct dating through annual layer counting. A number of different dating methods are currently used using radio-isotopes. Pb-210 (naturally emitted from continental land-masses) and Cs-137 (artificially injected by aerial atomic weapon tests or industrial nuclear accidents) are hence commonly used to date the last 100 years. However, conventional environmental *radioactivity* labs measuring gamma emission suffer from relatively high background, especially for low energy emissions such as the one of ^{210}Pb. Thus, paleolimnologists (scientists studying past lake system dynamics) are always looking for new accurate methodologies that may lead to more accurate and faster acquired lake chronologies. The **Underground Laboratory of Modane** (**LSM**) facility offers a perfect frame for this quest.

Lac du Bourget (Lake Bourget) is a lake in the Savoie department in South-East France. It is the largest (surface area 44.5 km^2) and the deepest (average depth 85 m) lake located entirely within France. In order to accurately reconstruct the evolution of both trophic state and hypolimnetic anoxia during the last century, geoscientists collaborated with Astroparticle Physicists from the **LSM** to carry out the radionuclide dating (^{210}Pb, ^{137}Cs and ^{241}Am) of sediments from this lake as part of a multivariable study: *radioactivity* is the main enemy of ApP experiments so physicists have invested in detectors capable of measuring very low radionuclide concentrations.

Collection of sedimentary carrots in the Alps in winter season (Credit: LSM)

^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am activities were measured by gamma spectrometry on one of two lake cores. These radionuclide measurements confirmed the annual rhythm of laminations in the upper sediment profile and allowed to date its lower part. Comparisons between different radionuclide dating methods and varve counts on two sediment cores lead to a chronology for the evolution of trophic state and deep-water anoxia in the lake: the onset of eutrophication and the first appearance of an anoxic facies occurred simultaneously in 1943±1 year in response to human–induced nutrient input.

Once one core has been dated, paleolimnologists are able to date others through a detailed stratigraphic correlation and to obtain increasingly sharp description of past environment. In the case of Lake Bourget, they were hence able to produce the first quantitative reconstruction of cyanobacteria abundance (some of them being highly toxic for humans), as tracked by their DNA archived in lake sediment. This promising study opens the era of a new way of studying ecological complex responses to multiple stressors using recent (< 100 years) lake sediments. This development will require more and more dating capacities. In this, the collaboration of paleoenvironmentalists and physicists around the LSM facilities is promised a brilliant future!

REFERENCES

Giguet-Covex C *et al.* (2010) “Sedimentological and geochemical records of past trophic state and hypolimnetic anoxia in large, hard-water Lake Bourget, French Alps” *Journal of Paleolimnology* **43**(1):171-190.

Savichtcheva O *et al.* (2011) “Quantitative real-time PCR enumeration of *Planktothrix* spp. and other Cyanobacteria in preserved DNA isolated from lake sediments” *Applied and Environmental Microbiology* **77**:8744-8753.

3.2.4. PALEOCLIMATE

How are volcanoes related to climate change?

Reliable paleoclimatic records and accurate knowledge of past variations of climate forcings, such as volcano eruptions, can be of great benefit to sophisticated climate models. Volcanic eruptions affect our planet's climate by emitting into the atmosphere large quantities of solid particles (ash) and gaseous substances which then enter the Earth's biochemical cycles.

Polar ice may be the purest solid substance on Earth, hence the few impurities it contains provide a rich record of Earth's past climate volcanism and allow us to determine the volcanoes' contribution to climate change.

Since the existence of dust layers, excreted by Antarctica's volcanoes (today there are at least two active volcanoes in the South Pole), can have a profound impact on achieving the best possible angular resolution of sources of high-energy neutrinos, members of the **IceCube** collaboration have used an optical dust-logging instrument that fits into the deep **IceCube** boreholes in glacial ice and provides signals from a rotating laser that sends pulses into the ice and records returned pulses as a function of depth.

The Dark Sector at the South Pole where many of the astrophysical experiments are located. At the bottom is the IceCube drill camp, which is building the neutrino detector under the ice. (Credit: Henry Malmgren/Antarctic Photo Library)

The optical dust logger is able to rapidly locate volcanic ash layers, record maxima and minima in the concentration of dust particles corresponding to glacial and interglacial climate, detect abrupt climate changes with a depth resolution of a few mm, and provide information about wind speed over the last 10,000 years. For the first time, the shear strain rate of a large volume of ice can be studied in three dimensions as a function of stress, impurity content and temperature down to -35°C.

Using this instrument, an apparent causal relationship between climate changes and faint volcanic fallout layers was detected. Surprisingly it was found that times of strong volcanic eruptions correlate strongly with onsets of global cooling. This correlation leads us to conclude that 'millennial-scale' global coolings are caused by a chain of events in which volcanoes emit ash particles rich in iron and sulphate, which supply phytoplankton in the Southern Ocean with normally missing nutrients, as a result of which they multiply, taking carbon dioxide out of the atmosphere.

In addition, abrupt changes in dust concentration with global temperature have been recorded. For example, a thick layer of high dust concentration at ~2,100 m has been recorded which corresponds to the glacial period that took place ~65,000 years ago. As a consequence, the dust log can serve as a proxy for global atmospheric temperature: high dust concentrations signal glacial periods. Using this technique, the bottom of the **IceCube** array was dated at between 90,000 and 100,000 years old.

Finally, a fully automated reconstruction of South Pole surface roughness was developed as a measure of past wind intensity, using dynamic warping feature recognition and internal consistency checks. It was found that South Pole surface roughness anticorrelated with curves of antarctic CO_2 and temperature, which could be connected through secular migrations of the Southern Hemisphere westerlies. This new paleoclimate signal may be direct evidence of atmospheric reorganization during the glacial period, helping to deconvolve the thermodynamics and biogeochemistry of climate change.

REFERENCES

Bay RC *et al.* (2010) "South Pole paleowind from automated synthesis of ice core records" *Journal Of Geophysical Research* **115**:D14126.

Martinez-Garcia A *et al.* (2011) "Southern Ocean dust–climate coupling over the past four million years" *Nature* **476**: 312-315.

3.2.5. VOLCANO TOMOGRAPHY using MUONS

Revealing the interior of volcanoes

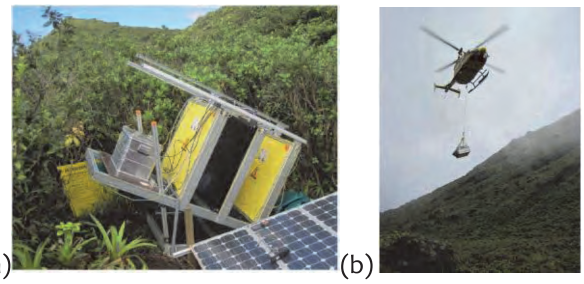
Muons come from the interaction of cosmic rays with the Earth's atmosphere and traverse layers of rock as thick as one kilometre at the same time being partially absorbed by the material they go through, much like X-rays. The greater the amount of matter they encounter on their journey, the greater the muon loss.

Thanks to recent progress made in **ApP**, compact and efficient solutions now exist to design and construct portable telescopes which can be operated under the difficult field conditions encountered on tropical volcanoes. Geoscientists placing these 'muon telescopes' on the slopes of volcanoes are thus able to detect the muon flux. When this is compared to a model determined using data on rock thickness crossed for the various angles of view, a muon tomography is obtained. But why is such a tomography needed? Muon tomographies provide a complementary tool to evaluate the present state of the volcano within its eruption cycle, estimate its evolution in the near future, and quantify the associated risk for surrounding inhabitants.

Three such projects already take tomographies of volcanoes present near populated areas. The **DIAPHANE**[24] project, which started in 2008, has already provided density profiles of underground structures (Mont-Terri project, Switzerland) and of active volcanoes (Soufrière de Guadeloupe, Etna). It is presently focusing on the Lesser Antilles, a subduction volcanic arc within which a dozen of either potentially or presently active volcanoes are located in populated areas and therefore require careful monitoring, with the deployment of a telescope on the Soufrière Hills of Montserrat.

The **MU-RAY (MUon RAdiographY)**[25] project at the Vesuvius volcano in Italy has an equally or even more challenging aim. From a technical point of view, performing muon tomography of Vesuvius is a challenge much beyond what has seen so far.

Finally, the **TOMUVOL**[26] collaboration is operating a muon telescope at the flank of the Puy de Dôme, an inactive volcanic dome in the Massif Central of South-Central France. After the first radiography with muons of the Puy de Dôme, the collaboration is currently focusing on taking a detailed three-dimensional map of the density distribution of the volcano and validate the results by comparing with ongoing gravimetric and electrical resistivity tomographies on the same site.



(a) Telescope on the slopes of La Soufrière in the first position. (b) The helicopter transportation that was used from one site to the other (Credit: Jacques Marteau).

REFERENCES

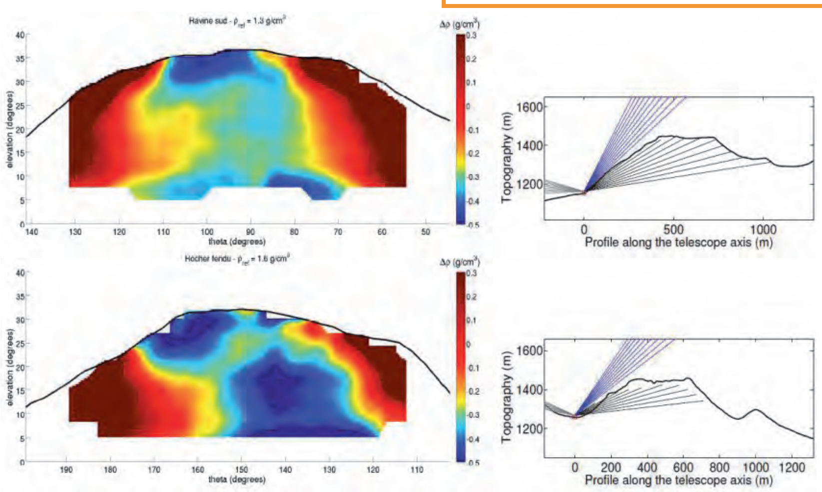
Lesparre N *et al.* (2011) "Design and Operation of a Field Telescope for Cosmic Ray Geophysical Tomography" *Geophysical Research Abstracts* **13**:EGU2011-5957.

Ambrosino F for the MuRay Collaboration Team (2011) "The MU-RAY project: volcanoes radiography with cosmic-ray muons" *Geophysical Research Abstracts* **13**:EGU2011-4764-2.

Gibert D *et al.* (2010) "Muon tomography : plans for observations in the Lessers Antilles" *Earth Planets and Space* **62**: 153-165.

Marteau J *et al*, (in press) "Muons tomography applied to geosciences and volcanology" *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, arXiv: 1201.6469.

Fehr F for the TOMUVOL Collaboration (2011) "Density Imaging of Volcanoes with Atmospheric Muons" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.



Density profiles obtained on two different views of la Soufrière de Guadeloupe and a sketch of the potential directions of sight (Credit: Jacques Marteau).

[24] http://sites.google.com/site/diaphanemuontomography/Home/diaphane-home-of-the-english-pages

[25] http://mu-ray.fisica.unina.it/

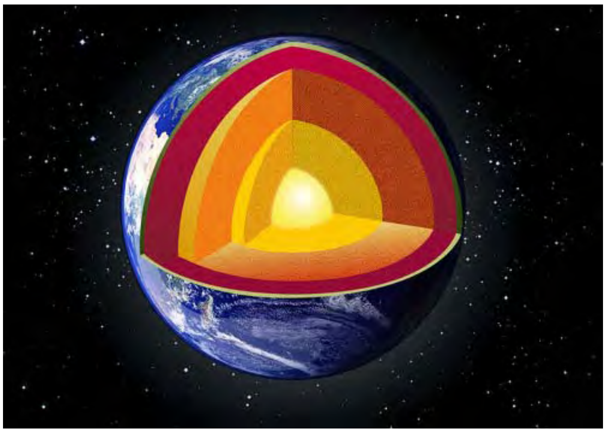
[26] http://www.tomuvol.fr/index.php

3.2.6. EARTH's INTERIOR using GEONEUTRINOS

What keeps the Earth heated?

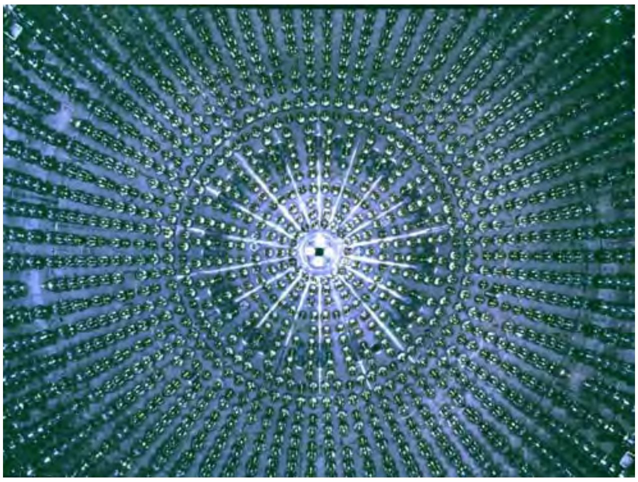
Even though Earth has cooled since it was formed, it has been estimated that its total thermal power is now 47.2 ± 2.0 terawatts. Radioactive decays of Uranium, Thorium and Potassium, long-lived radioactive isotopes present in the planet's interior, provide a continuing heat source, but their relative contribution to the planet's heat flux is uncertain. So far, information has come exclusively from indirect probes: seismology constrains the density profile, while geochemistry makes previsions based on chemical compositions of rocks from the upper layers of the Earth, chondritic meteorites, and the photosphere of the Sun.

In contrast, **BOREXINO**[27], an experiment based in **Gran Sasso Underground Laboratory** aims at the direct detection of the geo-neutrinos emitted by these radioactive decays with the same purpose. This experiment, contained inside an external, dome-shaped tank 16 metres in diameter beneath 1,400 metres of rock, 400 km away from the nearest nuclear power plant, is ideal for detecting a genuine signal of the Earth's natural radioactivity, making geo-neutrinos direct messengers of the abundances and distribution of radioactive elements within our planet. Furthermore, the study of geo-neutrinos constitutes the only direct method we know that allows us to study what happens deep within our planet, offering the opportunity to better understand the chemical composition, origin and evolution of the Earth.



The layers of the Earth: the thin upper crust, the viscous upper and lower mantle, the liquid core and the solid inner core. (Credit: ESRF)

This year, the **BOREXINO** collaboration opened a new viewport pointing directly to the interior of the Earth. Based on the analysis of two years of data, they obtained for the first time very clear evidence of the existence of geo-neutrinos and confirmed that radioactive decays contribute to more than 50% of the Earth's heat. This was also found by the **KamLAND** collaboration that uses a geoneutrino detector located in Japan, who combined its data on candidate antineutrino events with data from the **BOREXINO** experiment to calculate the contribution of uranium and thorium to Earth's heat production. They found that this was about 20 terawatts which meant that radioactive decay alone is not enough to account for Earth's heat energy. Whether the rest is primordial heat or comes from some other source is still an unanswered question.



The top of the BOREXINO detector showing the photomultipliers (Credit: INFN).

More experiments – some already under construction (**SNO+**) and others still in their R&D phase (**LENA**, **HANOHANO**) – will study geo-neutrinos as part of their scientific programme. If these experiments, which are located at different sites around the world, reach **BOREXINO**-class radiopurity, it might be possible to map the distribution of the heat in the mantle of the Earth, improving our understanding of volcanic activity and plate tectonics.

REFERENCES

Coltorti M *et al.* (2011) "U and Th content in the Central Apennines continental crust: A contribution to the determination of the geo-neutrinos flux at LNGS" *Geochimica et Cosmochimica ACTA* **75**(9): 2271-2294

Borexino Collaboration (2010) "Observation of geo-neutrinos" *Physics Letters B* **687**(4-5) : 299-304.

KamLAND Collaboration (2011) "Partial radiogenic heat model for Earth revealed by geoneutrino measurements" *Nature Geoscience* **4**: 647–651.

[27] http://borex.lngs.infn.it/

3.2.7. EARTH RADIOGRAPHY

Earth tomography with high–energy cosmic neutrinos

Neutrino radiography as an alternative tool to determine the internal structure of our planet – its density profile and the shape of the core, mantle and their boundary (CMB) - is not a new idea. Currently body-wave and free oscillation studies are used to obtain this information. These techniques may be more precise than *neutrino* radiography could be in the near future, but they are not able reduce ambiguities in models, such that at the present model of the CMB the trade off between density, temperature and chemical structure in the case of body wave studies increases uncertainty in density measurements and free-oscillation data can only reveal one dimensional structure.

Earth tomography with neutrinos can however provide information on the global structure of the CMB region. For energies around 25 TeV, the interaction length of atmospheric neutrinos, produced in collisions of cosmic rays with nuclei in the Earth's atmosphere is of the order of the Earth radius. For these neutrinos the Earth becomes opaque and hence they are able to sample the density profile along their path. Therefore, the detection using neutrino telescopes of the emerging charged leptons (mainly muons) versus the arrival direction, can be a promising approach for measuring at least some of the features of the Earth density profile.

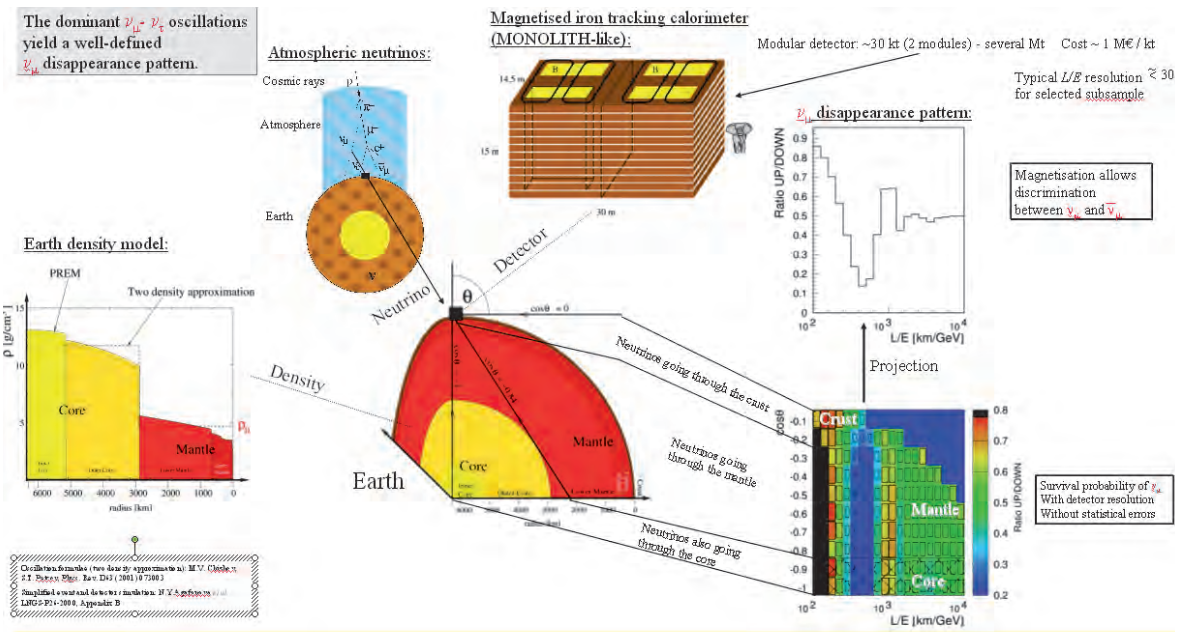
The development of cubic-kilometre underwater and under-ice neutrino detectors makes neutrino radiography possible. **IceCube**, already in its data-taking phase, is expected to confirm the averaged core and mantle densities as a function of longitude, in this way constructing the first independent global survey of CMB.

In the northern hemisphere, theoretical studies have indicated that in order to locate the CMB and calculate the averaged core and mantle densities, a one cubic kilometre neutrino detector like **IceCube** has to be operated for 10 years (with a 2% sensitivity in the case of the mantle density and 5% in the case of the core density). It is anticipated, however, that the operation of an even larger detector, like **KM3NeT** – the future large-scale underwater neutrino detector – will result in more precise global information on the CMB region.

REFERENCES

Miele G and Pisanti O (2011) "Neutrino Radiography" *Nuclear Physics B - Proceedings Supplements* **217**(1): 149-151.

Borriello *et al.* (2009) "Sensitivity on Earth Core and Mantle densities using Atmospheric Neutrinos" *JCAP* **06**:30 and arXiv:0904.0796.



Neutrino Oscillation Pattern (Credit: Geiser A, Kahle B (2002) "Tomography of the earth by the oscillation of atmospheric neutrinos: A study of principle". Poster presented at Neutrino2002, Munich, Germany.)

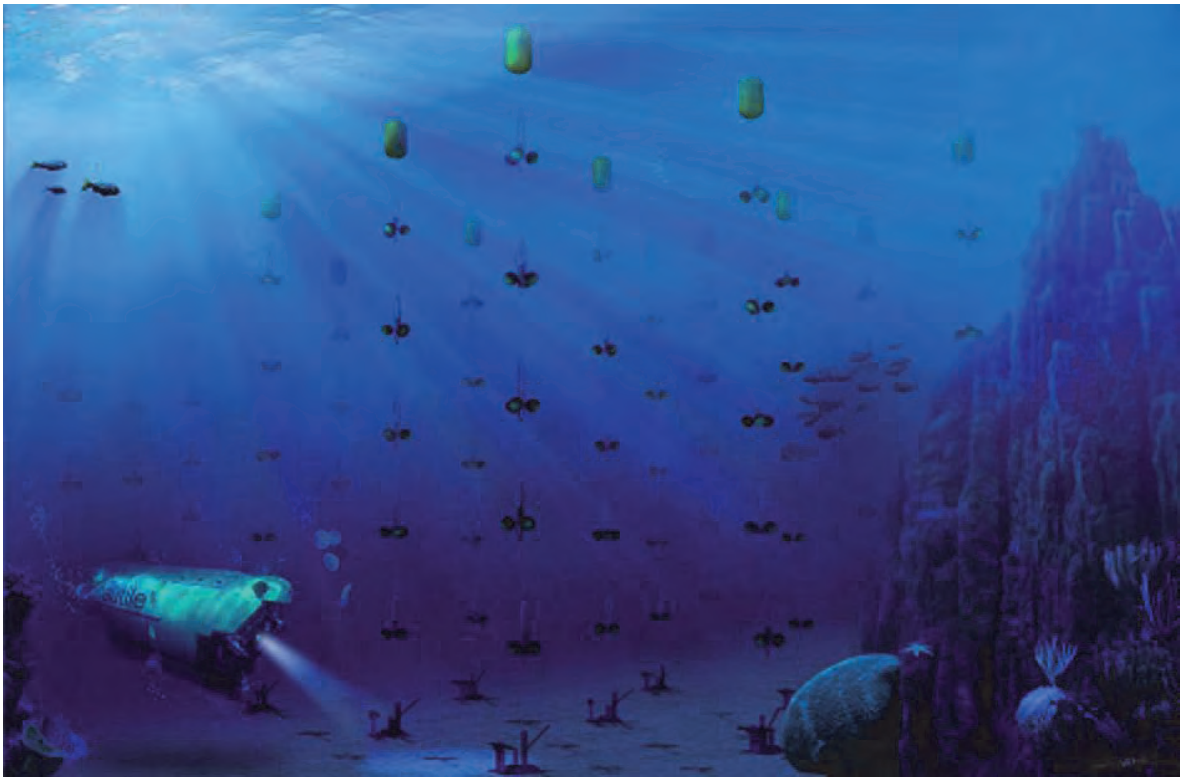
3.3. UNDERSTANDING THE OCEAN

Despite our realization of the importance of the ocean, there remain great challenges to fully exploring and understanding it. Meanwhile, its living resources are threatened by habitat loss and overharvesting, the climate of the planet is changing and the need for new compounds to cure human diseases and new energy sources is growing.

