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Life emergence conditions :
P2IO R&D project

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TITRE DU PROJET : INGMAR **IrradiatioN de Glaces et Météorites Analysées par Réflectance VIS-IR**
Nature de l'opération : projet expérimental
Début de l'opération : 2013
Fin de l'opération : 2017

RAPPORT INTERMÉDIAIRE

1. Project goals (approx. 15 lines)

Space weathering processes affect atmosphere-less bodies in the Solar System. They include irradiation by solar wind, galactic cosmic ions, electrons, UV and X-rays, and bombardment by micrometeorites. These processes cause variations in the optical properties of small Solar System bodies surfaces, affecting efforts to draw connections between specific meteorites and asteroid types. They have been widely studied for the Moon and S- and V-type asteroids, but little is known about carbonaceous asteroids weathering in space as previous studies have struggled to define a general spectral trend among dark surfaces. The INGMAR ("IrradiatioN de Glaces et Météorites Analysées par Réflectance VIS-IR") project aims at developing an experimental setup dedicated to VIS-IR spectroscopic analysis of solids of astrophysical interest to be coupled to different irradiation platforms. In particular, in the first phase of the project, meteorites, carbons, and ices that are analogs of carbon-rich asteroid surfaces will be irradiated (40 keV, as a simulation of solar wind) at the SIDONIE platform (CSNSM, Orsay) and analyzed by reflectance (micro-)spectroscopy. This activity is based on a close collaboration between IAS and CSNSM in Orsay, two laboratories of P2IO. It is developed in the frame of a very favorable international context, thanks to upcoming space missions OSIRIS-REx (NASA) and Hayabusa 2 (JAXA), designed to study and perform sample returns of primitive asteroids rich in organic compounds. In the longer term, the implementation of a dedicated irradiation platform for solids of astrophysical applications may provide a fundamental support to the JUICE mission (ESA).

2. Description of work achieved (approx. 2 pages)

Schedule:

2013	-	Validation of INGMAR experimental approach	(Completed)
		First irradiation of meteorites and ex-situ reflectance analysis	(Completed)
		Design and construction of the vacuum chamber	(Completed)
		Acquisition of the pumping system	(Completed)

		First test of micro-reflectance on Itokawa grains	(Completed)
		First applications to observations	(Completed)
2014	-	New irradiation on CM meteorite	(Completed)
		Acquisition of optical and spectroscopic components	(Completed)
		New measurements on two grains from Itokawa	(Completed)
		Tests with grains of the GIADA team (Rosetta)	(Completed)
		First tests with micrometeorites reflectance	(Completed)
		Assembling the vacuum chamber and pumping system	(Completed)
		Coupling vacuum chamber - spectroscopy	(Ongoing)
		Coupling in-situ irradiation - reflectance	(Ongoing)
		Renewal of the platform SIDONIE	(Ongoing)
2015	-	Irradiation of different classes of meteorites	
		Irradiation of analogue samples	
		Micro-reflectance of micrometeorites	
		Multi-analysis (electron microscopy, etc.)	
		Develop a weathering scenario for low albedo objects	
		Applications to astronomical observations	
2016 ...	-	Complete extension of INGMAR to micrometeorites and ices	
		Line open to external collaborations (outside the consortium)	
		Applications for space missions	

During the years 2013 and 2014, thank to funds received by P2IO and co-funding by PNP and DIM-ACAV, our experimental approach has been validated and the first results have been obtained and published. The vacuum chamber, pumping system, optical and spectroscopic components were acquired and assembled.

We performed ion irradiation experiments of the Allende meteorite, using 40 keV He^+ and Ar^+ ions at the SIDONIE platform, as a simulation of solar wind irradiation of primitive bodies surfaces. We used different fluences up to $3x10^{16}$ ions/cm^2, corresponding to short timescales of ~10^3-10^4 years in the main asteroid belt. Samples were analyzed before and after irradiation using visible to far-IR (0.4 – 50 µm) reflectance spectroscopy, and Raman micro-spectroscopy. Similarly to what is observed in previous experiments, results show a reddening and darkening of VIS-NIR reflectance spectra. These spectral variations are however comparable to other spectral variations due to viewing geometry, grain size, and sample preparation, suggesting an explanation for the contradictory space weathering studies of dark asteroids. After irradiation, the infrared bands of the matrix olivine silicates change profile and shift to longer wavelength (Fig. 1, left), possibly as a consequence of a more efficient sputtering effect on Mg than Fe (lighter and more volatile species are preferentially sputtered backwards) and/or preferential amorphisation of Mg-rich olivine. Spectral variations are compatible with the Hapke weathering model. Raman spectroscopy shows that the carbonaceous component is substantially affected by irradiation: different degrees of de-ordering are produced as a function of dose, to finally end with a highly disordered carbon. All observed modifications seem to scale with the nuclear elastic dose. These results are published in Icarus (Brunetto et al., 2014). We performed an extension of this work, by irradiating pellets of the CM Murchison meteorite. Results (submitted for publication, Lantz et al., 2014) show that the reddening/darkening trend observed on silicate-rich surfaces is not valid for all carbonaceous chondrites, and that the spectral modifications after irradiation are a function of the initial albedo.