Since the scientific infrastructure of oceanographic institutions, instruments and vessels that arose following WWII, the technology of deep sea exploration has greatly advanced and currently includes even ocean surveys from space and robotic exploration of the deep ocean floor. Thanks to these technological advances, it is now universally acknowledged that the deep ocean is a dynamic geological environment.

Because of the three dimensionality of the ocean and its temporal and spatial variabilities, in order to get an advanced understanding of the processes that take place, we can no longer rely only on satellite (i.e. remote observations), one-off expeditions using ships, or drifters, gliders and buoys that are highly sensitive to natural events (e.g. sea currents, earthquakes). Stable platforms are needed that include sensors designed to take long-term continuous and high-resolution geophysical/environmental data which can be used by a variety of disciplines.

ApP infrastructures can and are already being used in this manner. The underwater pilot Neutrino Detectors **ANTARES**, **NEMO** and **NESTOR** have been used to gather oceanographic data (see Section 3.3.1), to monitor sediment transport (see Section 3.3.2) and oxygen dynamics (see Section 3.3.3) and to measure the ocean's radioactivity (see Section 3.3.4) and frequency of internal waves (see Section 3.3.5). Germanium detectors at **Underground Laboratory of Modane** are used to date corals in a low radioactivity background in order to understand past ocean dynamics (see Section 3.3.6).



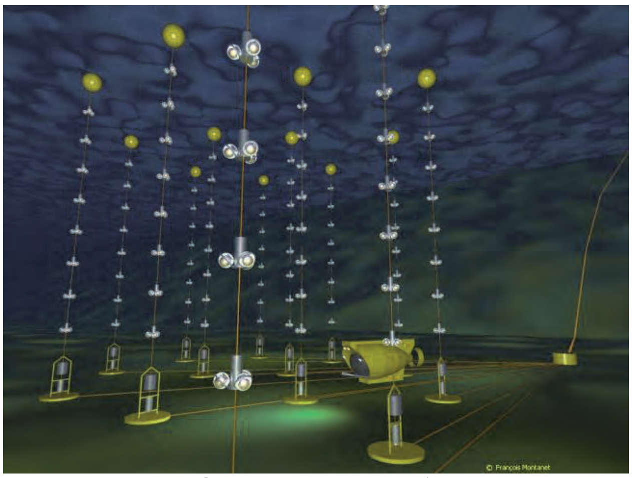
Artist's conception of ANTARES (Credit: ANTARES)

3.3.1. CONTINUOUS OCEANOGRAPHIC DATA

Sensing the Ocean Environment

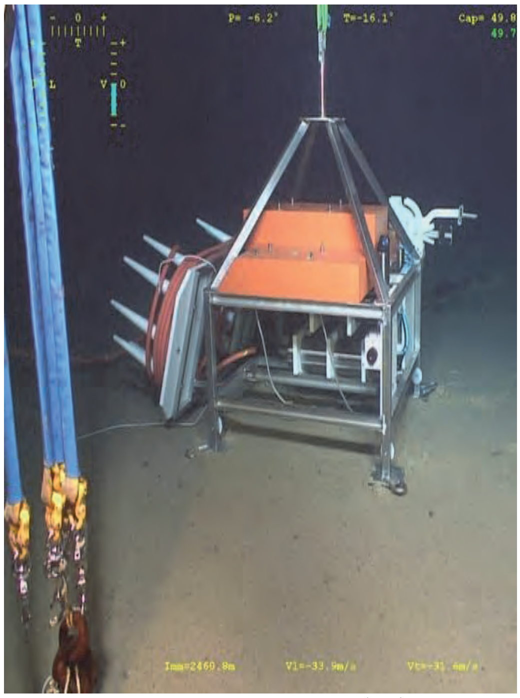
Progress in ocean model and assessment of system performance depends on rigorous validation against *in situ* data. Currently these are obtained by dropping instruments to the bottom of the sea and recovering them a few months later. Real time, long-term and continuous data from the bottom of the sea is a very rare achievement. For example, in the case of measurements of water motions that are fundamental to the understanding of the transfer of energy, heat, and chemical and biological variables in the ocean, oceanographic studies have focused on the upper few 100 meters below the surface, whereas very little is known about the deep-sea, i.e. below 1,000 m, i.e. about the unique ecosystem placed in permanent, high pressure, coldness and darkness.

Gathering oceanographic data from deep-sea *neutrino* telescope installations can greatly benefit the monitoring and forecasting of the ocean. In addition, the Mediterranean sea, where **ANTARES**, **NEMO** and **NESTOR** are placed, is a particularly suitable region both because it can be considered a laboratory basin for fundamental ocean processes, and because its outflow influences the Atlantic circulation.



View of the 0.1 km^2 ANTARES telescope (Credit: F. Montanet, CNRS/IN2P3 and UJF for Antares)

In order to study mesoscale phenomena like eddies, meandering boundary currents and their effects on the distribution of marine life, various oceanographic instruments has been deployed in the **ANTARES** neutrino detector, which provide a unique opportunity to compare high-resolution acoustic and optical observations near 2,475 m. Acoustic Doppler Current Profilers (ADCP) are used to monitor the water current flow along the full height of the detector strings. Conductivity–temperature–depth (CTD) sensors and dissolved oxygen sensors are used to monitor the temperature, salinity and dissolved oxygen content of the sea water at various depths in order to determine the water masses characteristics and their time evolution in relation to hydrological events at the basin scale and in relation with climate changes. Finally, sound velocimetres are used to monitor directly the sound velocity in sea water.



View of the Instrumented Interface Module (MII) that is hosting a CTD sensor, an oxygen sensor, a turbidity sensor, a currentmetre (ADCP) (Credit: ANTARES)

Recently, the **NEMO** collaboration developed **PORFIDO** (Physical Oceanography by RFID Outreach). **PORFIDO** is a system designed to gather oceanographic data (temperature, etc.) from passive RFID tags (WISPs) attached to the outside of the **NEMO** optical modules, with a minimum of disturbance to the main project and a very limited budget. Ten **PORFIDOs** will be deployed with the **NEMO** Phase 2 tower in 2012.

REFERENCES

van Haren H *et al.* (2011) "Acoustic and optical variations during rapid downward motion episodes in the deep north-western Mediterranean Sea" *Deep Sea Research Part I: Oceanographic Research Papers* **58**(8):875-884 .

Cordelli M, Martini A, Habel R and Trasatti L (2011) "PORFIDO: Oceanographic data for neutrino telescopes" *Nuclear Instruments and Methods in Physics Research A* **626-627**:S109–S110.

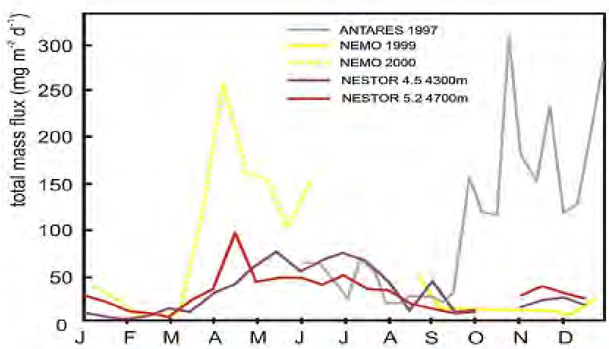
3.3.2. SEDIMENT TRANSPORT

Monitoring solid particles in the deep sea

The **KM3NeT** *neutrino* telescope will consist of a three-dimensional array of optical modules arranged on "storeys" that are supported by vertical structures anchored to the sea floor and kept upright by submerged buoys. The optical modules are housed in pressure-resistant glass spheres, the surfaces of which are exposed to sea water. There, they are likely to be fouled by the combination of two processes: living organisms growing on the outer surface (see Section 3.5.6), and sediments that fall on the upward-looking surfaces.

The downward flux of sediments can cover the optical modules and reduce the transmittance for Cherenkov light, thus decreasing the neutrino telescope's sensitivity. This effect depends on the angle of view (upward-pointing or downward-pointing) and was expected to be site-dependent, as sedimentation rate depends on local sources of sediments, such as nearby rivers. As a consequence, Astroparticle Physicists complemented measurements of light transmission by a detailed study of sedimentation at each of the three pilot sites (**ANTARES**, **NEMO** and **NESTOR**).

At the **ANTARES** site, time-series collections of samples in sediment traps attached to the mooring lines that hold the modules lead to the determination of the total mass fluxes and the composition of sediments for six months in 1997. In addition, particle concentration was measured in water samples taken at various depths since they can contribute to the scattering of light in sea water, and sedimentation rates were calculated from the ^{210}Pb activity in a sea floor core sample. It was found that despite a significant sedimentation rate at the site the sediments adhere loosely to the glass surfaces and can be washed off by water currents.



Monthly mass flux variations from ANTARES, NEMO and NESTOR sites. (Credit: KM3NeT)


Light Intensity Measuring System (LIMS) ready for deployment (Credit: KM3NeT)

Significant seasonal variation in the sediment flux was found at all three pilot sites (see figure on the bottom left). Even stronger variations are observed from year to year, presumably related to changes of the prevailing weather conditions and to singular occurrences of additional sediment material sources such as ashes from forest fires or sand from the Sahara.

Members of the **KM3NeT** collaboration also built a large number of autonomous systems, Light Intensity Measuring System (LIMS) (see figure above), in order to measure the sedimentation which stays on the optical modules by measuring light intensity variations on several positions on the glass spheres corresponding to different polar angles. In the course of over two years, 20 LIMS have been deployed in the sites **NESTOR4.5** (max depth 4,550 m) and **NESTOR5.2** (max depth 5,210 m). In all sites, light sensor response to external light sources roughly coincide for downward directions between nadir and horizontal, but they somewhat differ for upward directions of view, as to be expected from the different sedimentation rates.

REFERENCES

Anassontzis EG *et al.* for the **KM3NeT** consortium (2011) "A light intensity measuring system for sedimentation measurements on **KM3NeT** optical modules" *NIMA Proceedings* **626-627**:S111-S114.
ANTARES Collaboration (2003) "Sedimentation and fouling of optical surfaces at the **ANTARES** site" *Astroparticle Physics* **19**:253–267.

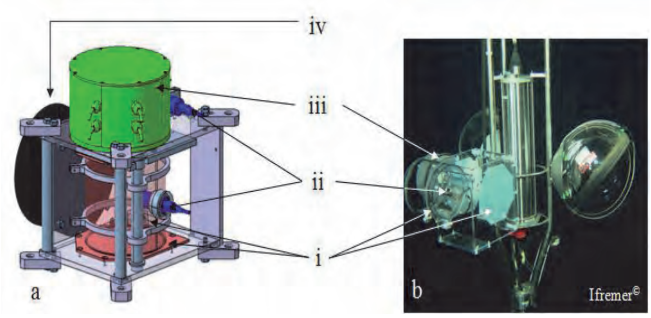
3.3.3. OXYGEN DYNAMICS

Mastering the oxygen dynamics in the open ocean

Oxygen is present in the oceans at various concentrations at all depths, mostly depending on the thermodynamics parameters (temperature and salinity) and oceanic circulation, and to a lesser extent on biological activity (photosynthesis and respiration). Measuring ocean O_2 concentrations is essential in order to detect O_2 concentration decreases due to global warming (global warming reduces the oxygen solubility and causes surface seawater to become lighter, therefore reducing oceanic ventilation and the ocean's oxygen content, in this way influencing biogeochemical cycles and having severe negative impacts on marine ecosystems). O_2 concentration measurements are also important in order to better assess the role of the micro-organisms in the global carbon cycle and understand possible effects of global warming on O_2 consumption, specifically respiration and organic matter remineralisation (for the latter see also Section 3.5.5).

Until recently, the common approach for measuring oxygen dynamics was to take samples in little glass bottles, incubate them at sea on a drifting line for 24 hours and then calculate the difference in O_2 concentration between the reference sample and either a dark incubated sample (in order to derive respiration rate) or a "light" incubated sample (to derive photosynthetic rate). Unfortunately this approach, although very accurate, is time-consuming and fastidious.

A new instrument has been recently developed by members of the **ANTARES** collaboration that allows *in situ* measurements of low O_2 consumption rates, at high frequency and over both short and long time periods (up to several months). **IODA6000** (*In situ* Oxygen Dynamic Autosampler) is an equipressure system able to reach 6 000 m deep, made of a 5-litre incubation chamber that records every 3 minutes temperature and O_2 concentration/dynamics in real-time.



Description of the In situ Oxygen Dynamics Auto-sampler (IODA$_{6000}$) a: 3D schema of IODA$_{6000}$. i: incubation chamber and tightness plates (pink). ii: oxygen optodes (blue). iii: equipressured electronic compartment (green). iv: equipressured battery compartment (black). b: picture of IODA$_{6000}$ on ANTARES L12 at 2000 m-depth (Credit: ANTARES/ Ifremer).

The **IODA6000** was deployed at 3,000 m-depth in the North West Mediterranean Sea (**ANTARES** site, L12) and has been acquiring data since December 2009. The mean O_2 consumption rate for this time series (from 2009 to 2011) is 0.2 ± 0.1 µmol O_2 dm^{-3} d^{-1}. When mean data of biological activity were collected from the 92 cycles available, respiration rates were found to be highly variable (range over 1 order of magnitude) and higher than expected if compared to the literature, implying that biological activity in the meso- and bathypelagic layers remains largely unknown and certainly underestimated.

This work was the first direct measurement of *in situ* O_2 consumption rates in the dark ocean, where changes in environmental conditions (temperature, hydrostatic pressure, light, concentration in organic matter etc.) can be significant.

ANTARES, as well as the greek pilot neutrino telescope site **NESTOR**, are both part of the Multidisciplinary European Open Ocean Observatory Network **EuroSITES**, which aims at the integration and enhancement of nine deep-ocean (water depth >1000 m) fixed point observatories around Europe into a coherent network.

REFERENCES

Lefevre D *et al.* (2010) "Assessing Metabolic Balance In Oligotrophic Gyres" Proceedings from the 2010 AGU Ocean Sciences Meeting.
Robert A *et al.* (submitted) "A new tool to assess production and respiration rates throughout the water column: the *In situ* Oxygen Dynamics Auto-sampler (IODA6000)".

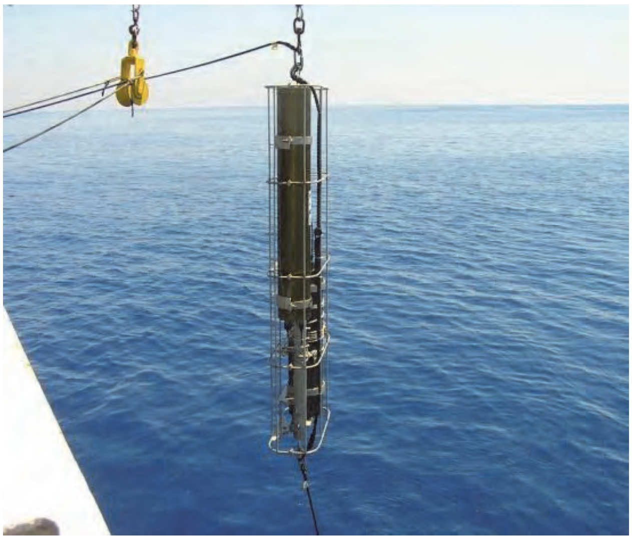
3.3.4. RADIOACTIVITY

Monitoring ocean radioactivity

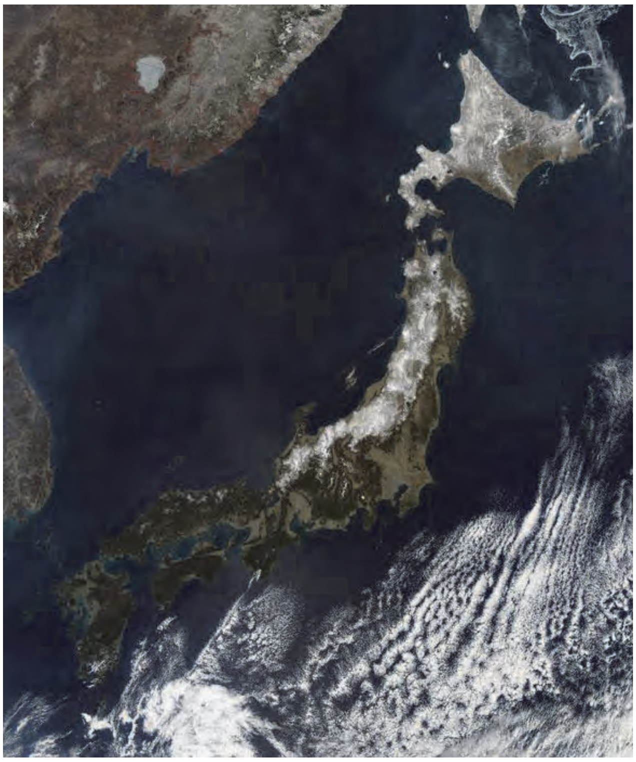
Over 60 radioactive elements are found in nature classified depending on their source as primordial, cosmogenic or anthropogenic. In the ocean, the largest source of *radioactivity* comes from naturally occurring substances such as potassium-40 (^{40}K) and uranium-238 (^{238}U). For example, the radioactivity associated with ^{40}K is approximately 2 x 10^{22} Bequerel, or roughly 530 billion curies, an enormous amount but spread throughout the ocean.

Astroparticle Physicists need to be able to monitor possible ^{40}K concentration variations over time – caused either by benthic sediment mobilization or water currents – in order to minimize background noise that could hinder the detection of Cherenkov light by **KM3NeT**. They therefore needed direct, *in situ*, detection of the activity and variation of radioactive elements in the sea, especially ^{40}K.

For this purpose, in the framework of **KM3NeT,** they developed **GEMS**, the **Gamma Energy Marine Spectrometer**, a prototype underwater gamma-spectrometer intended to monitor the radioactivity in seawater, in particular ^{40}K. GEMS successfully performed the first long-term continuous monitoring of radioactivity ever done in deep-sea (>3,000 m). The sensor can be used for monitoring natural radioactivity, or even man-made radioactivity in contaminated areas.



Deployment of GEMS in the Capo Passero-site (Credit: KM3NeT)



Japan from above (Credit: NASA Goddard/MODIS Rapid Response Team)

For example, in March 2011, due to the Earthquake that hit Japan, tons of radioactively contaminated water from the Fukushima Daiichi nuclear power plant poured directly into the ocean. Given that radioactive elements can be absorbed by phytoplankton and other marine life, and subsequently spread in the rest of the food chain, to fish, marine mammals, and even humans, the question on everyone's minds is how will this continuing contamination affect marine and human life. The answer to this question depends on whether radioactive element concentrations have increased after the earthquake, which can only be calculated accurately if long-term continuous radioactivity measurements are available, like those taken by instruments such as **GEMS**.

REFERENCE

Sartini L *et al.* (2011) "GEMS: Underwater spectrometer for long-term radioactivity measurements" *Nuclear Instruments and Methods in Physics Research Section A* **626**:S145-S147.

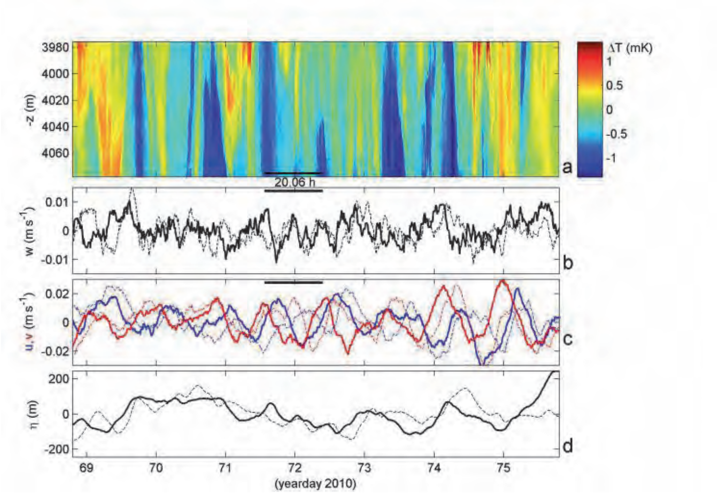
3.3.5. INTERNAL WAVES

Waves in the deep sea?

The Eastern Mediterranean deep sea was generally considered a dark, homogeneous and motionless environment: the dynamics of water motions seem to become weaker the further one gets from the surface and as the stable vertical stratification in density becomes very weak. But, it has now been found that the motion in the deep-sea is more dynamic than we thought. The spread of internal waves has the potential to influence large-scale ocean circulation and affect plankton distribution, so it can potentially have an impact on our climate. From an ApP point of view, understanding internal waves is important since they affect the performance of underwater technology, i.e. of the *neutrino* detectors, **ANTARES**, **NEMO** and **NESTOR**. A detailed understanding of all aspects of internal wave generation and evolution is therefore essential not only for oceanographers but also for members of the **KM3NeT** collaboration.

Vertical excursions were observed at various internal wave frequencies, which can be of magnitude of hundreds of metres in the weakly stratified deep Eastern Mediterranean. Thanks to **KM3NeT** it was possible to obtain for the first time not just one-time observations, but rather a yearlong record, and study the physics of these waves, of which little is known so far.

Using high-resolution modern electronics instrumentation, foremost temperature (T) sensors and some additional current meters, members of the **KM3NeT** collaboration found that deep sea dynamics do not come to a halt below, say, 3000 m. In fact, the motion in the deep-sea is observed to be as dynamic as that near the sea-surface, with permanently varying internal wave motions and turbulent instabilities. The 103 high-precision sensors revealed temperature variations within the range of only a few mK, but when precise correction for the adiabatic lapse rate was carried out during post-processing, the images are permanently dynamic (see figure). In strongly stratified (near-surface) waters low-frequency inertial internal motions are horizontal, but here they attain a vertical current amplitude sometimes comparable to horizontal currents. This results in occasionally very large internal wave amplitudes (250 m peak-trough), which are generated via geostrophic adjustment presumably from local collapse of fronts.



One week of deep internal wave observations. (a) Depth-temperature image relative to the adiabatic lapse rate. The inertial period is indicated. (b) Two-hourly smoothed vertical currents observed 2 m above uppermost T-sensor (solid) and 196 m below lowest (dashed). (c) Corresponding horizontal current components u (blue) and v (red). (d) Vertical excursions computed.(Credit: taken from van Haren and Gostiaux (2011)).

Thus, the deep Mediterranean trench waters are found never to lack motion and turbulent mixing. This is predicted to have consequences for life abundance in such waters. However, the collaboration found that if the above vertical motions are accounted for, they are not expected to be a hazard for the future kilometre-sized neutrino telescope.

REFERENCE

van Haren H and Gostiaux L (2011) "Large internal waves advection in very weakly stratified deep Mediterranean waters" *Geophysical Research Letters* **38**:L22603.

3.3.6. CORAL CHRONOLOGY

Long-lived historians

Deep-sea corals are found in all ocean basins within a range of temperature between 4°C and 12°C (> 50 to 1,500 m) and form growth rings, similarly to trees. A number of factors affect the pattern of these concentric bands, such as each coral's physiological rhythm, their food supply and the sediment influx. The age of corals has been mostly determined through radiometric methods based on lead, thorium, uranium, or radium isotopes depending on the timescale studied.

Polyps of the cold-water coral [Lophelia pertusa](). (Credit: [Murray Roberts]())

At the same time, since corals live for long time periods and their skeletons are preserved when they die, analysis of these growth rings allows investigations into past climate and ocean circulation changes in intermediate and deep-sea water masses. Methods to read these archives are still being perfected in order to be used for the reconstruction of a high-resolution time series of growth, temperature and ocean chemistry at different sea water depths.

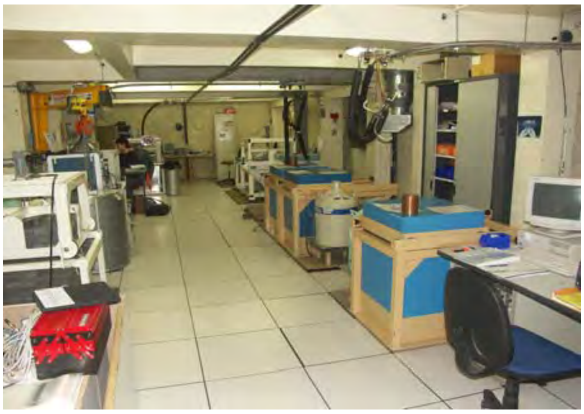
Scleractinian corals have an aragonitic skeleton affected by the composition of the seawater, environmental parameters such as temperature and biological vital effects. Thanks to its high uranium content, the skeletons of some deep-sea coral species are well suited to Uranium (U)-thorium (Th) analyses allowing absolute ages to be measured over many hundreds of thousands of years. But over the last century these methods have been tricky to apply to establish a precise chronology.

Within the framework of the European EPOCA (European Project on OCean Acidification) project, ^{210}Pb-^{226}Ra chronology was used to describe the age and growth rate of two post-modern scleractinian deep-sea corals (*Lophelia pertusa* and *Madrepora oculata*) collected in the North Atlantic waters (Rost Reef, Norwegian margin). This ^{210}Pb-^{226}Ra radiometric method has never been applied to these two main contributors to deep-sea reef building.

The ^{226}Ra activities were determined using Ge-detectors at the **Underground Laboratory of Modane** (**LSM**), developed for ApP research. For the **Neutrino Ettore Majorana Observatory (NEMO)** experiment, Astroparticle Physicists needed to select and control the natural *radioactivity* in the materials used to build the detector. For this reason they developed ultra low background gamma ray spectrometers based on the use of HPGe crystals. ^{210}Pb detection was accomplished by alpha-spectrometric determination due to its low activity.

For the specimen of *Madrepora oculata* (45.5 cm), a constant linear growth rate was estimated at 2 polyp.yr^{-1} or 11 mm.yr^{-1} with an age of 40 years. For the *Lophelia pertusa* (80 cm) traces elements revealed a high level of contamination of Mn-oxides for the oldest part but for the upper 15 cm a linear growth rate was estimated at 0.33 polyp.yr^{-1} or 8 mm.yr^{-1}.

The use of Germanium detectors in a low radioactivity background to date corals is an important step in the development and assessment of deep sea corals as archives of seasonal, interannual and decadal paleoclimate changes.



Gamma spectrometers protected by lead shielding at Underground Laboratory of Modane (Credit: LSM)

REFERENCE

Sabatier P *et al.* (2011) "Growth rate of deep-sea Scleractinian corals (*Madrepora oculata, Lophelia pertusa*) inferred from ^{210}Pb-^{226}Ra chronology" *Geophysical Research Abstracts* **13**:EGU2011-8747. Also at *Biogeosciences Discuss* **8**:12247-12283.

3.4. MEASURING AND ATTEMPTING TO PREDICT EARTHQUAKES

During 2011, more than 15,000 earthquakes with magnitude greater than 4 were located worldwide by United States Geological Survey (USGS). 2,273 of which have a magnitude of more than 5, causing in total at least 21,000 deaths. There is thus a real motivation to achieve reliable and repeatable earthquake forecasts that could help to enable effective earthquake disaster mitigation.

The Earth seems to be a lot more heterogeneous than geologists had hoped for, making accurate and timely earthquake prediction an immensely difficult task. The difficulties lie partly in the determination of what's happening before an earthquake compared to what is part of the natural complexity of earth processes, and in that earthquakes start from a very small source and then grow to a huge dimension, so it is still not possible to distinguish a small beginning of magnitude 9.0 from a small beginning of a magnitude 5.0 or 6.0. In addition, geoscientists have still not been able to find the so-called "magic" precursors.

An understanding of the underground world is also useful to Astroparticle Physicists: in order to build their underground research infrastructures, a detailed understanding of the surrounding rock structures is needed. In order to assure the safety of the infrastructures, geological hazards such as earthquakes need to be predicted.

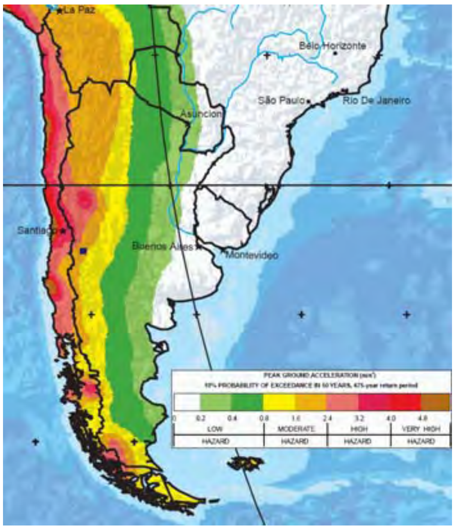
A number of studies have therefore been carried out in order to study the underground environment of ApP infrastructures but at the same time investigating earthquake prediction. In Argentina, the **Pierre Auger Observatory** looks for high energy cosmic rays, but also attempts to predict earthquakes (see Section 3.4.1). The underwater pilot Neutrino Detectors **ANTARES**, **NEMO** and **NESTOR** have also been used to predict earthquakes and tsunamis (see Section 3.4.2). Similar studies have also been carried out in Lake Baikal, in Russia, where the Baikal neutrino detector is placed in the largest fresh water volume in the world (see Section 3.4.3). At the **Low Noise Underground Laboratory (LSBB)** in France they are studying the seismo-electromagnetic effects (see Section 3.4.4). Finally, at the **Gran Sasso Underground Laboratory** in Italy slippage mechanisms are studied in high stress environments (see Sections 3.4.5-3.4.6).

The Andes Mountains, Peru. (Credit: Kevin Connors)

3.4.1. EARTHQUAKE MONITORING GRID

Spreading the net for a deeper understanding

The vast Pampa Amarilla plane in western Argentina, where the **Pierre Auger Observatory** is located, is an area very seismically active and which has had in the past important destructive earthquakes. For this reason a very detailed understanding of the geophysical environment that surrounds the ApP detectors is required, in particular the precise location of the plate Nazca, its seismicity and the seismic tomography and anisotropy of the region.



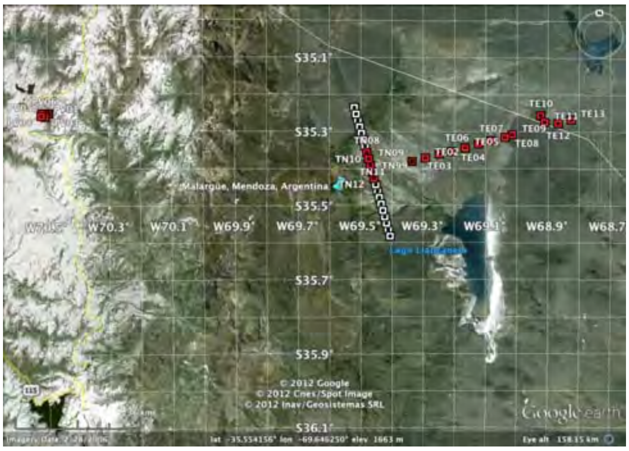
Different levels of shaking hazard for the south half of South America. The square in the western part of Argentina shows the location of the Pierre Auger Observatory. (Credit: Global Seismic Hazard Assessment Program)

For the investigation of cosmic ray showers of the highest energy, Astroparticle Physicists have placed 1,660 detectors on a very large area 3,000 km². The **Pierre Auger Observatory** therefore represents a unique opportunity to study for the first time geophysical and seismic properties on a long-term basis using novel methodologies on a dense array of seismic stations spanning many squared kilometres.

One of the correlations being investigated so far is the suggested change in the flux of low energy cosmic rays observed at the occurrence of a major earthquake. On the 27th of February 2010, an 8.8 magnitude earthquake occurred in Chile, with the epicentre 300 km south west from the **Pierre Auger Observatory**. The averaged scaler rate for the whole existing seismic station array and also for individual stations, showed a 24 σ decrease beginning 90±2 seconds after the earthquake. This delay is compatible with the propagation of seismic S-waves (secondary or shear waves) over that distance.

In order to take advantage of **Auger Observatory**'s building facilities, internet, power, and especially the help of its people, the establishment of a digital broadband permanent seismic network at the **Pierre Auger Observatory** has been proposed by an international team of geophysicists (TU Delft, ICES Argentina). They will install 40 temporary seismic stations in early 2012 in Malargüe, partially co-localised with Auger Observatory

This seismic array aims to monitor and image the subsurface and the Peteroa volcano, monitor the southern oceans, achieve detailed imaging of the lithosphere and to localize local seismic activity, all using recently developed techniques. In order to reach high-resolution subsurface imaging, for example, they will use seismic interferometry that uses not only earthquake responses but also ambient seismic noise.



Seismometers represented by the squares: red when already installed, white when installed in February 2012. (Credit: Pierre Auger Collaboration)

Through the collaboration of geoscience and ApP further synergies are being developed, like the coupling of seismic waves with atmospheric gravitational waves or lightning research.

REFERENCES

Wapenaar K *et al.* (2011) "Improved surface-wave retrieval from ambient seismic noise by multi-dimensional deconvolution" *Geophysical. Research Letters* **38**:L01313.
Pierre Auger Collaboration (2011) "The Pierre Auger Observatory III: Other Astrophysical Observations" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

3.4.2. EARTHQUAKE AND TSUNAMI MONITORING

Dealing with the consequences of Poseidon's rage

"No Geology without Marine Geology!"

Philip Kuenen (1958)

Earthquakes and tsunamis can lead to catastrophic infrastructure damages, loss of human life as well as perturbations to our ecosystem. Wave physicists are able to locate emerging areas of fault activity and determine if the energy and the characteristics of seismic events are hazardous.

Such semi-automated early warning systems have managed to reduce the impact of earthquakes, but for an improvement in probabilistic estimates, long-term and continuous measurements are necessary. More precisely, there is an urgent need for long-term and continuous data from the deep sea that is communicated in real-time to shore that are integrated in the already existing land-based seismic networks: even though the majority of Earth is covered by water currently less that 1% of the International Registry of Seismograph Stations operate below sea level. Furthermore, only about 0.2% of these sensors are below 1000 m depth and none of these are located in European Seas.

The **ANTARES** *neutrino* detector is near the continental plate boundaries of Southern Europe, where many of Earth's most seismogenic zones and active volcanoes occur. It is therefore a natural complement of the on-shore network and can lead to increases in location precision of the microseismicity. Astroparticle Physicists have already developed the instruments (broadband seismometer, an accelerometer, a differential pressure gauge, an absolute pressure sensor, sea floor deployment, data transmission) for studying the forces that can sway the buoys used to position the **ANTARES**'s photomultipliers, since such movements, caused by sea currents and of course earth movements, can affect **ANTARES**'s ability to detect high energy neutrinos. Seismological data are introduced in the real-time data flow analyzed for earthquake detection and location. Pressure data is transmitted to the RATCOM centre, a prototype of regional tsunami alert centre in Ligurian Basin, which is able to manage a complete tsunami alert ranging from the detection of the ongoing event to the population warning. It is important to note that, a recent study by the collaboration, found that despite the high noise level, good recordings of local/regional events are taken, showing that such instrumentation can usefully complement a land network for regional onshore-offshore seismic studies.

Data obtained so far from ANTARES's broadband seismometer at 2,500m depth have shown that the sea floor seismological noise is similar to land station noise at high frequencies, which means that the data can be used for micro-seismicity analysis. More recently, the seismometer system was proved to be well calibrated, when in March 2011 it unexpectedly recorded the Japanese earthquake on velocimetric sensor, but also on both pressure gauges.

Seismometer connected to the ANTARES secondary junction box (Credit: ANTARES)

Members of the **NEMO** collaboration have also been interested in geohazards since the **NEMO** detector is in a similarly seismogenic area as **ANTARES**, due to its proximity to Etna. Thanks to **NEMO-SN1** multidisciplinary facility, the **NEMO** collaboration found that about 30% of the events recorded were not reported on seismic bulletins. The **NEMO** collaboration has also been testing a Tsunami Early Warning System (also part of **NEMO-SN1**) that uses and automatically analyses real-time hydro-acoustic measurements to provide states of variable alert-level for coastal areas.

REFERENCES

Giacomelli G for the **ANTARES** Collaboration (2011) "Results from the **ANTARES** Neutrino Telescope" Contribution to the WASET International Conference on Neutrino Physics and Astrophysics, arXiv:1105.1245

Favali P, Beranzoli L, Italiano F, Migneco E, Musumeci M, Papaleo R on behalf of the **NEMO** Collaboration (2010) "NEMO-SN1 observatory developments in view of the European Research Infrastructures EMSO and KM3NeT" *NIMA Proceedings* **626-627**:S53-S56.

Deschamps A (2011) "RATCOM: an early-warning pilot network for near-field tsunamis in the Ligurian Sea" *Geophysical Research Abstracts* **13**: EGU2011-14189.

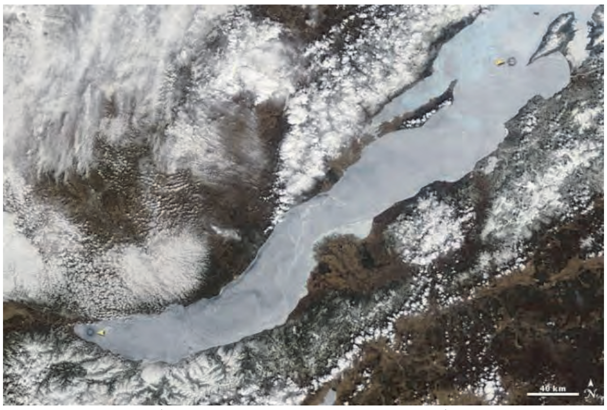
Frontera *et al.* and the ANTARES collaboration (submitted) "The Antares real time ocean bottom seismometer: analysis of 2 year continuous recordings".

3.4.3. STUDYING THE LAKE ENVIRONMENT

Looking at the world's largest fresh water volume

Many opportunities for environmental research are offered by lake Baikal, the legendary Holy Lake of the Russians. Its breathtaking beauty has fascinated generations of writers and poets. Located far in Siberia, it holds several world records. With a depth of 1,642 metres, it is the deepest lake of the world, and with a 23,000 km³ volume, it contains the largest amount of fresh water. Its length is 673 km and in the winter its surface freezes to more than one meter thickness. Finally, the lake's crystal clear waters are rich in biodiversity: they host 1,085 species of plants and 1,550 species and varieties of animals, about two third of them being endemic, i.e. existing nowhere else in the world. Unfortunately, there are concerns that this unique environment may be under danger due to a paper mill not far from the Baikal *neutrino* telescope and the poisoned inflow from some rivers.

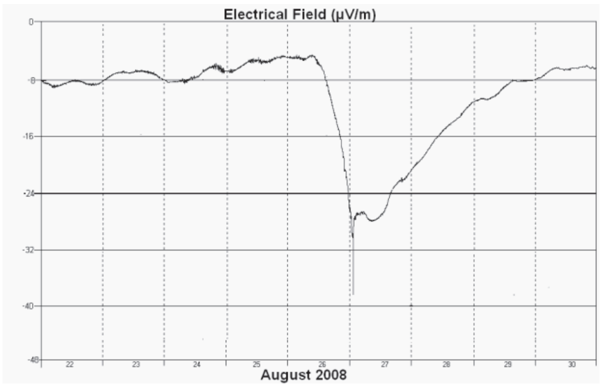
Since 1993, neutrino research has been conducted at the **Baikal** neutrino telescope which is located 1.1 km below the surface of the lake. It does not come as a surprise that the scientists took advantage of this detector for the monitoring of the water transportation processes deep in the lake.



(Credit: NASA Earth Observatory)

They record the light emitted by the luminescent bio-matter carried by the water and study the way the deep layers are fed with surface water rich with oxygen. Vertical flows of more the 2 cm/sec have occasionally been observed, velocities typical of horizontal flows but unexpected for vertical movements. They are thought to play a substantial role in deep water oxygenation.

Another peculiarity of Lake Baikal is its small electrical conductivity, smaller than that of most other natural fresh water reservoirs. It thus allows the measurement of the vertical electrical field of the Earth in water, over a length of more than one kilometre. Interestingly, there is a strong correlation to local Earthquakes, and intriguingly events have been observed were the Earthquake was not only accompanied by electrical signals (see Figure below), but also preceded by feeble signals a few days before the Earthquake.



Vertical electrical field measured in Lake Baikal over a vertical distance of 1250 m. The peak marks the time of an Earthquake. High-frequency fluctuations appear which are not observed in any other time period. (Credit: Nikolai Budnev)

Both the water monitoring and the study of the Earth's electric field and its correlation to other phenomena are integrated in the long-term research plan around the neutrino telescope.

REFERENCE

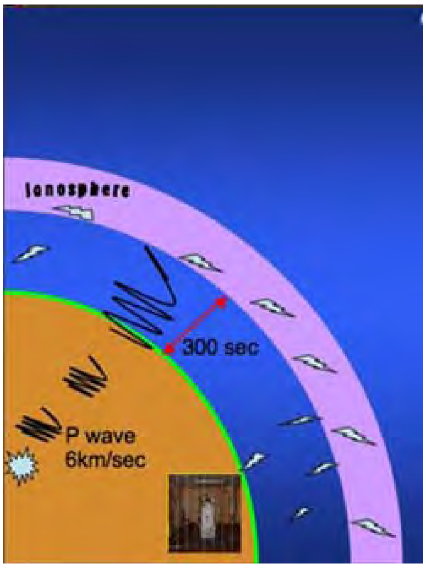
Korotaev SM *et al.* (2011) "The effect and precursors of the earthquake of August 28, 2008, in the vertical component of the electric field in Lake Baikal" *Doklady Earth Sciences* **438**(2): 842-845.

3.4.4. SEISMO-ELECTROMAGNETIC COUPLINGS

Predicting the Unpredictable

As much as society would like science to provide warnings before earthquakes, faced with the immense difficulty of identifying reliable and repeatable earthquake precursor signals, mainstream seismologists and physicists predominately work on prevention and early warning systems.

The quest for precursor signal identification has led geologists, hydrogeologists, physicists and geophysicist to develop interdisciplinary collaborations to develop new methods that will allow them to jointly study the Earth's tectonics, seismic events, the Earth's upper atmospheric ionosphere, Solar sun spots and flares, tidal movements, in order to identify the relationships between these phenomena in terms of processes and of coupled-induced effects. That is one of the motivations that contributed to the birth of the seismo-electromagnetics field, the study of electromagnetic phenomena in the lithosphere and the ionosphere associated with seismic activity and wave propagation. These seismo-electromagnetic effects are expected to be useful for the assessment of earthquake hazards.



Excitation model: the electromagnetic ionosphere signal arrives before the seismic ground wave if the epicentre is more than about 2,000 km away. (Credit: Geaoges Weysand).

A number of different processes are observed. First, electromagnetic emissions from the lithosphere that are radiated from the earthquake hypocenter area related to seismogenic tectonic effects during the earthquake preparation phase (Waysand G *et al.*, 2011). Second, the arrival of a seismic waves that shake the water-rock interfaces and create ionic currents inducing magnetic fluctuations. Specific devices set up in properly designed underground spaces with very low magnetic noise environments, enable us to properly study these perturbations, identified by their frequency spectra and correlations with seismometer signals. Furthermore, it can be attempted to look for a possible correlation of the amplitude of the collected signals with the hydro-geological situation (Bordes *et al.*, 2008).

Third, seismic waves may also be the source of the ionosphere's perturbations and fluctuations detected in the unique underground environments with high signal-to-noise ratio. For example, the ionosphere response to a seismic P-wave (primary or pressure wave) generated by an earthquake is signed by two magnetic responses produced at the ionosphere floor: the first corresponds to the arrival of the P-wave shaking the epicentre ground surface area and the second to the P-wave shaking the observation site. Both ground motions are converted at the surface and emitted as acoustic waves that spread up to the ionosphere (Waysand G *et al.*, 2009).

Beyond the processes described above, continuous recording of the electromagnetic signals in the low noise environment of **Low Noise Underground Laboratory (LSBB)**[28] (Rustrel, French Provence) allows detection and analysis of a wide class of ionosphere disturbances (Marfaing *et al.*, 2011; Pozzo di Borgo *et al.*, 2012). LSBB is a low noise laboratory for inter-disciplinary underground science and technology devoted to scientific and technological research and innovation in the fields of the observation, characterization, and modelling of the terrestrial and atmospheric environments and of the near Universe.

REFERENCES

Bordes C *et al.* (2008) "Evidence of the theoretically predicted seismo-magnetic conversion" *Geophys. J. Int. Geomagnetism, rock magnetism and palaeomagnetism* **174**:489-504. doi: 10.1111/j.1365-246X.2008.03828.x

Marfaing J *et al.* (2011) "Global observation of 24 November 2006 Pc5 pulsations by single mid-latitude underground [SQUID]2 system" *Ann. Geophysicae* **29**:1977-1984. doi: 10.5194/angeo-29-1977-2011

Pozzo di Borgo E, Marfaing J and Waysand G (in press) "Minimal global magnetic millihertz fluctuation level determined from mid latitude underground observations" *Europhysics Letters*.

Waysand G *et al.* (2009) "Seismo-ionosphere detection by underground SQUID in low-noise environment in LSBB, Rustrel, France" *European Physics Journal of Applied Physics* **47-1**:12705. doi: 10.1051/epjap:2008186

Waysand G *et al.* (2011) "Earth–ionosphere couplings, magnetic storms, seismic precursors and TLEs: Results and prospects of the [SQUID]2 system in the low-noise underground laboratory of Rustrel-Pays d'Apt" *Comptes Rendus Physique* **12**(2): 192-202.