In parallel to the irradiation activity, we have developed a micro-reflectance analysis of extraterrestrial particles. The reproducibility of the technique, at the ~20 µm scale, was evaluated through preliminary tests to estimate measurement uncertainty. For calibrations, natural San Carlos olivine 20-100 µm particles were used. The reflectance spectra of isolated particles were measured one by one using different microscope objectives (i.e. different sizes of the analytical spot, from 200 µm down to 20 µm). A second calibration was performed applying the same technique to terrestrial microparticles prepared by our colleagues of the GIADA instrument team (Rosetta mission). Some particles were covered with a thin layer of aromatic carbon (~ 200-500 nm). Thanks to spectral modeling, results will be used to constrain the effects of carbon inclusions in the reflectance spectra in the VIS-NIR spectral range. Results will be published in 2015.

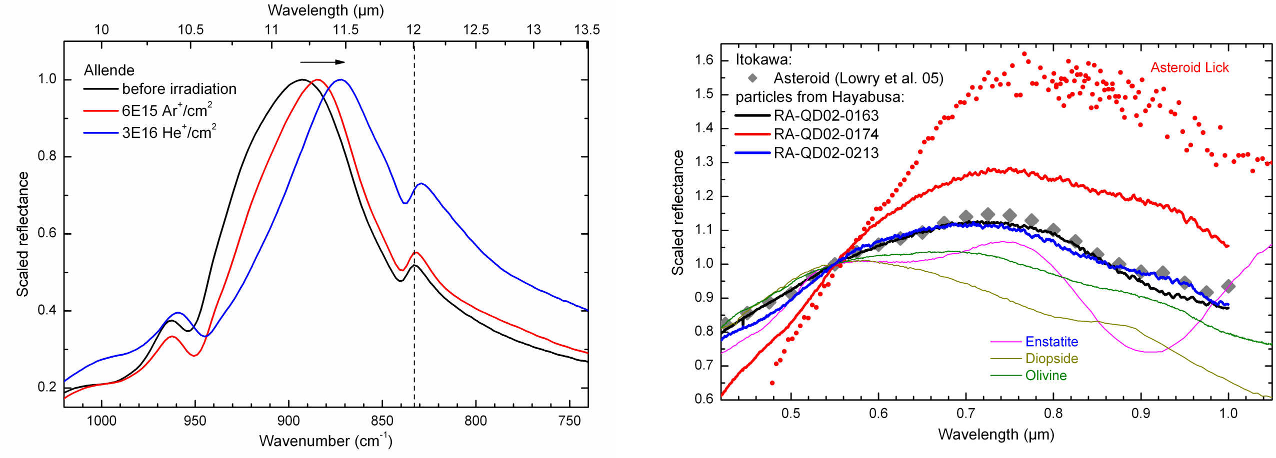

Figure 1. Left : The IR confocal microscopic (spot ~15 µm) reflectance spectra on Allende's matrix before (black) and after irradiation at maximum fluence for Ar+ (red) and He+ (blue) beams. Right: Comparison of the reflectance spectra of objects having experienced distinct extents of space weathering: our three Hayabusa particles (in black, blue and red), the ground-based spectra of asteroids Itokawa (in grey diamonds) and Lick (in red dots), and the laboratory spectrum of the Alta'ameem LL5 meteorite (in grey) reported by Hiroi et al. (2006).

Thanks to these calibrations, we were able to apply the micro-reflectance technique to three extraterrestrial grains returned from asteroid Itokawa by the Japanese Hayabusa mission. These samples offer a unique perspective to understand the link between asteroids and cosmomaterials available in the laboratory, and to get an insight on the early stages of surface space weathering. We characterized the mineralogy and the extent of space weathering of the three Itokawa particles RA-QD02-0163, RA-QD02-0174, and RA-QD02-0213 provided by JAXA to our consortium. Identification of the minerals, characterization of their elemental compositions and measurements of their relative abundances were led through Raman spectroscopy. Reflectance spectra in the visible and near-IR wavelength constrain the mineralogy of the grains and allow direct comparison with the surface of Itokawa (Fig. 1, right). The spectra reflect the extent of space weathering experienced by the three particles. We found that particle RA-QD02-0163 consists in a heterogeneous mixture of minerals: olivine (Fo76) dominates an assemblage of Ca-rich (En50, Wo50) and Ca-poor (En85) pyroxenes. Particles RA-QD-0174 and RA-QD02-0213 are solely composed of olivine, whose chemical composition is similar to what is observed in RA-QD02-0163. The NIR-VIS reflectance (incidence = 45°, light collection at e=0°) spectra of the three particles, in particular the 1-µm band, are consistent with the presence of both olivine and pyroxene detected via Raman. The spectra of particles RA-QD02-0163 and RA-QD02-0213 are also fully compatible with the ground-based observations of asteroid (25143) Itokawa in terms of both spectral features and slope. By contrast, particle RA-QD02-0174 has a similar 1-µm band depth but higher (redder) spectral slope than the surface of Itokawa. This probably reveals a variable extent of space weathering among the regolith particles. RA-QD02-0174 may contain a higher amount of nanophase metallic iron and nanophase FeS. Such phases are produced of space weathering induced by solar wind, previously detected on other Itokawa particles. Results have been submitted for publication in MAPS (Bonal et al., 2014).