[28] http://lsbb.eu/ The University of Nice (UNS), the University of Avignon (UAPV) and the Centre national de la recherche scientifique (CNRS/INSU) are the main institutes for higher education and research that manage and lead the academic and applied research at LSBB.

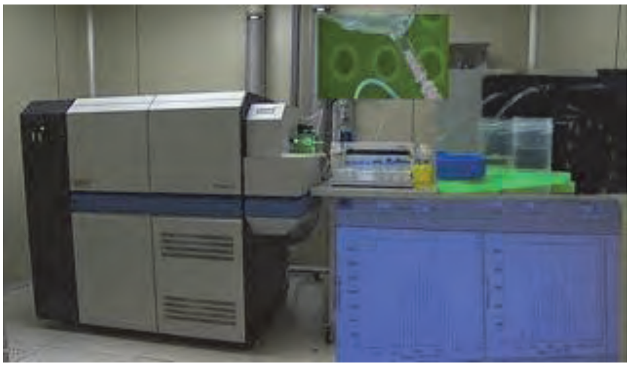
3.4.5. EARTHQUAKE PHYSICS

Is the parent better than the child?

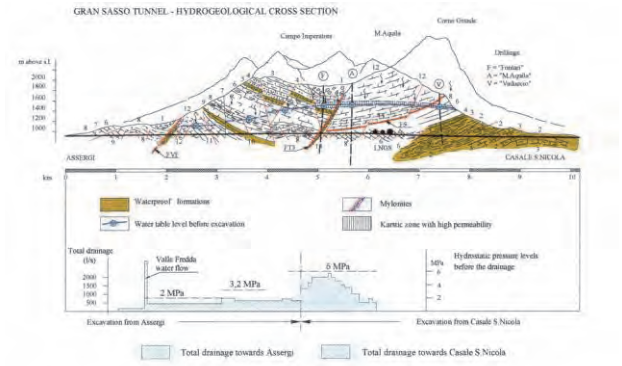
Groundwater is an essential part of the hydrologic cycle, of the daily water supply of more than 2 billion people worldwide, of a large proportion of the world's irrigated agriculture. At the same time, it is vital for the sustainability of streams, lakes, wetlands and ecosystems. High levels of *radioactivity* in groundwater will thus result in a huge water management crisis and reanalysis of human health risk assessment.

The natural radioactivity in rock and materials used for the internal structures of the **Gran Sasso Underground Laboratory** has been studied in great detail in order to determine the background Radon (^{222}Rn) contribution to the sophisticated ApP experimental apparatus and to check health physics standards for the personnel. Since it has been shown that the geodynamic processes leading to earthquakes can modify radon migration patterns in groundwater, it has been suggested that radon could be a candidate earthquake early precursor signal. Its air or groundwater anomalies have already been associated with earthquakes and air–rock or water–rock interactions in several seismogenic areas worldwide.

Within the framework of the INFN´s scientific program **ERMES (Environmental Radioactivity Monitoring for Earth Sciences)** radon (^{222}Rn), radiocarbon (^{14}C) and tritium (^{3}H) are monitored in the groundwater inside the **Gran Sasso Underground Laboratory**, and different chemical, physical and fluid dynamical characteristics of groundwater have been detected.



The inductively coupled plasma mass spectroscopy (ICP-MS) system. (Credit: INFN)



Hydro-geological section of the Gran Sasso massif. (Credit: INFN)

Since, however, the use of radon as a possible earthquake's precursor has not yet been clearly linked to crustal deformation, a vigorous R&D program is in progress, with special attention to radioactive tracers, especially uranium (^{238}U), and ^{226}Radon's parent radionuclide. Uranium groundwater monitoring started in the **Gran Sasso Underground Laboratory** in 2008 in order to test uranium's contribution to neutron flux background and uranium as potential strain indicator of geodynamic processes occurring before an earthquake, rather than the consolidated scheme for radon release due to stress–strain processes in the rock.

It was shown that uranium groundwater anomalies, which were observed in cataclastic rocks crossing the **Gran Sasso Underground Laboratory**, can be used as a possible strain meter in domains where continental lithosphere is subducted. There is clear evidence of sharp anomalies from July 2008 to the end of March 2009, related to a preparation phase of the seismic swarm, which occurred near L'Aquila, Italy. On the 6th of April 2009 an earthquake (Mw = 6.3) occurred in the same area. In the framework of the geophysical and geochemical models of the area, these measurements indicate that uranium may be used as a possible strain meter in extensional tectonic settings similar to those where the L'Aquila earthquake occurred.

REFERENCE

Plastino W *et al.* (2011) "Uranium groundwater anomalies and active normal faulting" *Journal of Radioanalytical and Nuclear Chemistry* **288**(1):101–107.

3.4.6. SLOW EARTHQUAKE MONITORING

ApP and the seismic slip deficit problem

Continuous, high-sensitivity measurements of crustal deformations can provide insight in the "seismic slip deficit" problem. Even though earthquakes are a key process in accommodating the relative motions of plates, there are far too few of them to account for all of the slips occurring along plate boundaries. Other processes were thus thought to be also involved, such as "slow" earthquakes: a locked fault will sometimes release strain by rupturing over a period of hours or days, instead of seconds as in earthquakes. The resulting energy release is difficult to detect with conventional seismometers, since their capability of detecting slow ground motion is limited, but not with high-precision geodetic strainmeter instruments capable of measuring ground displacements.

Laser strainmeters measure distance changes between two end points by means of optical interferometers and as a consequence allow an advanced study of geodynamic phenomena, both local (single-site measurement of seismic phase velocities, slow earthquakes, deformation induced by seasonal charging and discharging of the local or regional aquifer) and global (free oscillations of the Earth and strain tides).

GIGS geodetic interferometers (Credit: INFN)

The low noise associated with the underground setting and the high potential seismicity make the **Gran Sasso Underground Laboratory** an ideal site for high resolution seismic observations. The **GIGS** collaboration[29] installed, far below the surface, two geodetic interferometers able to perform high sensitivity continuous measurements of crustal deformation. These have been operating since summer 1994. Each interferometer is based on the classical unequal-arm Michelson set-up and compares the optical length (i.e. the length expressed in terms of the light wavelength) of a longer measurement arm (90 m in length) and a shorter fixed reference arm that is 20 cm in length.

In the same tunnel a small aperture seismic array characterised by a low detection threshold was installed by the **UnderSeiS** [30] **(UNDERground SEISmic Array Experiments)** collaboration in 2002. In its present configuration the array consists of 20 elements, each one equipped with a short period (1 Hz) three-component Mark L4C-3D seismometer. The array depicts an average sensor spacing of about 90 m, while the largest distance among sensors is about 550 m.

A Mark L4C-3D seismometer (Credit: INFN)

Their results suggest that the fault is currently failing exclusively through slow fracturing, and thus may have important consequences on evaluating seismic hazards: a fault's activity may be completely in the slow earthquake band with no response in the seismic band of the spectrum, so it would otherwise be considered inactive. Therefore, very-low frequency, high-sensitivity records of ground deformation contribute essential data to improve the real-time picture of seismic activity and this is presently done by the high performance and sensitivity of the **UnderSeiS** and **GIGS** projects at the **Gran Sasso Underground Laboratory**. Further experimental work will be of great help to understand if the tremor episodes can be recorded in the peculiar tectonic domain of the Apennines, the main seismic active zone of Italy.

REFERENCES

Scarpa R *et al.* (2008) "Slow earthquakes and low frequency tremor along the Apennines, Italy" *Annals of Geophysics* **51**: 527-538.

Amoruso A and Crescentini L (2010) "Limits on earthquake nucleation and other pre-seismic phenomena from continuous strain in the near field of the 2009 L'Aquila earthquake" *Geophysical Research Letters* **37**:L10307.

[29] http://www.lngs.infn.it/lngs_infn/index.htm?mainRecord=http://www.lngs.infn.it/lngs_infn/contents/lngs_en/research/experiments_scientific_info/experiments/current/gigs/

[30] http://www.lngs.infn.it/lngs_infn/index.htm?mainRecord=http://www.lngs.infn.it/lngs_infn/contents/lngs_en/research/experiments_scientific_info/experiments/current/underseis/index.htm

3.5. BIODIVERSITY

At least 40 per cent of the world's economy are derived from biological resources. In addition, the richer the diversity of life, the greater the opportunity for medical discoveries, economic development, and adaptive responses to such new challenges as climate change.

— The Convention about Life on Earth

Biodiversity is a modern term for "the variety of life on earth". It can be measured on several different levels: genetic (variation between individuals of the same species), species (variety of species in a given region) and ecosystem level (communities of species interlinked with their environment).

Even if the existence of life in terrestrial, marine, polar and deep subsurface extreme environments has been known for a long time, it is only recently that these environments have been considered as ecosystems containing unique biodiversity. Consequently, many questions on biodiversity, evolution, energetics and interactions of organisms in these environments remain poorly answered.

Over the last decades, researchers have been focusing on certain environments, such as hot deserts and high-altitude ecosystems, but the true breadth of extreme environments has been barely researched. What is known so far is that they are distributed across the globe and that they represent the most important part of our biosphere (CAREX, 2011).

Why study life at extreme environments? First of all, to gain insights on the origins of life on earth, since the conditions under which the earliest life arose were similar to these extreme environments (see Section 3.5.8). Similarly, research on extreme life can provide valuable analogues for studying the possibilities for extraterrestrial life (see Section 3.5.3). Second, an understanding of species adaptation to many different types of extreme environments will have an impact on our lives, by leading to considerable opportunities in the biotechnological, pharmaceutical, energy, food, health and climate sectors (see Section 3.5.4). Last but not least, climate change is predicted to have an amplified impact on life in extreme environments, severely threatening their survival. This means that these species can be used as particularly sensitive indicators for climate change (see Section 4.1). More importantly, however, this also means that, due to our limited knowledge on extreme biodiversity, especially its interactions in the biosphere, it is not known in what indirect manner we will be affected by their extinction.

(Credit: Dr. Peter Hardt)

known so far is that they are distributed across the

For all these reasons, the understanding of biodiversity in deep sea, polar and subsurface environments, at the genetic, species and ecosystem level, is one of the major challenges of the 21st century. Given the complexity and location of these extreme environments, the study of extreme biodiversity needs to be multidisciplinary in form, combining scientific expertise from various fields. Given that ApP infrastructures are placed by definition in extreme environments – since only deep inside mountains and under huge volumes of water and ice astroparticle detection is possible – ApP infrastructures can become the platforms required for such multidisciplinary collaborations to prosper.

But Astroparticle Physicists will not just provide their infrastructures for biologists, but also their advanced technologies, computing skills and understanding of the extreme environments in which their detectors are placed.

Polar and deep sea extreme environments show enormous diversity. In fact, these conditions have become necessary for the survival of organisms, which have reached the limits of their physiological potential in order to adapt to these environments. Unique adaptations and survival mechanisms have been detected that bring valuable new insights to our knowledge of biological processes, from molecular biology to physiology, ecology and evolution.

Astroparticle Physicists in collaboration with biologists have already contributed in understanding biodiversity deep underwater and under polar ice. In the former case, the underwater pilot neutrino detectors include instruments for sound monitoring (see Section 3.5.1), detecting luminescent sea life (see Section 3.5.2), studying oil-eating bacteria (see Section 3.5.4) and investigating pressure effects on marine prokaryotes (see Section 3.5.5). In addition, correct data transmission and to secure equipment lifetime, it is essential for Astroparticle Physicists to understand the nature of biofouling in these waters (see Section 3.5.6). Similarly, members of the **IceCube** collaboration have constructed an instrument that can study biodiversity *in situ* many meters below the ice surface with implications for astrobiology (see Section 3.5.3).

Underground, deep below the surface that walk on, light disappears, temperatures and pressures are higher and the surrounding chemical composition changes. Down there, biologists hunt for life that can survive in an environment where nutrients are scare, pace of life is slow, where the surrounding rock breaks and moves, and the demand on DNA repair mechanisms is intense. They are trying to answer questions such as what species are present in the subsurface? What adaptations allow them to do so? What were their origins? What is their impact on the geology and chemistry of their surroundings? What can these organisms tell us about the origin of life but also about extra-terrestrial life? Significant scientific uncertainty still surrounds life below the surface, even if around half of the earth's biomass thrives underground.

Continuous and direct access to underground environments is required in order to attempt to tackle all or any of these questions. This access can be given by the current ApP underground laboratories. Cell cultures are monitored in almost zero radiation conditions in order to investigate the effect of radiation on DNA damage and repair (see Section 3.5.7). Halophilic are studied in the **Boulby Underground Laboratory** mine in order to understand their evolution and metabolism (see Section 3.5.8).

3.5.1. UNDERWATER SOUND MONITORING

Detectors have ears

The sea environment is filled with natural sounds, but increasingly many anthropogenic sources contribute to the general noise. Given that sound is thought to be used by many aquatic animals for communication between members of their species, but also to create a visual 3D image of their environment, the so far unknown impact of anthropogenic noise could have serious consequences. It was thus considered essential to develop infrastructures for the long-term quantification of sounds, in order to 1) automatically identify and classify non-biological and biological sounds, 2) monitor marine organisms and population dynamics, and 3) assess and control the long-term effects of anthropogenic sources on marine organisms.

It turned out that such infrastructures already existed. Given that the sensitivity of the high-energy *neutrino* observatory hydrophones used by Astroparticle Physicists in the **NEMO** and **ANTARES** platforms allows the detection of marine mammal calls, marine biologists could use them to achieve all the tasks above at a reduced cost.

NEMO and **ANTARES** detectors include arrays of hydrophones – ultra-sensivite deep-sea microphones - that can provide information about the presence of animals that pass through this acoustic 'sensor grid'. This information can then be used to identify species and track individuals. Indeed, these sounds can travel tens of kilometres, at a speed five times faster than in the air, so they can give a better insight in the species biology than images or videos.

A few years ago, an especially exciting finding came from the **NEMO-ONDE (NEutrino Mediterranean Observatory – Ocean Noise Detection Experiment)** experiment, when it detected instead of neutrinos, sperm whales. Until then, sperm whales were considered to be very rare in the region. In fact, the Mediterranean depths were thought to be much more silent than this data showed. Marine biologists now hope to use the future **KM3NeT** infrastructure to collect more reliable data on cetacean density and distribution, affording further clues to their behaviour.

The necessity of understanding the effects of noise on the marine ecosystems lead to the creation of the **LISTENING TO THE DEEP-OCEAN ENVIRONMENT (LIDO)** [31] program, an international network of multidisciplinary seafloor observatories, which includes the three objectives mentioned above. Although **LIDO** concentrates primarily on the effects of noise on marine mammals, it also considers species (e.g. fish) that are part of the food web on which marine mammals depend. **NEMO** and **ANTARES** form two of **LIDO**'s nodes.

REFERENCE:

André M, van der Schaar M, Zaugg S, Houégnigan L, Sánchez AM, Castell JV (2011) "Listening to the Deep: Live monitoring of ocean noise and cetacean acoustic signals" *Marine Pollution Bulletin* **63**:18–26.

It is possible to listen to the whales live from home with a personal computer connected to the web, thanks to the LIDO platform (Listen to the Deep Ocean), which uses among others the acoustics detectors of the undersea neutrino detectors (Credit: LIDO)

[31] http://www.listentothedeep.com/

3.5.2. DEEP SEA BIOLUMINESCENCE

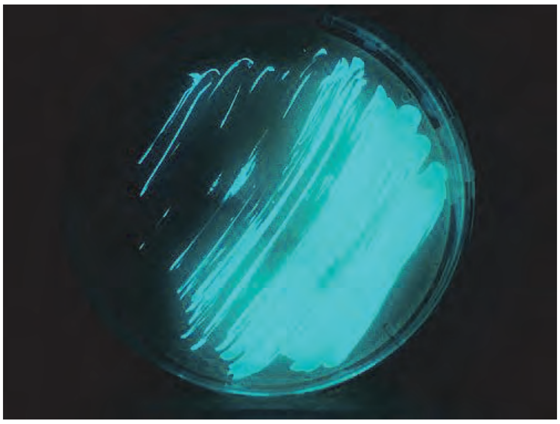
Glowing Sea Life

Bioluminescence is the emission of visible light by an organism as a result of a natural chemical reaction. In most of the ocean it is the primary source of light (in the deep ocean 90% of pelagic organisms are bioluminescent), whereas on land it is rare. A remarkable diversity of marine animals and microbes are able to produce their own light. In order to understand the distributions of luminous marine organisms, new instruments and platforms are needed to allow observations on individual to oceanographic scales.

KM3NeT, the future kilometre-sized deep sea *neutrino* detector in the Mediterranean Sea, and its current pilot detectors – **ANTARES**, **NEMO** and **NESTOR** could be such a platform since its globular eyes pick up light from bioluminescent bacteria at the bottom of the ocean. For Astroparticle Physicists, the light from bioluminescent bacteria picked up by their globular eyes are a potential source of neutrino signal perturbations. For biologists, the detection of free-swimming bioluminescent bacteria under such high-pressure conditions (typical of deep-sea depths) was thought to be impossible until recently.

(Credit: catalano82/Flickr)

Members of the KM3NeT collaboration used high sensitivity Intensified Silicon Intensified Target (ISIT) video cameras in order to measure the density of bioluminescent organisms in the water column at the **NESTOR** and **ANTARES** sites. They found that faunal groups are less abundant by a factor of about 10 in the deep Mediterranean at comparable depths of the deep ocean. Furthermore, in the Mediterranean itself, variability a factor of 10 in abundance is found at any given depth between different basins, with the lower values found in the eastern basin around Greece.



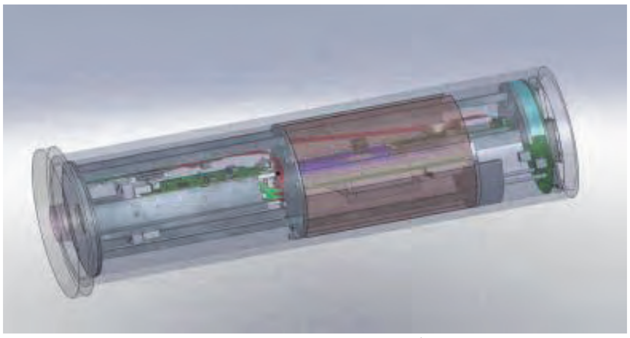
Photobacterium phosphoreum is a Gram-negative bioluminescent bacterium that emits a bluish-green light. (Credit: Peter Edin/Flickr)

In addition, members of the **ANTARES** collaboration estimated the relative abundances of *Vibrinoceae* family bacteria. At 2,200 m depth, *Vibrionaceae* appeared to be far from negligible, representing 40% of γ -proteobacteria, 25% of Bacteria and 9% of the total DAPI-stained cells, while Bacteria and Archaea represented 35% each. Furthermore, during a high luminous background period detected by the neutrino telescope, we isolated from a 2,200 m depth sample, a piezophilic luminous bacterium, phylogenetically determined as *Photobacterium phosphoreum* strain ANT-2200. Since its immersion in October 2010 and after 2 months of calibration, dark count measurement and trigger threshold tuning, the LuSEApher prototype worked well and continues to survey the deep sea 24h 7 days a week. Almost 900 bioluminescence sequences have been recorded.

P. phosphoreum is known as a symbiotic bacterium that lives in the light organ of some marine fishes, but can also live freely in seawater. Thus, this strain was used to investigate the effect of hydrostatic pressure on bioluminescence by developing a new high-pressure apparatus. The first assays carried out showed that the bioluminescence intensity was 5 times higher at 22 MPa than at 0.1 MPa (atmospheric pressure).

Similarly, members of the **KM3NeT** collaboration investigated the correlations between the bacterial-produced light and the direction of sea currents, by studying bacterial density at the other two **KM3NeT** pilot sites, the **NEMO** and **NESTOR** *neutrino* telescope sites in the west and east Ionian Sea respectively. They found a west to east decrease in organism density and a significant seasonal effect in the west but not in the east Ionian Sea.

Even more recently, members of the **ANTARES** collaboration developed an ebCMOS camera, called LuSEApher, a marine bioluminescence recorder device adapted to extreme low light level that will open a new window on bioluminescence studies in the deep sea. This prototype is based on the skeleton of the LUSIPHER camera system originally developed by the collaboration for fluorescence imaging. The LuSEApher camera has been installed at 2500m depth at the site of the **ANTARES** neutrino telescope, mounted on the Instrumented Interface Module (IIM, see Section 3.3.1) installed for environmental science purposes as part of the **European Seas Observatory Network (ESONET)**. The LuSEApher is a self-triggered photo detection system with photon counting ability that produces movies of bioluminescence of sensitivity and frame rate never obtained before. The collaboration is also investigating the existence of a correlation between images and sea conditions measured at the position of the neutrino detector (current speed and direction, temperature, see Sections 3.3.1, 3.3.3 and 3.3.5).



The complete integrated LuSEApher camera (Credit: from Dominjon A *et al.* (in press))

The results coming from the measurement from December 2007 to June 2010 of light intensity time-series at the ANTARES IL07 mooring line (expressed in ANTARES's photomultiplier tubes' median counting rates, temperature, salinity and current speed) will have important implications for climate change. These extensive datasets revealed several weeks-long bioluminescence outbursts connected to atmosphere-driven dense water formation events, which episodically renew the deep waters of the Western Mediterranean Sea. It was concluded that a direct link exists between atmospheric forcing and biological activity in the deep-sea and that the deep-sea ecosystem responds rapidly to physical processes that initiate at the ocean surface.

REFERENCES

Al Ali B, Garel M, Cuny P, Miquel J-C, Toubal T, Robert A, Tamburini C (2010) "Luminous bacteria in the deep-sea waters near the **ANTARES** underwater neutrino telescope (Mediterranean Sea)" *Chemistry and Ecology* **26**(1): 57-72.

Barbier R *et al.* (2011) "A single-photonsensitive ebCMOS camera: The LUSIPHER prototype" *Nuclear Instruments and Methods in Physics Research A* **648**: 266–274

Craig J, Jamieson AJ, Bagley PM and Priede IG (2011) "Seasonal variation of deep-sea bioluminescence in the Ionian Sea" *NIMA Proceedings* **626-627**(1): S115-S117.

Priede IG *et al.* (2008) "The potential influence of bioluminescence from marine animals on a deepsea underwater neutrino telescope array in the Mediterranean Sea" *Deep Sea Res Part I* **55**: 1474–1483.

Dominjon A *et al.* (in press) "An ebCMOS camera system for marine bioluminescence observation: the LuSEApher prototype" *Nuclear Instruments and Methods in Physics Research A*.

Tamburini *et al.* (submitted) "Enhancement of deep-sea pelagic activity by dense water formation after a unique long-term bioluminescence record"

VIDEOS: https://www.ipnl.in2p3.fr/spip.php?article1297&lang=fr

3.5.3. BIODIVERSITY UNDER ICE

Bacteria where there was no life give insights for life in other planets

Glacial ice holds a record of past microbial diversity, but this biodiversity has not been extensively explored until recently, due to the labour-intensive nature of direct counts of microbial concentrations and identification of taxa by molecular methods. Scientists from the **AMANDA/IceCube** collaboration, however, while working on the enormous *neutrino* observatory at the South Pole, took a big step forward: they constructed in-ice borehole instruments that measure microbial life as a function of depth. Their method took advantage of the fact that the strong autofluorescence of many biomolecules, such as tryptophan, chlorophyll, NADH and F420, allows the detection of cellular life by fluorescence spectroscopy at extremely small concentrations, quickly, non-destructively and *in situ*.

A Sensor String Descends into a Borehole (NSF/B. Gudbjartsson)

They constructed the Biospectral Logger (BSL), which consists of a laser and seven phototubes that select discrete wavelength bands of fluorescence light emitted by biomolecules. Analysis of the shapes of these autofluorescence emission spectra distinguishes biomolecules from other organic and mineral aerosols. In addition, intensities are converted to microbial concentrations by making direct counts and measurements of cell sizes at several depths. BSL can detect a microbial concentration as low as ~1 cell per cubic centimetre of ice: with such precise localization, it should be possible to extract single cells for molecular identification.

The resulting data strengthened the evidence that microorganisms can live in ice at temperatures tens of degrees below 0°C. It also led to the discovery of a third habitat for microbial metabolism in ice: redox reactions with dissolved small molecules such as CO_2, O_2, N_2, CO, and CH_4 diffusing through the ice lattice. There is an adequate supply of diffusing molecules throughout deep glacial ice to sustain metabolism for >10,000 years. Interestingly, most of the autofluorescing cells in ice consist of two genera of submicron-size cyanobacteria – *Prochlorococcus* and *Synechococcus* – which have been shown to give rise to almost half the oxygen in the atmosphere and thus have serious environmental implications.

Furthermore, for NASA's future mission to the icy northern plains of Mars, an instrument was needed that would be able to locate biomolecules and organics such as polycyclic aromatic hydro-carbons (PAHs), in such extreme conditions. Any study of extraterrestrial organic chemistry would greatly benefit from understanding the distribution and presence of PAHs in the solar system, since they are among the most ubiquitous organic compounds in the universe. Given that they have been identified in Martian meteorites, understanding them also has implications for the search for life on Mars.

Luminescence spectroscopy had been shown by the **IceCube** collaboration to be a powerful and well-suited tool because among others it is very sensitive to organic molecules. A prototype was thus constructed that would be able to inspect boreholes in Martian icy plains. This included a miniature Biospectral Logger (mBSL) and a Borehole Neutron Probe (BNeuP). The mBSL is a miniaturized version of BSL developed in the context of the **IceCube** collaboration, that fits into a 5-cm borehole in ice or permafrost. This new instrument was tested in 2008 at Mount Lassen with great success.

Miniaturized BSL Deployed at Mount Lassen (Credit: NASA)

REFERENCES:

Rohde RA and Price PB (2007) "Diffusion-controlled metabolism for long-term survival of single isolated microorganisms trapped within ice crystals" *PNAS* **104**(42): 16592–16597.

Rohde RA *et al.* (2008) "*In situ* microbial metabolism as a cause of gas anomalies in ice" *PNAS* **105**(25): 8667–8672.

Fairén *et al.* (2010) "Astrobiology through the Ages of Mars: The Study of Terrestrial Analogues to Understand the Habitability of Mars." *Astrobiology* **10**(8):821-43.

Bramall NE, Rohde RA, Bay RC and Price P (2006) "Optical Probes for Remotely Sensing Microbial Life in Antarctica and Beyond" Poster presentation at AGU Fall Meeting, San Francisco.

3.5.4. BIODEGRADATION

Bacteria make a meal of oil

Oil can affect almost any form of life it comes in contact with and can be detected in the environment even 30 years after discharge. After the sinking of the tanker "Prestige" in 2002, off the northern Spanish coasts and at a depth of 2,400 metres, many questions were posed about the fate and environmental impact of the spilled oil in deep-sea environments. More crucially, whilst such accidental oil spills receive the most attention, chronic oil pollution – the continuous stream of oil spills and deliberate/illegal "operational" discharges of oily waste from vessels – is a much bigger and constant threat. For example, oil released into the Mediterranean sea as a result of operational discharges is nearly 20 times that spilled by "Prestige". Furthermore, as our planet's more accessible oil reservoirs are being emptied, a search for marine and particularly deep-sea reservoirs has begun, generating new threats to marine ecosystems as demonstrated by the recent BP Deepwater Horizon Gulf of Mexico oil spill. It is thus no surprise that interest in the microbial biodegradation of oil has been recently intensified.

Biodegradation is a result of the metabolic activity of hydrocarbon-degrading microbial communities, by a remarkable group of specialists, the so-called hydrocarbonoclastic bacteria (HCB), which have only recently been discovered. The time scale for biodegradation spans from days to weeks (and even years in unfavourable environments like in muddy anoxic sediments).

In the framework of the French national program **ANR POTES (pressure effects on marine prokaryotes)**, the *in situ* biodegradability of heavy fuel oil (Prestige oil) and its impact on the biodiversity of sedimentary microbial and macrofaunal communities were studied at the **ANTARES** site, the pilot *neutrino* telescope located at 2,400m-depth.

Sediment was distributed into polyvinyl chloride (PVC) cores with or without a massive addition of Prestige fuel oil (~9 g kg/1 dry wt) and integrated in experimental devices. This experimental device was deployed using the remotely operated underwater vehicle Victor at the **ANTARES** site off the French Mediterranean coast, at 2,400 m water depth, using the manned submarine Nautile.

Sediments from the water/sediment interface were sampled with a multicorer and were promptly enriched with Maya crude oil as the sole source of carbon and energy.

Sediment was distributed into PVC cores with or without a massive addition of Prestige fuel oil(~9 g kg^{-1} dry wt) and integrated in experimental devices. (Credit: ANTARES).

Alkane-degrading bacteria belonging to the genera *Alcanivorax* (the first HCB to have its genome sequenced), *Pseudomonas*, *Marinobacter*, *Rhodococcus* and *Clavibacter*-like were isolated, indicating that the same groups were potentially involved in hydrocarbon biodegradation in deep sea as in coastal waters. The results also confirm that members of *Alcanivorax* are important obligate alkane degraders in deep sea environments and coexist with other degrading bacteria inhabiting the deep subsurface sediment of the Mediterranean.

The fact that bacteria make a meal of oil at the **ANTARES** deep-sea station was further confirmed by the observed typical microbial alteration of n-alkanes of Prestige fuel oil during the experiment. Interestingly, long term macrobenthic recolonisation and sediment reworking activity do not seem to have been affected by the contamination.

REFERENCES

Tapilatu Y, Aquaviva M, Guigue C, Miralles G, Bertrand J-C, Cuny P (2010) "Isolation of alkane-degrading bacteria from deep-sea Mediterranean sediments" *Letters in Applied Microbiology* **50**:234-236.

Cuny P, Gilbert F, Militon C, Acquaviva M, Tamburini C, Stora G, Grossi V (in prep.) "Effects of Prestige fuel oil on macro- and micro-benthic communities of deep-sea Mediterranean sediments near the **ANTARES** underwater neutrino telescope".

3.5.5. MICROBIOLOGY

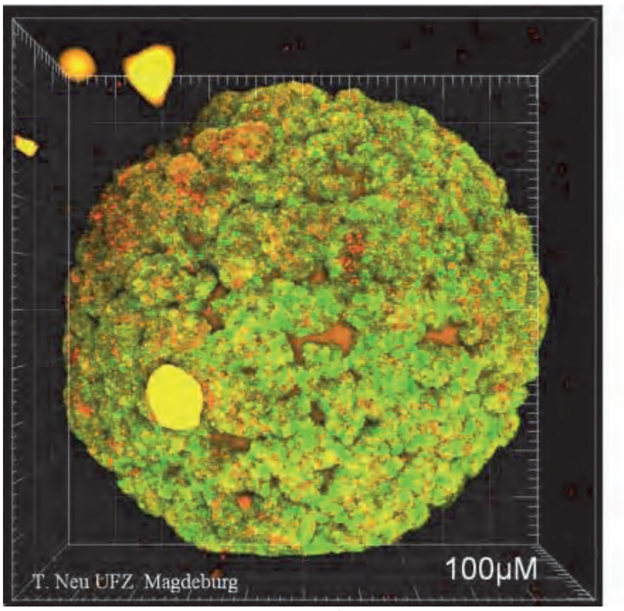
Pressure effects on marine prokaryotes

The biological pump is a major component of the global carbon cycle that transports approximately ten gigatonnes of carbon per year from the atmosphere to the oceans interior. Its role therefore, in the context of the global warming is now recognized, even if data used in CO_2 flux modelling mainly come from the surface layer (euphotic layer 0-200 m). Nonetheless nearly 50% of the surface production (representative of the biological pump) is exported in the deeper zone as dissolved and particulate organic material (DOM and POM respectively). These constitute the main vector of exportation of carbon and energy in the intermediary and deep waters through bacteria-mediated mineralization, which leaves only but a small fraction reaching deep sediment.

Despite their crucial importance, there are only few studies in mesopelagic (200-1,000 m) and bathypelagic (>1000 m) zones of the bacterial processes involved in POM mineralization, such as regulation of genes involved in the degradation of certain organic compounds. Furthermore, there is very little available information on the role of hydrostatic pressure on marine prokaryote mineralization of POM and DOM, and the regeneration of biogenic compounds (silicates, carbonates) in the meso- and bathypelagic zones of the ocean. Only with microbial rates measured under *in situ* conditions (e.g. high-pressure, low temperature, ambient food availability) do realistic calculations of the flow of matter and energy as mediated by microbes become possible for the deep sea, and hence throughout the water column.

Members of the **ANTARES** collaboration have used a innovative double approach based on laboratory experiments and *in situ* studies at the **ANTARES** neutrino detector site in the deep Mediterranean sea. In order to determine the pressure effects on prokaryotes (e.g. community structure) and on their activity (transformation and mineralization of organic matter). In the laboratory, using the "PArticle Sinking Simulator", it was demonstrated that continuously increasing pressure to simulate the transit between 200 m and 800 m (depth-simulated) resulted in reduced rates of silica dissolution and hence organic matrix hydrolysis of freshly prepared diatom detritus, as compared to rates measured under atmospheric pressure conditions.

More recently, a new piezotolerant alkane-degrading bacterium (*Marinobacter hydrocarbonoclasticus* strain #5) was isolated from deep Mediterranean (3,500 m) seawater and grown at atmospheric pressure (0.1 MPa) and 35 MPa, with hexadecane as sole source of carbon and energy for 13 days. Modification of the hydrostatic pressure influenced neither the growth rate nor the amount of degraded hexadecane. However, the lipid composition of the cells sharply differed under the two pressure conditions, showing that bacterial cells are able to modify their membrane lipid composition in response to changes in environmental conditions such as temperature or pressure.



Marinobacter hydrocarbonoclasticus (Credit: Dr. Thomas R. Neu UFZ Madgeburg)

Thanks to the invention of **IODA6000** (see Section 3.3.3) by the **ANTARES** collaboration, it is now possible to investigate more extensively the *in situ* hydrostatic pressure effects on microbial activity, because the **IODA6000** is submerged for longer time periods and at different depths.

REFERENCES

Grossi V *et al.* (2010) "Hydrostatic pressure affects membrane and storage lipid compositions of the piezotolerant hydrocarbon-degrading Marinobacter hydrocarbonoclasticus strain #5" *Environmental Microbiology* **12**(7): 2020–2033.

Tamburini C *et al.* (2009) "Effects of hydrostatic pressure on microbial alteration of sinking fecal pellets" *Deep Sea Research Part II: Topical Studies in Oceanography* **56**(18):1533-1546.

3.5.6. BIOFOULING

Protecting underwater vessels and equipment

Surfaces exposed to the marine environment are typically affected by biofouling, the undesirable accumulation of micro-organisms followed by plants, algae, and/or animals. Biofouling has a great socioeconomic impact because it affects shipping and leisure vessels, very expensive oceanographic instruments that are deployed in long-term studies, and aquaculture systems. In the case of ships, it leads to decreases in their speed, increases in their fuel consumption and resulting gas emissions.

KM3NeT, the kilometre sized *neutrino* telescope, will be constructed in deep Mediterranean waters in which it might also be affected by biofouling. Thus, in order to secure correct data transmission and to secure equipment lifetime, it is essential for Astroparticle Physicists to understand the nature of biofouling in these waters, especially since most biofouling research has focused on shallow waters due to technical difficulties.

Biofouling made by barnacles. (Credit: *Rafal Konkolewski*)

An experimental study was conducted by members of the **KM3NeT** collaboration at the **NESTOR** 4.5 site (max depth 4,550m) for observing potential growth of organisms that settle on artificial substrata after long-term deployment in the Ionian Sea, the deepest part of the Mediterranean with 5,121 m depth and one of the sites proposed for the deployment of **KM3NeT**. This site, near Pylos in Greece, is characterized by small temperature and salinity fluctuations between the deep-water layers, making it ideal to test parameters that influence in coastal areas the composition of biofouling communities.

Four new experimental platforms (GKSS prototype), each in a different depth (4,500, 3,500, 2,500 and 1,500 m) and with five artificial substrates (titanium and aluminium metals; limestone and shale, materials typical natural hard substrates in the Mediterranean; and glass, used for the photomultiplier spheres of the neutrino telescope) in two orientations (horizontal and vertical) were deployed for 155 days at the study site (see figure below). After retrieval, all substrates in every depth were visually inspected using Scanning Electron Microscopy (SEM) while the molecular biological analyses of samples was done via Terminal Restriction Fragment Length Polymorphism, a DNA-based fingerprinting method (T-RFLP).

Deployment of biofouling platforms; R/V Aegaeo (Credit: © Nikoleta Bellou)

Analyses showed an evident absence of macrofouling – attachment of larger organisms, such as barnacles, mussels, and seaweed. A loosely adhered biofilm (microfouling) was nevertheless observed. SEM revealed the presence of substrate attached bacteria. A direct counting of all microorganisms was not possible via SEM due to the thinness of biofilms. However, the visual presence of substrate attached bacteria was detected at all depths, substrates and both orientations, except on glass substrate in 2500, 3500 and 4,500 m depth, the substrate of most interest to Astroparticle Physicists. Further research is needed to understand the ecology and the processes regulating biofilm communities in an extreme oligotrophic deep sea environment.

On the other hand, bacteria were detected in all samples through molecular biological analyses. Furthermore, T-RFLP clearly showed that depth has a higher influence on the deep sea biofilm community composition compared to substrate type and deployment orientation throughout depth. Indications are given that the latter is related to the surrounding water masses.

REFERENCES

Bellou N, Colijn F, Papathanassiou E (2011) "Experimental settlement study in the Eastern Mediterranean deep sea (Ionian Sea)" *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **626-627**: S102-S105 .

Bellou N, Papathanassiou E, Dobretsov S, Lykousis V and Colijn F (final proofs) "The effect of substrate type, orientation and depth on the development of deep-sea bacterial communities on artificial substrata deployed in the Eastern Mediterranean" *Biofouling*

3.5.7. IMPACT OF RADIATION

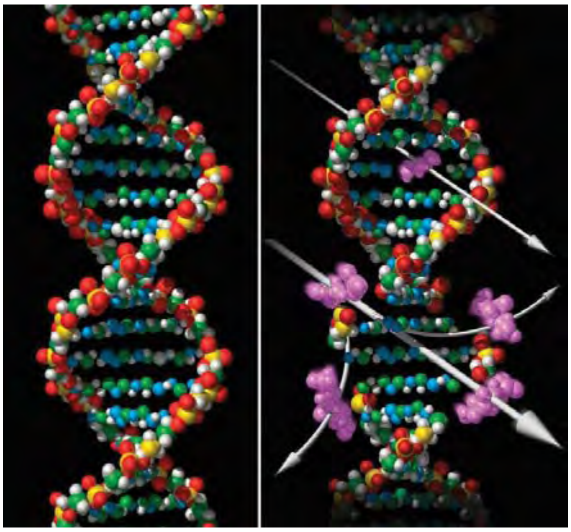
Did radiation help in the origins of life?

Life has evolved on Earth in the presence of background ionizing radiation that affects the biochemical behaviour of living organisms. Would life on Earth differ in the absence of this radiation? What are the effects of radiation on mutation rates, localization of mutations, gene expression and DNA breaks? In order to answer these questions, the ideal experimental design contains two sets of cell or animal cultures, the first in a laboratory with no background radiation and the second in a reference laboratory at "normal" background radiation levels. Then, the cultures will be monitored for the onset of differential behaviours between the two laboratories.

In the context of **Geant4DNA** project, research was carried out to investigate the effects of radiation on biological systems such as cell survival rate, DNA single or double strain breaks and genomic mutations. In this case they used a triple set up experiment: one culture grown in normal laboratory conditions, one culture bombarded with beam irradiation (γ, e^-, p, α). Finally they needed one culture to be grown in an environment with almost no radiation, an environment provided by the **Underground Laboratory of Modane (LSM)**. Compared to normal laboratory conditions, where cultures are exposed to tens of millions cosmic rays per day per square meter, in the **LSM** radiation exposure has been reduced down to four cosmic rays per day per square meter.

The laboratory, all doors open. Direct access by the Frejus tunnel. (Credit: CNRS / Benoit RAJAU)

In similar experiments, the **Gran Sasso Underground Laboratory** was used to grow cultures in almost zero radiation conditions. Several measurements were conducted on human TK6 cell cultures maintained for six months under reduced (underground laboratory) or reference (normal laboratory) background radiation environments. Their results strongly suggested that TK6 cell cultures develop different behaviours under reduced background radiation environments: cells cultured underground were more sensitive to acute exposures to radiation, as measured both at the level of DNA damage and repair, and oxidative metabolism, i.e. management of reactive oxygen species (ROS) balance. These results were found to be compatible with the hypothesis that ultra-low dose rate ionizing radiation, i.e. normal background radiation in the environment, may act as a conditioning agent in the radiation-induced adaptive protective response in human TK6 cells. It was also speculated that evolution of life on Earth may have been different in the absence of environmental, background ionizing radiation.



Effects of radiation on DNA's double helix (Credit: NASA)

REFERENCES

Carbone MC *et al.* (2009) "The Cosmic Silence experiment: On the putative adaptive role of environmental ionizing radiation" *Radiation and Environmental Biophysics* **48**(2): 189-196.

Carbone MC *et al.* (2010) "Effects of deprivation of background environmental radiation on cultured human cells" *Nuovo Cimento della Societa Italiana di Fisica B* **125**(4): 469-477.

3.5.8. EXTREMOPHILES

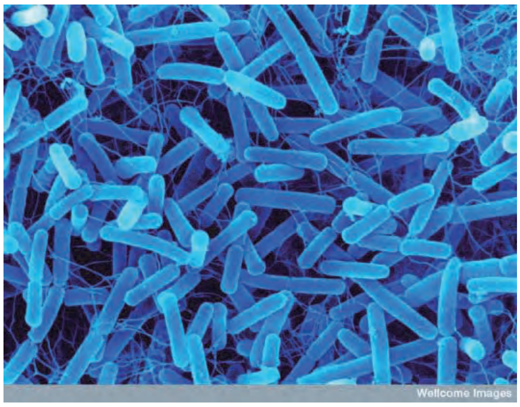
A subterranean biosphere

Conditions deep below the surface, currently defined as extreme, were predominant at the origins of life. The study, therefore, of extremophiles can help us understand how our planet's biosphere evolved. Increasing evidence is emerging of a highly diverse microbe biosphere residing kilometres below the Earth's surface, in geological formations that are millions of years old. In order to survive, these microbes had to adapt: unusual evolution at the genome level has been coupled with a novel multi-functionality at the protein level and lead to considerable ecophysiological diversity. A deeper understanding of these extremophiles could have serious societal implications. For example, there is concern that halophilic (i.e. salt-loving) microbial communities in subterranean salt deposits could lead to biodeterioration of containers holding toxic and nuclear waste. Similarly, these communities have been found to play an important role in shale weathering, i.e. in early events of shale degradation and coastal erosion.

Many questions remain to be answered about these halophilic communities. What are their origins? Were they trapped in salt when the evaporites formed millions of years ago? Are they always dormant or do they grow and multiply, perhaps interspersed with relatively short periods of dormancy? How are they surviving in their salty subterranean world? What adaptations were necessary for them to transition from moderate to extreme halophiles? What is the molecular basis of this adaptation? To answer these questions *in situ* experiments need to be performed in underground laboratories that include an analysis by transcriptomics and proteomics.

Rock salt (halite) from Boulby Potash Mine, North East coast of England. (Credit: British Geological Survey)

Haloarchaeal diversity was examined at the Boulby Underground Laboratory **(BUL)**, located deep within the Boulby mine in the United Kingdom where rock salt is mined. Rock salt is the key ingredient in the 'grit' which keeps the road network moving despite ice and snow. Thus, its availability becomes critical to the British economy during the winter. The salt formed 200–300 million years ago, when much of Britain was covered by a shallow sea surrounded by hot dry desert lands. As the water from this sea evaporated, salt crystals formed from the brine, along with other useful minerals such as potash (used for fertiliser).



(Credit: David Gregory & Debbie Marshall, Wellcome Images)

Two separate enrichments from the Boulby mine were first examined to find two identical strains, with novel polar lipid profiles and which were phylogenetically distinct. Detailed taxonomic analyses of halophilic isolates have been carried out, comparing strains from the Boulby salt deposits with those from surface environments. Phylogenetic analysis of 16S rRNA sequences suggests the presence of a probably very diverse microbial community in ancient rock salt. The resulting phylogenetic tree was used in order to investigate the rate of the molecular clock for these species. Slow growth over geological time would be expected to decrease the mutation rate, while stressful conditions may accelerate it. For the strains isolated so far, the 16S rRNA clock was found to be slow. In addition, data supports the hypothesis that the halophilic isolates from subterranean salt deposits could be the remnants of populations that inhabited once ancient hypersaline seas. These pieces of evidence mean that revived microorganisms could be used as living biomarkers to determine palaeotemperatures.

Further *in situ* experiments are being developed at the **BUL**. These will be able to provide new insights into the evolution of genomes and proteins, and to yield catalytic proteins with useful environmental and industrial applications.

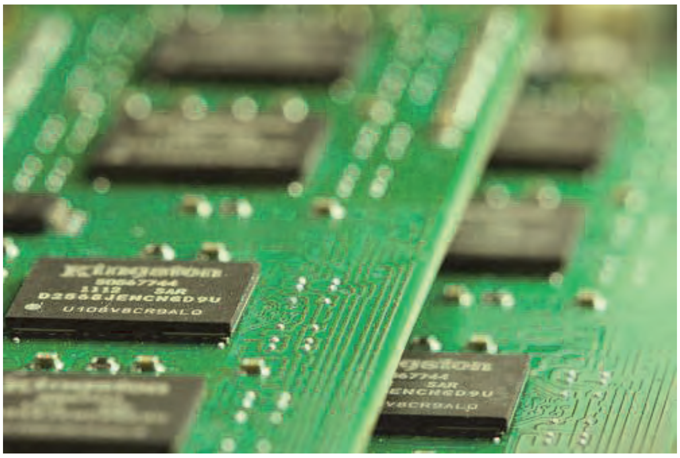
REFERENCES

Cockell CS *et al.* (2011) "Molecular Characterization and Geological Microenvironment of a Microbial Community Inhabiting Weathered Receding Shale Cliffs" *Microbial Ecology* **61**:166–181.
McGenity TJ *et al.* (2000) "Origins of halophilic microorganisms in ancient salt deposits" *Environmental Microbiology* **2**(3):243-250.

3.6. APPLICATIONS

(Credit: willia4/Flickr)

Salt mound (Credit: anijdam/Flickr)



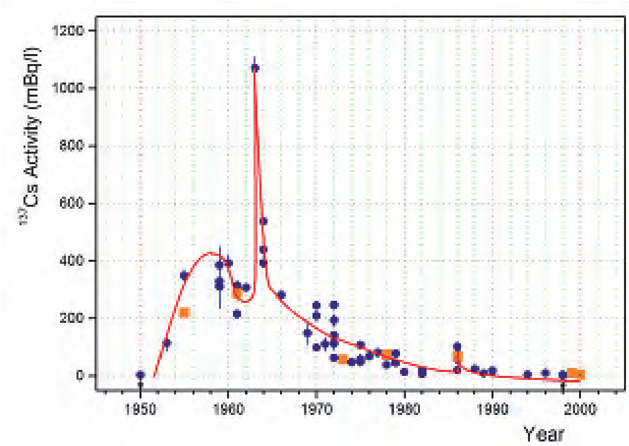
(Credit: Reilly Butler /Flickr)

Auger Borer Twin Boom (*Courtesy of A. Franks*)

3.6.1. WINE DATATION

From the mass of the neutrino to the dating of wine

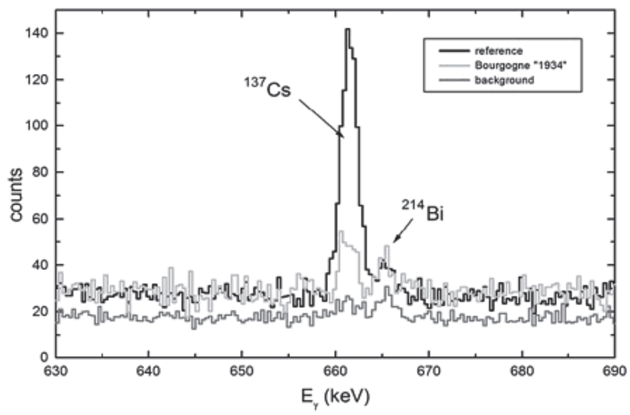
Every material contains some *radioactivity* so its measurement is useful to various disciplines, ranging from ApP to medicine, environmental sciences, archaeology, etc. The process of radioactivity corresponds to the spontaneous transformation of a nucleus into a daughter nucleus, followed by one or several gamma rays whose energies are typical of the decaying nucleus. The detection of these rays with a high energy resolution gamma spectrometer indicates the presence of the radioactive nuclei in the measured sample. Moreover, the intensities of the lines are directly related to the activity (in Bq/kg) or number of radioactive nuclei present in this sample.



Activity (mBq/l) of the ^{137}Cs radioactive isotope as a function of the wine vintage. The solid circles correspond to measurements after reduction of the wine into ashes, the orange squares correspond to non-destructive measurements, i.e., without opening the bottles. ^{137}Cs activity starts to be observable in wines from the beginning of the 1950s, reaches a maximum in 1963, date of the signature of the Partial Test Ban Treaty limiting atmospheric nuclear tests, and then decays down to 1986, date of the Chernobyl accident. (Credit: from Hubert P *et al.* (2009))

The **Neutrino Ettore Majorana Observatory (NEMO)** experiment currently running in the **Underground Laboratory of Modane (LSM)** is studying the neutrinoless double beta decay. To select and control the natural radioactivity in the materials needed to build the detector, ultra low background gamma ray spectrometers based on the use of HPGe crystals have been developed. Although this was the main purpose of these low background detectors, Astroparticle Physicists were asked a few years ago by the DGCCRF (a French government agency charged with protecting consumers and preventing fraud) to look at the possibility of dating expensive bottles of wine from the late 19th or early 20th century through this technique. The reason was that, as for any expensive material, some people had launched on the market fake bottles, whose detection was almost impossible, especially if the glass, label and cork have been retrieved from an authentic bottle, i.e. a bottle from that era.

Using the LSM low background detectors on red Bordeaux wines, physicists at the Centre d'Etudes Nucléaire de Bordeaux Gradignan (CENBG) have detected presence of very weak traces of isotope ^{137}Cs (below 1 Bq/l). Moreover they have shown that the ^{137}Cs activity is dependant on the wine's age. Therefore, CENBG and **LSM** researchers investigated the possibility of finding a set of certified "millésimes" (ages) in order to create a reference curve against which wines can be tested (see figure on the left): according to this curve, wine keeps the memory of the atmospheric nuclear tastings (1950–1963) and the Chernobyl accident (1986). Such a curve can be exploited to estimate the age of a given wine, or at least to control the year written on the label or on the cork and detect any anomalies. If a wine is said to be from before 1950 and it has ^{137}Cs traces, then it is counterfeit (see figure below). The technique has been developed to such an extent that it is now possible to carry out these measurements without even opening the bottle, an especially important achievement given the purpose for which it is used.



Partial gamma spectra showing the ^{137}Cs line recorded with three different bottles: first with a bottle of Médoc 1963 (reference), second with a bottle of Bordeaux 2003 used for a background measurement and third with a red Bourgogne labeled 1934. The ^{137}Cs peak at 661 keV is clearly visible in the Bourgogne spectrum, showing immediately that this bottle is a counterfeit.(Credit: from Hubert P *et al.* (2009)).

REFERENCES

Hubert P (2007) "From the mass of the neutrino to the dating of wine" *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **580**(1): 751-755.

Hubert P *et al.* (2009) "Radioactivity measurements applied to the dating and authentication of old wines" *Comptes Rendus Physique* **10**(7):622-629.

3.6.2. SALT CHARACTERISATION

Salt extraction site from around 5,500 BC

The salt spring near the village of Moriez in the Alpes-de-Haute-Provence (France) is located in the southern subalpine chains, at the junction of two overthrusted units. The local geology consists of a group of strike-slip faults evolving sometimes into overthrusts in its southern parts. Artefacts found at the salt spring of Moriez were removed from these Triassic evaporitic formations: a shaft was dug into them, in the alluvial deposits of a torrent.

In 1998-1999, archaeological excavations took place in the interior of the shaft, which is in the centre of a circular room built of limestone. At the bottom, at a depth of 9.2m and a few centimetres below the base of the foundations, several fragments of wood were discovered, stuck vertically into a detritic sediment of gravel packed in compact clay. These small stakes, split in their upper part, were disposed at equal distances from each other. Twelve of these artefacts were discovered, and six of them were studied and dated. Wood samples were taken for ^{14}C dating at the **Underground Laboratory of Modane (LSM)**.

The results from these analyses lead to the hypothesis that the pieces of wood are contemporary and may have an average age of 6,795 ± 40 years BP (calibrated dates 5,735, 5,624 BC). These dates are among the oldest in Europe, and are comparable to those obtained for the salt extraction sites of Lunca-Poiana Slatinii in Romania, recently dated to the Cucuteni culture.

View of the site from inside the drystone wall. (Credit: D. Morin).

The stakes may be the remains of older structures devoted to salt extraction, interpreted as a structure for collecting salt by a mesh system, using interlaced branches, perhaps the remains of a tank or supports for evaporation structures.

The examination of the wood resulted in an interpretation of reasoned actions, which confer upon these vestiges the status of one among the oldest salt extraction sites known in Europe. Although partial, this information also brings to light a previously unknown aspect of the implementation of a process in the evolution of wood working techniques in Europe over these last eight millennia.

The shaft bottom. The sticks, being pointed at by the person on the left, can be clearly seen. The artefacts are sunk into the highly salty clay sediment levels, beneath the first level of modern foundations. (Credit: D. Morin)

REFERENCE

Morin D, Lavier C & Guiomar M (2006) "The beginnings of salt extraction in Europe (sixth millennium BC): The salt spring of Moriez (Alpes-de-Haute-Provence, France)" *Antiquity* **80**:309.

Fontugne M, Jaudon M And Reyss JL (1994) "Low background CO2-gas proportional counters at the Underground Laboratory of Modane (73)" 15th International Radiocarbon Conference, Glasgow (UK).

3.6.3. SOFT-ERROR RATE IN ELECTRONICS

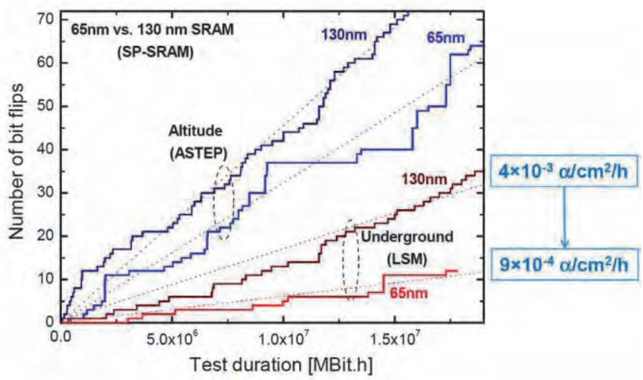
Semiconductor memory errors

Soft-errors induced by natural radiation are considered as one of the most important primary limits for modern digital electronics reliability. Complementary metal–oxide–semiconductor (CMOS) is a technology for constructing integrated circuits (ICs). CMOS technology is used in microprocessors, microcontrollers, static RAM (SRAM), and other digital logic circuits. As CMOS devices continue to be scaled down, the sensitivity of integrated circuits to radiation coming from the natural terrestrial environment (primarily atmospheric neutrons) or induced by on-chip radioactive impurities (source of alpha particles) has been found to seriously increase, sufficiently to be considered as a major reliability problem by several semiconductor manufacturers. Current memory ICs become more and more sensitive to single-event upset (SEU) due to the constant reduction of the supply voltage and node capacitance.

Test benches installed at LSM (Credit: LSM)

The accurate characterization of the soft-error rate (SER) of circuits at ground level however is rather a complex task because one cannot clearly separate the contribution of atmospheric particles (the external constraint) to SER from the one due to natural alpha-particle emitters generated from traces of radioactive contaminants in CMOS process or packaging materials (the internal constraint).

At ground level – on the Altitude Single-event Effect Test European Platform (ASTEP) – and at the **Underground Laboratory of Modane** (**LSM**), natural radiation-induced soft errors in static memory SRAM technologies (130 nm and 65 nm) were evaluated a real-time (i.e. life testing) approach based on the constant monitoring of several hundred of high capacity circuits. These long-time experiments (more than 20,000 h of operation at **LSM** for the 130 nm technology) allowed us to detect and to separate the rare events – changes in the logical state (0→1 or 1→0 transitions) of a few tens of memory points on several billions – induced by atmospheric neutrons from that caused by on-chip alpha-particle emitters. This later was found to be five times larger than the neutron contribution at sea-level, demonstrating the importance of alpha-particle emitter contamination of silicon and other microelectronics materials at ppb (part per billion) level and below. These experiments also clearly show and quantify in natural environment the growing importance of the multiple cell upsets (MCU) mechanism (upset of two or more adjacent cells by a single ionizing particle) when considering decananometer technologies. In the example below, the 130 nm technology exhibits a higher soft-error rate (directly linked to the slope of the curves) than the 65 nm one, both for underground and altitude tests. In addition, these two technologies show differences in MCU occurrence, clearly highlighted by the "staircase shape" of the curves: the 130 nm distribution has very regular stairs (each step corresponding to a single event upset or bit flip), whereas the 65 nm curves exhibit irregular and marked stairs, which correspond to a kind of "visual signature" of MCU events.



Comparison of error rate between 65 and 135 nm technologies in altitude and in LSM (Credit: LSM)

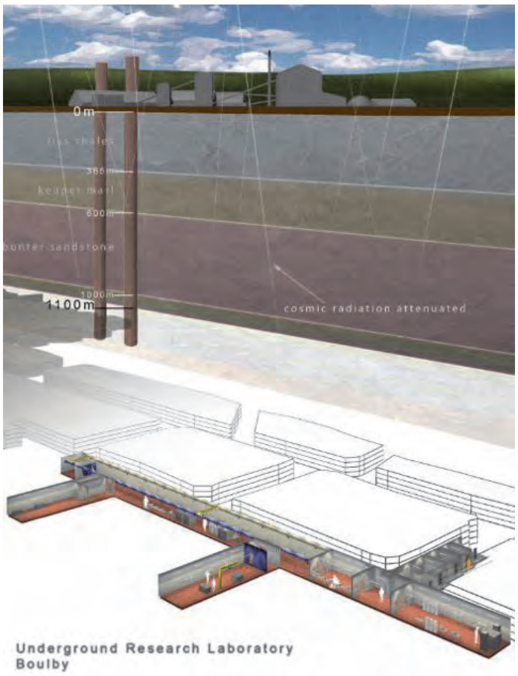
REFERENCE

Autran JL *et al.* (2010) "Soft-errors induced by terrestrial neutrons and natural alpha-particle emitters in advanced memory circuits at ground level" *Microelectronics Reliability* **50**(9-11): 1822-1831.

3.6.4. ROCK DEFORMATION

How does a rock body change during deformation?

Rock mechanics and engineering are more and more integrated in society in order to assist in the discovery of minerals, construction of storage facilities as well as city planning. Challenges of rock engineering in the mining industry include the development of experience-based design criteria, the determination of reliable input parameters for numerical modelling, the intelligent use of the changing stress field, the support of temporary mining excavations and maximising extraction of the mineral deposit whilst maintaining high safety standards.



(Credit: Boulby Underground Laboratory)

The Boulby Mine, situated on the northeast coast of England, is a major source of potash, primarily for use as a fertiliser, with rock salt (halite) as a secondary product (see Section 3.5.8). The deposits are part of the Zechstein formation and are found at depths of between c. 1,100 and 1,135 m below sea level. The evaporite sequence also contains a range of further lithologies, including anhydrite, dolomite and a mixed evaporate deposit.

From a scientific perspective, the dry uncontaminated nature of the deposits, the range of lithologies present and the high stress conditions at the mine provide a unique opportunity to observe rock deformation *in situ* in varying geological and stress environments. To this end, the **Boulby Underground Laboratory (BUL)** Geoscience Project was established to examine the feasibility of developing an underground research laboratory at the mine.

Information regarding the mechanical properties of the strata at the Boulby Mine is required to develop our understanding of the strength and deformation behaviour of the rock over differing timescales in response to variations in the magnitude and duration of applied stresses. As such data are currently limited, a laboratory testing programme has been developed that examines the behaviour of the deposits during the application of differential compressive stresses.

Experiments have been carried out using a high pressure Virtual Infinite Strain (VIS) triaxial apparatus (250 kN maximum axial load; 64 MPa maximum cell pressure) manufactured by GDS Instruments. Conventional compression tests under uniaxial and triaxial conditions have been undertaken to determine the effects of axial stress application rate, axial strain rate and confining pressure on behaviour and failure mechanisms.

The experimental programme also includes advanced testing into time-dependent creep behaviour under constant deviatoric stress; the effects of variations in temperature and stress path loading on peak shear strength and deformation behaviour; and the effects of low frequency cyclic loading on evolution of material properties. These results have major implications for the design of sub-surface excavations.

Heliminer and operator at Boulby potash mine (Courtesy of A. Franks)

REFERENCE

Brain MJ *et al.* (2009) "The **Boulby** Geoscience Project Underground Research Laboratory: Initial Results of a Rock Mechanics Laboratory Testing Programme" American Geophysical Union, Fall Meeting 2009, abstract #H23E-0997.

4. PERSPECTIVES FOR THE FUTURE

The large but not exclusive list of synergies presented in this report proves that **Astroparticle Physics** research can be multiply linked to other scientific fields through its advanced methodologies, technologies and infrastructures. Successful collaborations with scientists working in the fields of oceanography, seismology, climatology, volcanism, glaciology, atmospheric physics and chemistry, meteorology, geodynamics, environmental radioactivity, biodiversity, microbiology and many others have been established. Thanks to the great diversity of the scientific fields involved, ASPERA has been encouraging Astroparticle Physicists to seek the cooperation of communities from other sciences, not only for the benefit of the results in these other fields, but to ease access of the general scientific community to the large-scale ApP projects.

In addition, these synergies will also facilitate the tackling of socially relevant issues that demand a more integrated approach, that has not achieved so far. As more processes are identified and evaluated, the need to compare and understand potential connections and feedbacks between processes is increasing. A clear way to bring greater continuity across disciplines, in terms of both space and time, is to promote collaborations between scientists from different disciplines around research infrastructures characterised by their ability to take standardised and integrated *in situ* observations.

The synergies that are mentioned in this report could be said to relate to four broad socioeconomically important topics that span numerous spatial and temporal scales: Climate change, Geo-hazards, Energy and Biodiversity. Given the gravity of these issues for our planet's future, in this section each of these topics will be further discussed. If the synergies described in Section 3 of this report were described in order to show advances that come out of collaborations of scientists from different fields, the following sections are meant to stimulate a debate on possible innovative synergies that have not yet or have been partly touched.

(Credit: °Florian/flickr)

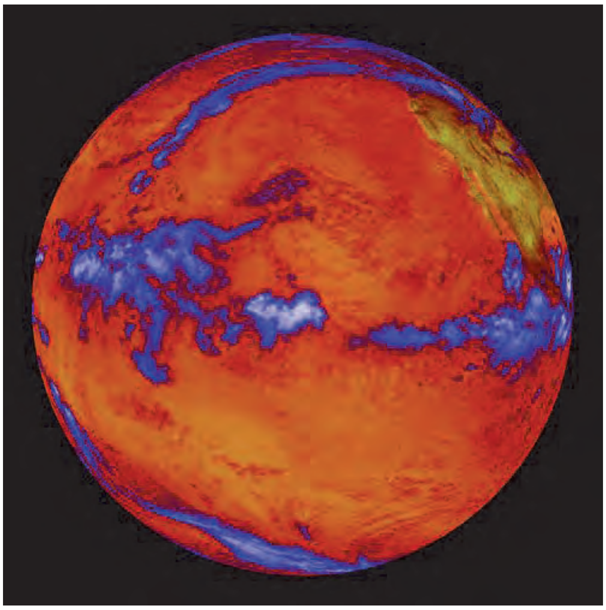
4.1. CLIMATE CHANGE

The significant implications of climate change for both the human population and the ecosystems that we depend on have already become apparent. Our oceans for example, are already suffering from increasing environmental degradation, acidification, hypoxia, over-fishing and loss of habitat and biodiversity. An improved understanding of the effects of these changes on the ocean environment is thus necessary for our continued existence. It is thus not surprising that climate is increasingly the subject not just of public debate but also of intensive scientific research.

Until recently, efforts have been centred on two responses to climate change: mitigation and adaptation. Mitigation is the long term reduction of emissions of greenhouse gases by all sectors of society (e.g. energy production, transportation). The other currently used option is adaptation which concentrates on the protection of important assets such as power stations, transport links and population centres from the predicted effects of climate change, i.e. flooding, overheating and sea level rises. Geo-engineering, the technology that will slow the global temperature rise by either removing carbon dioxide directly from the atmosphere or reflecting solar radiation back into space, represents a third option, not used yet since research in this area is still at the infancy level.

In this report, a number of ways that ApP infrastructures have been used to contribute to our understanding of past and present climate have been described. At the **Pierre Auger Observatory** a large database of atmospheric measurements has been created, which includes aerosol and cloud coverage data (see Section 3.1.2). The recently published **CLOUD** results showed that ionisation from cosmic rays significantly enhances aerosol formation, a finding that will contribute to a better assessment of the effects of clouds on climate models (see Section 3.1.3). At the **IceCube** neutrino detector in Antarctica, background muon rates were found to be a very good proxy of atmospheric temperature variation at the level of the ozone layer (see Section 3.1.4).

At the **Underground Laboratory of Modane (LSM)** radionuclide datings (^{210}Pb, ^{137}Cs and ^{241}Am) of lake sediments were carried out in order to understand the paleoclimate of the lake (see Section 3.2.3). Furthermore, the **IceCube** collaboration developed a new instrument that detected an apparent causal relationship between climate changes and faint volcanic fallout layers (see Section 3.2.4).



As the surface and atmosphere warm, they emit thermal long wave radiation, some of which escapes into space and allows the Earth to cool. This false colour image of the Earth was produced by the Clouds and the Earth's Radiant Energy System (CERES) instrument flying aboard NASA's Terra spacecraft. The image shows where more or less heat, in the form of long-wave radiation, is emanating from the top of the Earth's atmosphere. (Credit: NASA Marshall Space Flight Centre Collection)

Finally, the Mediterranean underwater neutrino detectors are measuring the most important ocean components, including salinity, temperature, dissolved gases (oxygen and carbon dioxide), radioactivity, nutrients, and pH (see Sections 3.3.1, 3.3.2, 3.3.3 and 3.3.4). Given that the ocean plays a critical role in our climate system and is significantly impacted by climate change, the very detailed real-time records of the state of the oceans produced by these detectors is predicted to greatly contribute to climate change research. Furthermore, at the **LSM**, dating methods are used to determine the ages of corals to obtain insights into past climate and ocean circulation changes in intermediate and deep-sea water masses (see Section 3.3.5).

But these synergies are only a small sample of how ApP infrastructures, placed underground, underwater or overground, originally constructed to study our universe and to serve the needs of Astroparticle Physicists, could contribute in the field of climate research. Climate scientists should collaborate with

Astroparticle Physicists in order to find other ways in which the ApP infrastructures can serve their interests.

For example, underground ApP research infrastructures could be ideal for investigating the issue of carbon capture and storage (CCS). Also known as carbon sequestration, CCS is a type of response to climate change that belongs to the family of geoengineering methodologies, supported by those who believe that there is little chance of reducing CO_2 levels to the appropriate levels. Consequently, CO_2 – especially from power stations – has to be captured and be permanently stored underground. Once the CO_2 has been captured, it needs to be liquefied, transported and buried, either in suitable geological formations, deep underground saline aquifers or disused oil fields.

A good understanding of the geological environment in which CO_2 will be buried in is thus required. The **CRONUS-EU** project are using cosmogenic nuclides to measure how fast Earth's surface changes from forces such as erosion (see Section 3.2.1). In the UK, at the **Boulby Underground laboratory** , scientists are already researching rock mechanics (see Section 3.6.1). They are also studying coastal geomorphology, in order to predict the effects of the implied threats of climate change and sea-level rise on coastlines (see Section 3.2.2).

Another option is to store the CO_2 in underwater emptying natural gas fields. But not all countries have access to such fields. It has therefore been suggested to pipe waste gas directly into the sea, since in very deep waters CO_2 is thought to form a dense slush that could stay on the seabed for hundreds of years. The deep sea pilot detectors in the Mediterranean and the future cubic kilometre sized neutrino detector, **KM3NeT**, could be used in order to investigate the feasibility of underwater CCS and its impact on deep-sea life.

Credit: TONY CRADDOCK/SCIENCE PHOTO LIBRARY

4.2. GEOHAZARDS

Geohazards are events caused by geological processes that pose severe threats to humans and our environment, whether natural or built, such as earthquakes, floods, landslides, volcanoes, avalanches and tsunamis. Given the thousands of deaths caused yearly by geohazards and the great costs of repairing the damages that they create, it is urgently required to understand the technical risks posed by geohazards and how can we best deal with them. The need is accentuated by increased vulnerability of rapidly growing urban centres in geohazard-prone areas and by climate change that will result in even more extreme weather in the future, leading to an increased frequency of geohazards.

Accurate and timely earthquake prediction is still an elusive goal for geologists. But how will the science of earthquake prediction come out of the Dark Ages and enter into the 21st century? The help of non-traditional fields or theories might be able to break this apparent "logjam" that has been developing in the last decades.

(Credit: DAVID PARKER/SCIENCE PHOTO LIBRARY)

There are growing scientific bodies seeking to address earthquake prediction and forecasting using various alternative methodologies, some of which were mentioned in this report. Near the **Pierre Auger Observatory** in Malargüe, Argentina, an array of 80 seismic stations will be installed in 2012, aiming to monitor and image the subsurface and the Peteroa volcano over a large area, achieve detailed imaging of the lithosphere and to localize local seismic activity, all using recently developed techniques in collaboration between Astroparticle Physicists and geoscientists (see Section 3.4.1). At the **Low Noise Underground Laboratory (LSBB)** of Rustrel and the **Gran Sasso Underground Laboratory** in Italy, Astroparticle Physicists with other scientists are investigating if electromagnetic signals and uranium groundwater anomalies, could be the 'magic' earthquake precursors that could allow accurate earthquake prediction (see Sections 3.4.4 and 3.4.5). In addition, very-low frequency, high-sensitivity records of ground deformation are used to improve the real-time picture of seismic activity by the **UnderSeiS** and **GIGS** projects at the **Gran Sasso Underground Laboratory** (see Section 3.4.6).

Finally, the **ANTARES** underwater neutrino detector, near the continental plate boundaries of Southern Europe, includes instruments (broadband seismometer, an accelerometer, a differential pressure gauge, an absolute pressure sensor, sea floor deployment, data transmission) for studying the forces that can sway the buoys used to position the photomultipliers (see Section 3.4.2). Underice (and in the future underwater) neutrino telescopes are and will be carrying Earth tomography with high–energy cosmic neutrinos that will provide information on the global structure of our planet's core, mantle and their boundary region (see Section 3.2.7).

Even if earthquakes are often considered the most important geohazards, tsunami is another type of geohazard that is relatively rare, but as was shown by the recent tragic event in Japan, can have devastating consequences. At the **ANTARES** neutrino detector, pressure data is transmitted to the RATCOM centre, a prototype of regional tsunami alert centre in Ligurian Basin, which is able to manage a complete tsunami alert ranging from the detection of the ongoing event to the population warning (see Section 3.4.2). The **NEMO** collaboration has also been testing a Tsunami Early Warning System that uses and automatically analyses real-time hydro-acoustic measurements to provide states of variable alert-level for coastal areas (see Section 3.4.2).

Finally, the **DIAPHANE**, **MU-RAY** and **TOMUVOL** projects have developed a technique that allows them to take volcano muon tomographies, which can be used to evaluate the present state of the volcano within its eruption cycle, estimate its evolution in the near future, and quantify the associated risk for surrounding inhabitants (see Section 3.2.5). Such a tool could become useful in predicting volcano eruptions.

These are just a few of the possible ways that ApP infrastructures could contribute in the field of geohazard research. For example, ApP infrastructures are likely to be ideal for placing subsurface imaging -sensor networks for geohazard detection. Such research is being planned at the american ApP underground laboratory **DUSEL**, where they are proposing to install a vertical array of 2D tiltmeters spanning nearly 2km in depth, ultimately having 10 high-accuracy tiltmeters ranging from 300-ft depth to 6800-ft depth (Dahlgren *et al.*, 2010). This array, in addition to studying the health of the facility, the enhanced array would permit study of "Earth tides" and performing time-series and correlation analysis of wideband ground motion.

4.3. ENERGY

The energy needs of the human population are predicted to increase massively by the middle of the 21st century, both because of the population increase but also of the change of lifestyle. In order to supply this increasing thirst for energy, great efforts are being put to drain and use more efficiently energy resources store them and monitor their environmental impact.

ApP infrastructures have been involved on all aspects of these efforts. Only examples will be described below.

Underwater 10 megawatt tidal stream project in the Sound of Islay between the Hebridean islands of Islay and Jura. (Credit: ScottishPower Renewables)

a) ENERGY PRODUCTION

Increasingly, scientists and engineers around the world are trying to discover new sources of energy that are not aggravating climate change. The underwater neutrino detectors in the Mediterranean sea could be used in various ways to contribute in research that goes into marine energy. For instance, scientists have been exploring how to exploit sea currents to produce energy. Tidal turbines, in other words underwater windmills, are among the studied marine energy technologies. Tidal energy is predictable – since tides are regular – and very efficient – since tides are very frequent – meaning that a relatively small device can create a relatively large amount of electricity. Before tidal energy becomes the new champion energy however, it should be kept in mind that only 20% of present global energy demand could be generated by tidal power (if we could extract it all) and that it is expected to have devastating effects on the ocean ecosystem since turbines are placed in extraordinarily rich in ecologically fragile marine life (van Haren, 2010).

Neutrino detectors, given that they are placed in deep waters, they can help investigate how effective would such schemes be if they are placed in deep waters, where the environmental consequences are likely to be diminished. Furthermore, wet mate connectors have been developed in the context of the Antares neutrino telescope and are currently in the industrialisation phase[32]. They could play a major role in the transfer of offshore renewable energy. Patents for both deep sea windmills and deep sea connectors have been deposed.

b) ENERGY STORAGE

Our current levels of energy consumption produce a variety of waste compounds, such as CO_2, NO_x and SO_x. Although great efforts are put in the development of more efficient and alternative energy systems that may indeed lead to reductions in the levels of emissions, in the 21st century at least, fossil fuel will remain the most common energy source.

Reduced emission targets for waste compounds such as those mentioned above could be reached if these compounds are stored below the surface, either on land or in the oceans. But how they will be stored is still not known. Given the relatively young age of research in this field, whereas many sequestration methods have been proposed, their relative effectiveness is still being debated. In the case of energy storage below the Earth's surface on land, facilities are needed that will allow us to compare and test in the field these methodologies. Because before these are used, it is vital that the rates of CO_2 leakage and conversion to bicarbonate and carbonate have been evaluated. Equally important is to predict the impact that such storage will have on subsurface microbial ecosystems (e.g. Section 3.5.8) and the physical properties of the rock (e.g. Section 3.6.4). Underground facilities developed for ApP can allow

[32] In 2011, consequent funding was received from the Provence Alpes Côte d'Azur (PACA) Marine Competitivity Centre for the project PowerMate in which ANTARES researchers, industrial partners (SubseaTech,EDF) whereas co-financiers included FUI (France-UK-Ireland (FUI) electricity region) and European Regional Development Fund (ERDF). PowerMate aims at the development and qualification of a completely new concept of underwater electrical connector to transmit to shore power produced by renewable energy systems at sea.

testing of this new strategy for emission reduction *in situ* and through the analysis of real time data.

For instance, studies carried out in the ApP underground laboratories will allow the prediction of what could be the effects of induced fractures during the underground storage of CO_2 or other waste compounds. In addition, research could also be carried out to investigate how induced fractures could affect the methods used for the storage of nuclear waste and other similarly hazardous materials, already stored in underground repositories. Knowledge of fractures and fracture networks is also important to studies of groundwater flow, recovery of gas and oil and rock mechanics.

More generally, underground laboratories can perform multi-variable studies to determine the relation among thermal, mechanical, hydrological, chemical, and biological processes in the subsurface environment by instrumenting large subsurface areas and characterize fracture zones (for more details see McPherson *et al.* (2003)).

c) ENERGY EFFICIENCY

The development of distributed networks of smart autonomous sensors are one of the ways of increasing the energy consumption efficiency. The technologies developed in the **Pierre Auger Observatory** but also other **ApP** infrastructures have been pushing this frontier, by instrumenting large and hostile areas with smart sensors. In particular, some of the experimental work in underground laboratories focuses on the development and testing of low-cost miniaturized sensors, which can deployed and distributed over a large area. Another requirement is that researchers must be able to obtain through these sensors high-quality data, at high sampling rates and for long durations. Thus, underground and underwater laboratories can serve as a test bed for new sensor technologies in extreme environments.

D) ENVIRONMENTAL IMPACT

Accidental oil spills and chronic oil pollution are great and constant threats to the ocean environment. For instance, the *in situ* biodegradability of heavy fuel oil and its impact on the biodiversity of sedimentary microbial and communities were studied at the **ANTARES** neutrino detector site, in order to investigate their oil degrading abilities (see Section 3.5.4).

(Credit: marinephotobank/Flickr)

4.4. BIODIVERSITY

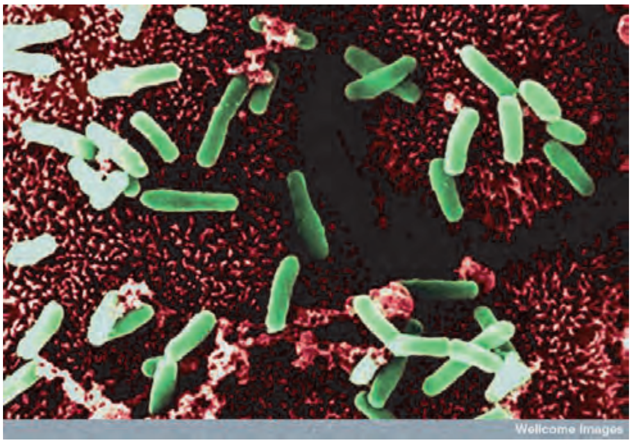
Biodiversity is a vast but undervalued resource, which through its interactions with the lithosphere, the hydrosphere and the atmosphere is shaping our planet. It is thus important to understand it at every level, from single-cell organisms to ecosystems. This is of special interest to humanity since it allows us to live the way we do, providing us with food, energy and materials, but also services such as protection against diseases. Biodiversity also affects the environment in which we live in, from the soil on which we build our houses, to the air with breath and the water we drink.

Over the past decades, biologists collaborating with Astroparticle Physicists have greatly contributed in our understanding of biodiversity, taking advantage of the exotic environments in which their research infrastructures are placed.

The **Pierre Auger Observatory** provides the necessary infrastructures for biologists to measure temperatures and further parameters in the soil and above ground over a large area of the Argentinean pampa amarilla and over extended periods of time. The data obtained by these data loggers are used to determine the possibility of extinction of populations of three species of lizards as a result of the gradual increase of temperature due to climate change. Even if it has been predicted that climate change will cause species extinctions and distributional shifts, data to validate these predictions are relatively scarce, so the role of the **Pierre Auger Observatory** will be vital in finding such data.

(Credit: Med. Mic. Sciences Cardiff Uni, Wellcome Images)

The approximately radiation-free environments of the Underground Laboratories of **Modane** and **Gran Sasso** are used to investigate the effect that radiation has on DNA and what could have been its effect on the origins of life (see Section 3.5.7). On a larger scale, when the **NEMO** neutrino detector was used to listen to the deep ocean world, sperm whales were detected that were previously considered to be very rare in the region (see Section 3.5.1).



(Credit Med. Mic. Sciences Cardiff Uni, Wellcome Images)

A wide range of studies have been carried out in microbiology. In the ocean, the globular eyes of **ANTARES** neutrino telescope were used to pick up light from bioluminescent bacteria (see Section 3.5.2). In addition, microbial rates were measured under *in situ* conditions (e.g. high-pressure, low temperature, ambient food availability) to investigate flow of matter and energy (see Section 3.5.5). In the ice, the Biospectral Logger developed by members of the **IceCube** collaboration detected bacteria that are capable of living in ice at temperatures tens of degrees below 0°C (see Section 3.5.3). Underground, at the **Boulby Laboratory**, scientists are trying to discover the origins and biology of ancient halophilic communities (see Section 3.5.8).

The above synergies have shown that the contribution of ApP research infrastructures to microbiology has been especially successful. Recommending that collaborations such as these should continue is thus a logical conclusion. However, scientists collaborating around ApP infrastructures have the ability to go one step further, by taking advantage of the extreme environments in which the infrastructures are placed:

the biological processes, genes, characteristics of organisms that live in these extremely restricting environments, could lead to insights into the field of microbial engineering, the practice of genetically optimizing metabolic and regulatory networks within cells to increase production and/or recovery of certain substance from cells. In this way, collaborations of Astroparticle Physicists with other sciences have the potential to contribute in medicine, engineering, energy, etc.

A major challenge in this field is the identification of the key components and their subsequent production. To face this challenge, extensive ecological observations are required in order to improve our capability for producing these valuable natural products. *In situ* metagenomics, which can take place at ApP infrastructures, could give clues into the interactions of genes with their environments, in this way revealing important metabolic aspects, which are not otherwise discernable in the restrictive laboratory settings. *In situ* measurements can also reveal information on microbial ecosystems and microbial oceanography. Collaborations with existing European collaborations such as **Marine Genomics Europe**[33] and **LifeWatch**[34], are likely to be especially fruitful.

In addition, underwater neutrino detectors could become great sensors of climate change. As demonstrated in this report, they are taking *in situ* continuous and real-time measurements of the many factors that are affected and affect phytoplankton: temperature, underwater currents, temperature, pollution, sediments, CO_2 concentrations etc. Phytoplankton is especially important for the health of our oceans, and indirectly of our climate, by forming the base of the marine food chain. Given that even small changes in the growth of phytoplankton may affect atmospheric carbon dioxide concentrations then feeding feed back to global surface temperatures, phytoplankton is the first indicator of climate change. Thus, through measuring all the factors that affect it, the ApP infrastructures could become the first climate change sensors.

[33] http://www.marine-genomics-europe.org/
[34] http://www.lifewatch.eu/

4.5. TOWARDS COLLABORATIONS WITH OTHER SCIENCES

Even if scientific research aims to understand a fully integrated world, until recently it has been largely confined in separate disciplines due to the traditional one-discipline departmental structure of universities, research centres and research funding bodies. When synergies between different sciences take place however, the benefits are expected to add up to more than the sum of the involved disciplines. Especially in the case of the emerging complex global challenges, such as those in Sections 4.1-4.4, new approaches and skills are required in order to benefit from the new ideas that emerge, which will in turn lead to major technological and scientific breakthroughs, such as those that have been known to happen on discipline intersections. Until recently, much research falling under this category has tended to slip between the cracks of different disciplines. A re-integration of disciplines is needed, but what is the best way to do this?

In Sections 3 and 4.1 - 4.4 of this report, the existing or possible advantages of collaborations between ApP and other sciences have been shown. In this Subsection, it is first investigated what could be the best format for such collaborations and then what barriers have been detected in existing collaborations. **ASPERA** also asked ApP scientists already collaborating with other fields, what actions are required in order to get the necessary major breakthroughs.

(Credit: created by *Libby Levi* for opensource.com)

4.5.1. WHAT TYPES OF COLLABORATION?

In current literature, in the future Framework Programme 8 "Horizon 2020" and increasingly in funding body future plans, interests appear to promote "interdisciplinary research", a general term used to describe research carried out by collaborations of scientists from different disciplines.

Interdisciplinarity is often used as an all encompassing term, which includes "multidisciplinarity". There is however great debate on what each term means and what types of research should be described as the one or the other. The definition of these terms is beyond the scope of this report, but before any further discussion takes place, it is necessary to mention that have the two terms are distinguished according to how the scientific problem is defined: a study is considered to be interdisciplinary when the resolution of a scientific problem in one field requires knowledge and/or originating in another field. The true sign of convergence is when theories and instruments are merged on the frontier of the two fields. On the other hand, a study is considered to be multidisciplinary when the problem or the infrastructure comes from one discipline, but both fields are involved in the methodology used to tackle the program (EURAB, 2004). As a consequence, in the former case publications of the findings are shared between the disciplines – the language used intelligible to all fields involved in the research – whereas in the latter case, scientists from each discipline publish separate publications (Aboelela *et al.*, 2007).

In a recent report by **ASPERA**, a questionnaire was distributed to the ApP community in order to understand what types of collaborations the community was considering for the interaction between ApP and environmental sciences. Two models at the ends of the spectrum were the "Multidisciplinary Platform" model (which could be said that belongs to the multidisciplinary approach) and the "Integrated Project" model (which could be said that belongs to the interdisciplinary approach).

According to the "**Multidisciplinary Platform**" model there is a transfer of technologies and methodologies from the ApP domain towards the environmental sciences, but the project is fully motivated by a scientific problem defined within the environmental sciences. The key features of this model are: the application of specific sensors for environmental science research on existing ApP infrastructure and the use of ApP data for environmental sciences research. In this model, ApP scientists collaborate with the environmental scientists, but the results of the environmental science are not of direct interest for ApP research. Typical examples of this model are the marine synergies at the **ANTARES** underwater site (see Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.4.2 for examples).

The second model, named "**Integrated Project**", the environmental science project is intimately linked to the ApP project. In this case, the ApP physicists develop or apply procedures and technologies for environmental research, modify them and integrate them in their own infrastructure. A typical example is atmospheric science at the **Pierre Auger Observatory**, where high-end equipment developed for atmospheric physics is used (see Sections 3.1.2). It is interesting to note that in the **Pierre Auger Observatory**, the competence in atmospheric physics has been developed within the collaboration and that, as mentioned above, scientists in charge of these activities are now integrating the community of atmospheric physics and chemistry. These "integrated projects" are double-sided: firstly they are aimed at supporting the ApP collaboration by providing the required understanding of the media used (ice, water, mountains, atmosphere) and, secondly, they target scientific issues within the environmental science domain.

4.5.2. WHAT BARRIERS? WHAT CHANGES ARE NEEDED?

A number of papers have investigated the factors that could affect the likelihood of success of such collaborations. Siedlok and Hibbert (2009) for example list a variety of factors which can contribute to their failure, grouped into four categories: (1) Disciplinary (such as cultural barriers), (2) Personal (such as lack of experience and time constraints), (3) Institutional (such as funding schemes, career constraints and authorship/patenting issues) and (4) Procedural (such as lack of access to evaluation tools). Jacobs and Amos (2010) concluded that barriers include communicative and methodological differences between disciplines, the lack of appropriate personal skills of participants, lack of experience of managing such projects, disputes arising between project members, a lack of institutional support, and a lack of appropriate funding and promotional structures within universities.

As part of the workshop "From the Geosphere to the Cosmos" in 2010, a discussion took place amongst the participants on the possible issues that could arise when collaborations between, in this case, environmental scientists and Astroparticle Physicists become a reality. The aim was for members of the community to exchange experiences and opinions, some of which will be mentioned here.

To begin with, all participants recognised the importance of such collaborations. Given that environmental science involves by definition multiple disciplines due to the complexity of the different systems that make up our planet (ecological, geological, hydrological, climate, etc), the participants considered it obligatory that **ASPERA** brings scientists from different disciplines working together around ApP infrastructures. In addition, a large number of similarities in research carried out in the context of different disciplines were found. As a consequence, bringing these scientists together was considered to lead by default to an increase in efficiency and to quicker solutions to the complex global environmental issues.

(Credit: sun dazed/Flickr)

A number of difficulties were however identified by the community. First, it was emphasized that because the environmental issues are very diverse, exchange between scientists can be difficult, especially when no history of collaboration exists, and this is something that should not be ignored.

Furthermore, it was mentioned that there are differences in the way associated fields are structured: environmental sciences seem to be more fragmented than in the case of **ApP.** Actually, in many cases the interaction with ApP was found to have helped other fields to become more structured, through the requirements set by the large research infrastructures. For example, the advantages of using the GRID for data dissemination has united the submarine acoustics community.

Moreover, there are difficulties in integrating data taken by ApP infrastructures to the global data depositories since Astroparticle Physicists do not necessarily know what the universal standards are when other sciences are concerned. For example, atmospheric monitoring data at **Pierre Auger Observatory** must be formatted according to an English standard (e.g. albedo), if data from the **Pierre Auger Observatory** are to be integrated in meteorological network. The equipment used in the observatory for the measurements may be standard, but the environment in which these are placed has to be designed according to universal standards and sometimes this is not the case. At the same time, given how innovative are these synergies, sometimes no standards have been developed so far, as in the case of lightening monitoring (meteorological, aeronautics) (see Section 3.1.3).

But it is not just associated sciences that will benefit from such an interaction: ApP will also benefit from the integration of other sciences into their ApP collaborations, even if such integrations can take a long time due to lack of similar collaborations in the past. For example, **Pierre Auger Observatory** scientists have been slowly integrating the small atmospheric fluorescence community, but it took this community about eight years to be integrated and use methodologies and equipment developed by atmospheric physicists or chemists for ApP research.

A serious issue is the authorship order when research is about to be published. Different disciplines for historical reasons have different rules about how many authors will be in the paper and in which order. For example, biological sciences papers are most usually written by a small number of people, whereas in the majority of ApP papers the whole collaboration is the author, the names of the members of the collaboration in alphabetical order. For example, it was only after more than two years of discussion that a special authorship rule was agreed by the **ANTARES** collaboration, which said that scientists from other fields that have used the **ANTARES** infrastructure to carry out their research will sign the papers first followed by the words 'and the **ANTARES** collaboration'. Different collaborations find different solutions to go around this issue, which can of course deter scientists from other fields in collaborating with Astroparticle Physicists.

Finally, an important issue is the degree of data sharing in these collaborations, since different disciplines are accustomed to different levels of data sharing. Large amounts of public resources are invested on research, facilities and instruments, which generate massive amounts of data. If access to these data was effectively open, science would advance exponentially, but there is a great number of stakeholders involved in the development (or not) of data access regimes: governments, research funding agencies, universities and not-for profit research institutes, international scientific organizations, industry, individual researchers and the general public, each of which promotes their own interests. There is a number of policy considerations that should be taken into account – legal, socio-economic, ethical and governance etc – which may limit the free and unrestricted access to and use of scientific data. In addition, since scientific publications have been for a long time the career drive for scientists, they do not have an incentive to do so. Given that open data access will, among others, reinforce open scientific inquiry, encourage diversity of analysis and opinion, promote new research and new types of research, governments, funding bodies, international collaborations, such as those developed around ApP infrastructures, should focus on promoting open data access.

4.6. SYNERGIES USING ApP INFRASTRUCTURES

"Your planet is very beautiful," [said the little prince]. "Has it any oceans?"

"I couldn't tell you," said the geographer . . . .

"But you are a geographer!"

"Exactly," the geographer said. "But I am not an explorer. I haven't a single explorer on my planet. It is not the geographer who goes out to count the towns, the rivers, the mountains, the seas, the oceans, and the deserts. The geographer is much too important to go loafing about. He does not leave his desk."

Antoine de Saint Exupery (The Little Prince)

Science and technology drive economic prosperity and social development, by providing tools and solutions to tackle the global unprecedented challenges, growing in scale and sophistication and shaping the 21st century world: ecological catastrophes, natural disasters, climate change, increasingly unstable energy security, decreasing levels of mineral and other natural resources, water and food scarcity, etc. The "Europe 2020" strategy objectives of smart, sustainable and inclusive growth depend on research and innovation as key drivers of social and economic prosperity, by providing innovative solutions.

The Innovation Union, one of the seven flagship initiatives of the "Europe 2020" strategy, has called for linking future EU funding programmes more closely to the above societal challenges and bringing researchers from across Europe together in collaborative networks. In many areas of science, the ability to undertake new research is critically dependent on access to advanced research infrastructures, such as the ones constructed for **ApP.** These infrastructures – and the technologies and methodologies developed in their framework – have been found to be fundamental in achieving progress, by laying the base for a vibrant and strong scientific environment in Europe.

As science progresses, a need arises in various disciplines (including **ApP**) for new, more powerful research infrastructures. 36 synergies between ApP and other sciences were described in this report, in order to demonstrate that undertaking joint research with other disciplines around the same already existing research infrastructure produces truly innovative results both across and within disciplines.

Such research should not be undertaken just for the financial benefits that arise from the sharing of resources, but because mixing people from difference backgrounds and with different ideas has been often praised for contributing towards scientific breakthroughs, addressing societal problems and fostering innovation, being better at problem-solving, generating new research avenues by contesting established beliefs and for being a source of creativity (Rafols *et al.*, 2011). One of the drivers behind all these advantages could be that in many of the associated sciences involved in the synergies described in this report, the easily accessible work has been and is being extensively accessed. However, many of the remaining questions being posed defy easy categorisation and fall outside the current easily accessible areas: ApP infrastructures can therefore provide direct access to pose these remaining questions.

In order for these types of research to continue and thrive, the planned ApP research infrastructures first need to be built. The "Magnificent Seven" described in the first **ASPERA** Roadmap (2008) are expected to address some of the most exciting questions about the Universe, but most are currently under design study (e.g. **LAGUNA**) or preparatory phase (e.g. **KM3NeT**, **CTA**). Furthermore, their construction requires large amounts of funding, of the order of hundreds of millions of euros, so access should be provided not just to Astroparticle Physicists, but to the large scientific community.

5. GLOSSARY of ApP CONCEPTS

Cherenkov light: the light emitted when a particle (such as a muon) passes through a medium at a speed greater than the phase velocity of light in that medium. The particle polarizes the molecules of that medium, which then turn back rapidly to their ground state, emitting radiation in the process.

Cosmic Rays: are protons and atomic nuclei that travel across the Universe close to the speed of light. When these particles hit the upper atmosphere, they create a cascade of secondary particles, called an air shower.

Dark Matter: a currently-undetermined type of matter hypothesized to account for a large part of the mass of the universe, but which neither emits nor scatters light or other electromagnetic radiation, and so cannot be directly seen with telescopes. Dark matter is estimated to constitute around 23% of the universe.

Energy measures: the energy unit in ApP is the electronvolt (eV). One eV is equivalent to 1.6×10−19 J. GeV (gigaelectronvolt) is equal to 1 billion eV and TeV (teraelectronvolt) is equal to 1,000 billion eV. These are the energy ranges most interesting to Astroparticle Physicists.

Fluorescence: is the emission of light by a substance that has absorbed light or other electromagnetic radiation. It is a form of luminescence.

Gamma Rays: are electromagnetic radiation of high frequency/energy (very short wavelength). Electromagnetic radiation of high energy is treated as a particle through the particle/wave duality and called generically photon (see *Radiation/Radioactivity* below).

Muon: is an elementary particle similar to the electron, with a unitary negative electric charge and a spin of ½. Together with the electron, the tau, and the three neutrinos, it is classified as a lepton. It is represented by the Greek letter mu (μ).

Neutrino: is an electrically neutral, weakly interacting elementary subatomic particle with a half-integer spin. The neutrino (meaning "small neutral one" in Italian) is denoted by the Greek letter ν (nu). All evidence suggests that neutrinos have mass and that their mass is very small even by the standards of subatomic particles.

Radiation/Radioactivity: Radiation is a process in which energetic particles or energetic waves travel through a medium or space. Radioactivity is ionising radiation, the process by which an atomic nucleus of an unstable atom loses energy by emitting particles. The emission is spontaneous, in that the atom decays without any physical interaction with particles outside the nucleus.

6. ABBREVIATIONS

ADCP	Acoustic Doppler Current Profilers
AMS	Accelerator Mass Spectrometry
APF	Aerosol Phase Function Monitors
BSL	BioSpectral Logger
CCS	Carbon Capture And Storage
CLF	Central Laser Facility
CMB	Core-Mantle Boundary
CTD	Conductivity–temperature–depth
EAS	Extensive Air Showers
FD	Fluorescence Detector of the Pierre Auger Laboratory
FRAM	Photometric Robotic Telescope for Atmospheric Monitoring
GDAS	Global Data Assimilation System
H.E.S.S.	High Energy Stereoscopic System
HAM	Horizontal Attenuation Monitor
IACT	Imaging Atmospheric Cherenkov Telescope
ICME	Interplanetary Coronal Mass Ejections (or magnetic clouds)
IMF	Interplanetary Magnetic Field
IRCC	Infrared Cloud Cameras
LASS	Lightning Air Shower Study
LIDAR	Light Detection And Ranging
LIMS	Light Intensity Measuring System
LMA	Lightning Mapping Array
m.a.s.l./m.b.s.l	metres above/below sea level
MAGIC	Major Atmospheric Gamma-ray Imaging Cherenkov Telescope
PMTs	PhotoMultiplier Tubes
SD	Surface Detector of the Pierre Auger Laboratory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
XLF	eXtreme Laser Facility
LSM	Underground Laboratory of Modane
BUL	Boulby Underground Laboratory

7. REFERENCES

Aboelela SW *et al.* (2007) "Defining Interdisciplinary Research : conclusions from a critical review of the literature" *Health Services Research* **42**(1 Pt 1):329-46.

Al Ali B, Garel M, Cuny P, Miquel J-C, Toubal T, Robert A, Tamburini C (2010) "Luminous bacteria in the deep-sea waters near the **ANTARES** underwater neutrino telescope (Mediterranean Sea)" *Chemistry and Ecology* **26**(1): 57-72.

Ambrosino F for the MuRay Collaboration Team (2011) "The MU-RAY project: volcanoes radiography with cosmic-ray muons" *Geophysical Research Abstracts* **13**:EGU2011-4764-2.

Amoruso A and Crescentini L (2010) "Limits on earthquake nucleation and other pre-seismic phenomena from continuous strain in the near field of the 2009 L'Aquila earthquake" *Geophysical Research Letters* **37**:L10307.

Anassontzis EG *et al.* for the **KM3NeT** consortium (2011) "A light intensity measuring system for sedimentation measurements on **KM3NeT** optical modules" *NIMA Proceedings* **626-627**:S111-S114.

André M, van der Schaar M, Zaugg S, Houégnigan L, Sánchez AM, Castell JV (2011) "Listening to the Deep: Live monitoring of ocean noise and cetacean acoustic signals" *Marine Pollution Bulletin* **63**:18–26.

ANTARES Collaboration (2003) "Sedimentation and fouling of optical surfaces at the **ANTARES** site" *Astroparticle Physics* **19**:253–267.

ARGO-YBJ Collaboration (2011) "Mean interplanetary magnetic field measurement using the ARGO-YBJ experiment" *The Astrophysical Journal* **729**:113.

ASPERA (2011) "European Roadmap for Astroparticle Physics".

ASPERA (2008) "European Strategy for Astroparticle Physics".

Autran JL *et al.* (2010) "Soft-errors induced by terrestrial neutrons and natural alpha-particle emitters in advanced memory circuits at ground level" *Microelectronics Reliability* **50**(9-11): 1822-1831.

Barbier R *et al.* (2011) "A single-photonsensitive ebCMOS camera: The LUSIPHER prototype" *Nuclear Instruments and Methods in Physics Research A* **648**: 266–274

Bay RC *et al.* (2010) "South Pole paleowind from automated synthesis of ice core records" *Journal Of Geophysical Research* **115**:D14126.

Bellou N, Colijn F, Papathanassiou E (2011) "Experimental settlement study in the Eastern Mediterranean deep sea (Ionian Sea)" *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **626-627**: S102-S105 .

Bellou N, Papathanassiou E, Dobretsov S, Lykousis V and Colijn F (final proofs) "The effect of substrate type, orientation and depth on the development of deep-sea bacterial communities on artificial substrata deployed in the Eastern Mediterranean" *Biofouling*

Bordes C *et al.* (2008) "Evidence of the theoretically predicted seismo-magnetic conversion" *Geophys. J. Int. Geomagnetism, rock magnetism and palaeomagnetism* **174**:489-504. doi: 10.1111/j.1365-246X.2008.03828.x

Borexino Collaboration (2010) "Observation of geo-neutrinos" *Physics Letters B* **687**(4-5) : 299-304.

Borriello *et al.* (2009) "Sensitivity on Earth Core and Mantle densities using Atmospheric Neutrinos" *JCAP* **06**:30 and arXiv:0904.0796.

Boswell R and Collett TS (2011) "Current perspectives on gas hydrate resources" *Energy & Environmental Science* **4**:1206-1215.

Brain MJ *et al.* (2009) "The **Boulby** Geoscience Project Underground Research Laboratory: Initial Results of a Rock Mechanics Laboratory Testing Programme" American Geophysical Union, Fall Meeting 2009, abstract #H23E-0997.

Bramall NE, Rohde RA, Bay RC and Price P (2006) "Optical Probes for Remotely Sensing Microbial Life in Antarctica and Beyond" Poster presentation at AGU Fall Meeting, San Francisco.

Carbone MC *et al.* (2009) "The Cosmic Silence experiment: On the putative adaptive role of environmental ionizing radiation" *Radiation and Environmental Biophysics* **48**(2): 189-196.

Carbone MC *et al.* (2010) "Effects of deprivation of background environmental radiation on cultured human cells" *Nuovo Cimento della Societa Italiana di Fisica B* **125**(4): 469-477.

Cockell CS *et al.* (2011) "Molecular Characterization and Geological Microenvironment of a Microbial Community Inhabiting Weathered Receding Shale Cliffs" *Microbial Ecology* **61**:166–181.

Coltorti M *et al.* (2011) "U and Th content in the Central Apennines continental crust: A contribution to the determination of the geo-neutrinos flux at LNGS" *Geochimica et Cosmochimica ACTA* **75**(9): 2271-2294

Cordelli M, Martini A, Habel R and Trasatti L (2011) "PORFIDO: Oceanographic data for neutrino telescopes" *Nuclear Instruments and Methods in Physics Research A* **626-627**:S109–S110.

Craig J, Jamieson AJ, Bagley PM and Priede IG (2011) "Seasonal variation of deep-sea bioluminescence in the Ionian Sea" *NIMA Proceedings* **626-627**(1): S115-S117.

Cuny P, Gilbert F, Militon C, Acquaviva M, Tamburini C, Stora G, Grossi V (in prep.) "Effects of Prestige fuel oil on macro- and micro-benthic communities of deep-sea Mediterranean sediments near the **ANTARES** underwater neutrino telescope".

Dahlgren R, Stetler LD, Freund FT, Volk JT, Shiltsev V, Peters RD (2010) "Subsurface tiltmeter arrays at Homestake DUSEL" American Geophysical Union, Fall Meeting .

DUSEL (2006) "Deep Science : A deep underground science and engineering initiative" http://www.deepscience.org/DUSEL_121306.pdf .

Deschamps A (2011) "RATCOM: an early-warning pilot network for near-field tsunamis in the Ligurian Sea" *Geophysical Research Abstracts* **13**: EGU2011-14189.

Dominjon A *et al.* (in press) "An ebCMOS camera system for marine bioluminescence observation: the LuSEApher prototype" *Nuclear Instruments and Methods in Physics Research A*.

McPherson BJ and the Earthlab Steering Committee (2003) "Laboratory and Observatory to Study Microbial Life, Fluid Flow and Rock Deformation" Geosciences Professional Services, Inc (a report for National Science Foundation, USA).

EURAB - European Union Research Advisory Board (2004) "Interdisciplinarity in research", EURAB 04.009.

Fairén *et al.* (2010) "Astrobiology through the Ages of Mars: The Study of Terrestrial Analogues to Understand the Habitability of Mars." *Astrobiology* **10**(8):821-43.

Favali P, Beranzoli L, Italiano F, Migneco E, Musumeci M, Papaleo R on behalf of the **NEMO** Collaboration (2010) "NEMO-SN1 observatory developments in view of the European Research Infrastructures EMSO and KM3NeT" *NIMA Proceedings* **626-627**:S53-S56.

Fehr F for the TOMUVOL Collaboration (2011) "Density Imaging of Volcanoes with Atmospheric Muons" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

Fontugne M, Jaudon M And Reyss JL (1994) "Low background CO2-gas proportional counters at the Underground Laboratory of Modane (73)" 15th International Radiocarbon Conference, Glasgow (UK).

Frontera *et al.* and the ANTARES collaboration (submitted) "The Antares real time ocean bottom seismometer: analysis of 2 year continuous recordings".

Geiser A, Kahle B (2002) "Tomography of the earth by the oscillation of atmospheric neutrinos: A study of principle". Poster presented at Neutrino2002, Munich, Germany.

Giacomelli G for the **ANTARES** Collaboration (2011) "Results from the **ANTARES** Neutrino Telescope" Contribution to the WASET International Conference on Neutrino Physics and Astrophysics, arXiv:1105.1245

Gibert D *et al.* (2010) "Muon tomography : plans for observations in the Lessers Antilles" *Earth Planets and Space* **62**: 153-165.

Giguet-Covex C *et al.* (2010) "Sedimentological and geochemical records of past trophic state and hypolimnetic anoxia in large, hard-water Lake Bourget, French Alps" *Journal of Paleolimnology* **43**(1):171-190.

Gosse JC (2011) "Terretrial cosmogenic nuclide methods: taming elephants in the room" *GSA Annual Meeting*.

Grossi V *et al.* (2010) "Hydrostatic pressure affects membrane and storage lipid compositions of the piezotolerant hydrocarbon-degrading Marinobacter hydrocarbonoclasticus strain #5" *Environmental Microbiology* **12**(7): 2020–2033.

Hubert P *et al.* (2009) "Radioactivity measurements applied to the dating and authentication of old wines" *Comptes Rendus Physique* **10**(7):622-629.

Hubert P (2007) "From the mass of the neutrino to the dating of wine" *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **580**(1): 751-755.

IceCube Collaboration (2010) "Solar Energetic Particle Spectrum on 2006 December 13 Determined by Icetop" *The Astrophysical Journal* **689**:L65.

Jacobs N and Amos M (2010) "Removing Barriers to Interdisciplinary Research" arXiv:1012.4170.

Jickells TD *et al.* (2005) "Global Iron Connections Between Desert Dust, Ocean Biogeochemistry, and Climate" *Science* **308**(5718): 67-71.

KamLAND Collaboration (2011) "Partial radiogenic heat model for Earth revealed by geoneutrino measurements" *Nature Geoscience* **4**: 647–651.

Keilhauer B for the Pierre Auger Collaboration (2010) "The Balloon-the-Shower programme of the Pierre Auger Observatory" *Astrophysics and Space Sciences Transactions* **6**:27–30.

Kirkby J *et al.* (2011) "Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation" *Nature* 476: 429–433.

Korotaev SM *et al.* (2011) "The effect and precursors of the earthquake of August 28, 2008, in the vertical component of the electric field in Lake Baikal" *Doklady Earth Sciences* **438**(2): 842-845.

Krehbiel PR *et al.* (2008) "Upward Electrical Discharges from Thunderstorms" *Nature Geoscience* **1**:233 – 237.

Lal D (2011) "Using Cosmogenic Radionuclides for the Determination of Effective Surface Exposure Age and Time-Averaged Erosion Rates" in Handbook of Environmental Isotope Geochemistry (ed. M. Baskaran), Advances in Isotope Geochemistry, Springer-Verlag, Berlin Heidelberg.

Lefevre D *et al.* (2010) "Assessing Metabolic Balance In Oligotrophic Gyres" Proceedings from the 2010 AGU Ocean Sciences Meeting.

Lesparre N *et al.* (2011) "Design and Operation of a Field Telescope for Cosmic Ray Geophysical Tomography" *Geophysical Research Abstracts* **13:**EGU2011-5957.

Lim M, Rosser NJ, Allison RJ, Petley DN and Keen M (2010) "Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire" *Geomorphology* **114**(1-2):12-21.

Lim M, Rosser NJ, Petley DN and Keen M (2011) "Quantifying the Controls and Influence of Tide and Wave Impacts on Coastal Rock Cliff Erosion" *Journal of Coastal Research* **27**(1):46-56.

Louedec K for the Pierre Auger Collaboration (2011) "Atmospheric Monitoring at the Pierre Auger Observatory – Status and Update" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

Marfaing J *et al.* (2011) "Global observation of 24 November 2006 Pc5 pulsations by single mid-latitude underground [SQUID]2 system" *Ann. Geophysicae* **29**:1977-1984. doi:10.5194/angeo-29-1977-2011

Marteau J *et al,* (in press) "Muons tomography applied to geosciences and volcanology" *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, arXiv: 1201.6469.

Martinez-Garcia A *et al.* (2011) "Southern Ocean dust–climate coupling over the past four million years" *Nature* **476**: 312-315.

McGenity TJ *et al.* (2000) "Origins of halophilic microorganisms in ancient salt deposits" *Environmental Microbiology* **2**(3):243-250.

Miele G and Pisanti O (2011) "Neutrino Radiography" N*uclear Physics B - Proceedings Supplements* **217**(1): 149-151.

Morin D, Lavier C & Guiomar M (2006) "The beginnings of salt extraction in Europe (sixth millennium BC): The salt spring of Moriez (Alpes-de-Haute-Provence, France)" *Antiquity* **80**:309.

Nolan SJ, Pühlhofer G and Rulten CB (2010) "Detailed studies of atmospheric calibration in imaging Cherenkov astronomy" *Astroparticle Physics* **34**(5): 304-313.

Pierre Auger Collaboration (2010) "A study of the effect of molecular and aerosol conditions in the atmosphere on air fluorescence measurements at the **Pierre Auger Observatory**" *Astroparticle Physics* **33**:108–129.

Pierre Auger Collaboration (2011) "The Pierre Auger Observatory III: Other Astrophysical Observations" Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

Pierre Auger Collaboration (2011) "The Pierre Auger Observatory scaler mode for the study of solar activity modulation of galactic cosmic rays" *JINST* **6**:01003.

Pierre Auger Collaboration (in press) "Description of Atmospheric Conditions at the Pierre Auger Observatory using the Global Data Assimilation System (GDAS)" *Astropart. Phys.*

Plastino W *et al.* (2011) "Uranium groundwater anomalies and active normal faulting" *Journal of Radioanalytical and Nuclear Chemistry* **288**(1):101–107.

Pozzo di Borgo E, Marfaing J and Waysand G (in press) "Minimal global magnetic millihertz fluctuation level determined from mid latitude underground observations" *Europhysics Letters*.

Priede IG *et al.* (2008) "The potential influence of bioluminescence from marine animals on a deepsea underwater neutrino telescope array in the Mediterranean Sea" *Deep Sea Res Part I* **55**: 1474–1483.

Rafols I *et al.* (2011, *Submitted to Research Policy*) "How journal rankings can suppress interdisciplinarity: A comparison of innovation studies and business & management" PDF.

Robert A *et al.* (submitted) "A new tool to assess production and respiration rates throughout the water column: the *In situ* Oxygen Dynamics Auto-sampler (IODA6000)".

Rohde RA and Price PB (2007) "Diffusion-controlled metabolism for long-term survival of single isolated microorganisms trapped within ice crystals" *PNAS* **104**(42): 16592–16597.

Rohde RA *et al.* (2008) "*In situ* microbial metabolism as a cause of gas anomalies in ice" *PNAS* **105**(25): 8667–8672.

Sabatier P *et al.* (2011) "Growth rate of deep-sea Scleractinian corals (*Madrepora oculata, Lophelia pertusa*) inferred from ^{210}Pb-^{226}Ra chronology" *Geophysical Research Abstracts* **13**:EGU2011-8747. Also at *Biogeosciences Discuss* **8**:12247-12283.

Sartini L *et al.* (2011) "GEMS: Underwater spectrometer for long-term radioactivity measurements" *Nuclear Instruments and Methods in Physics Research Section A* **626**:S145-S147.

Savichtcheva O *et al.* (2011) "Quantitative real-time PCR enumeration of Planktothrix spp. and other Cyanobacteria in preserved DNA isolated from lake sediments" *Applied and Environmental Microbiology* **77**:8744-8753.

Scarpa R *et al.* (2008) "Slow earthquakes and low frequency tremor along the Apennines, Italy" *Annals of Geophysics* **51**: 527-538.

Siedlok F and Hibbert P (2009) “Interdisciplinary research: A review of contextual and process factors” presented at Australia and New Zealand Academy of Management: Sustainable Management and Marketing, Melbourne, Australia.

Stuart FM and Dunai TJ (2009) “Advances in cosmogenic isotope research from CRONUS-EU” *Quaternary Geochronology* **4**: 435.

Tamburini C *et al.* (2009) “Effects of hydrostatic pressure on microbial alteration of sinking fecal pellets” *Deep Sea Research Part II: Topical Studies in Oceanography* **56**(18):1533-1546.

Tamburini *et al.* (submitted) “Enhancement of deep-sea pelagic activity by dense water formation after a unique long-term bioluminescence record”

Tapilatu Y, Aquaviva M, Guigue C, Miralles G, Bertrand J-C, Cuny P (2010) “Isolation of alkane-degrading bacteria from deep-sea Mediterranean sediments” *Letters in Applied Microbiology* **50**:234-236.

Tilav S *et al.* for the **IceCube** Collaboration (2010) “Atmospheric Variations as Observed by **IceCube**” Contribution to the 31st International Cosmic Ray Conference, Łódź, Poland, arXiv:1001.0776.

Tonachini AS for the Pierre Auger Collaboration (2011) “Observation of Elves with the Fluorescence Detectors of **the Pierre Auger Observatory**” Contribution to the 32nd International Cosmic Ray Conference, Beijing, China.

van Haren H (2010) “Tidal Power? No Thanks.” *New Scientist* 205(2754): 20-21.

van Haren H and Gostiaux L (2011) “Large internal waves advection in very weakly stratified deep Mediterranean waters” *Geophysical Research Letters* **38**:L22603.

van Haren H *et al.* (2011) “Acoustic and optical variations during rapid downward motion episodes in the deep north-western Mediterranean Sea” *Deep Sea Research Part I: Oceanographic Research Papers* **58**(8):875-884 .

Wapenaar K *et al.* (2011) “Improved surface-wave retrieval from ambient seismic noise by multi-dimensional deconvolution” *Geophysical. Research Letters* **38**:L01313.

Waysand G *et al.* (2009) “Seismo-ionosphere detection by underground SQUID in low-noise environment in LSBB, Rustrel, France” *European Physics Journal of Applied Physics* **47-1**:12705. doi: 10.1051/epjap:2008186

Waysand G *et al.* (2011) “Earth–ionosphere couplings, magnetic storms, seismic precursors and TLEs: Results and prospects of the [SQUID]2 system in the low-noise underground laboratory of Rustrel-Pays d'Apt” *Comptes Rendus Physique* **12**(2): 192-202.

8. INDEX OF ApP INFRASTRUCTURES and PROJECTS

Published 2012

www.aspera-eu.org

ASPERA