The good results obtained on Itokawa and GIADA grains in 2014 allowed us to measure (for the first time in this wavelength range) micro-reflectance spectra of two Antarctic micrometeorites of possible cometary origin. For both micrometeorites we measured an albedo compatible with that of cometary nuclei. The results are very promising and this activity will continue in the forthcoming months. Four student interns L3 were supervised on these activities during 2013 and 2014.

The in-situ coupling between the spectrometers and the irradiation line in the vacuum chamber is in progress. A complete renewal of the SIDONIE platform is performed at the same time. We plan to have a complete operational setup in the spring of 2015 (see schedule above). The extension to icy samples will be performed in 2016.

3. Publications

Brunetto, R., Loeffler, M.J., Nesvorny, D., Sasaki, S., Strazzulla, G., 2014. Asteroid Surface Alteration by Space Weathering Processes. In Asteroids IV, Eds. P. Michel, F.E. DeMeo, W.F. Bottke, submitted.

Lantz, C., Brunetto, R., Barucci, M.A., Dartois, E., Duprat, J., Engrand, C., Godard, M., Ledu, D., Quirico, E., 2014. Ion irradiation of the Murchison meteorite: VIS and MIR spectroscopic results. Astronomy and Astrophysics, submitted.

Bonal, L., Brunetto, R., Beck, P., Dartois, E., Dionnet, Z., Djouadi, Z., Duprat, J., Füri, E., Kakazu, Y., Montagnac, G., Oudayer, P., Quirico, E., Engrand, C., 2014. Visible-IR and Raman micro-spectroscopic investigation of three Itokawa particles collected by Hayabusa: mineralogy and degree of space weathering based on non-destructive analyses. Meteoritics and Planetary Science, submitted.

Brunetto, R., Lantz, C., Ledu, D., Baklouti, D., Barucci, M.A., Beck, P., Delauche, L., Dionnet, Z., Dumas, P., Duprat, J., Engrand, C., Jamme, F., Oudayer, P., Quirico, E., Sandt, C., Dartois, E., 2014. Ion irradiation of Allende meteorite probed by visible, IR, and Raman spectroscopies. Icarus 237, 278-292.

Brunetto, R., Bonal, L., Beck, P., Dartois, E., Dionnet, Z., Djouadi, Z., Füri, E., Kakazu, Y., Oudayer, P., Quirico, E., Engrand, C., 2014. Visible-IR and Raman micro-spectroscopic investigation of three Itokawa particles collected by Hayabusa. Talk at Asteroids, Comets, and Meteors, June 30th – July 4th Helsinki, Finland.

Lantz, C., Brunetto, R., 2014. Ion irradiation of carbonaceous chondrites for a Vis-IR space-weathering study on primitive objects: CV Allende and CM Murchison. Talk at Asteroids, Comets, and Meteors, June 30th – July 4th Helsinki, Finland.

Quirico, E., Orthous-Daunay, F.-R., Beck, P., Bonal, L., Brunetto, R., Dartois, E., Pino, T., Montagnac, G., Rouzaud, J.-N., Engrand, C., Duprat, J., 2014. Origin of insoluble organic matter in type 1 and 2 chondrites: New clues, new questions. Geochimica et Cosmochimica Acta 136, 80–99.

Brunetto, R. 2013. "Space weathering" laboratory experiments in support of spectroscopic studies of asteroids. Invited talk at ASSG2013: Asteroid Spectroscopy in Support of Gaia, 6-7 Jun 2013 Nice, France.

Bonal, L., Engrand, C., Brunetto, R., Dartois, E., Dionnet, Z., Djouadi, Z., Kakazu, Y., Oudayer, P., Baklouti, D., Beck, P., Duprat, J., Füri, E., Gounelle, M., Merouane, S., Quirico, E. 2013. Raman, IR and optical micro-spectroscopic investigation of Hayabusa particle RA-QD02-0163. Hayabusa 2013 Symposium of Solar System Materials.

4. Relevance of the project within P2IO and specific added value for P2IO (approx. 20 lines)

I. Relevance of the project

The project fills a lack of experimental data on ion irradiation of carbon-rich ice, meteorites and micrometeorites, and analysis by VIS-NIR reflectance. This project provides the community with a unique experimental tool with excellent online equipment, a wide range of temperature conditions to explore, the connection with a valuable collection of micrometeorites and an extensive support of multiple analyses.

II. Matching priority research themes of P2IO

Through the study of small bodies and micrometeorites, the project is centered on the origin and evolution of the Solar System, in the P2IO theme "Formation de systèmes stellaires et les conditions d'émergence de la vie". The development of an irradiation line dedicated to solids of astrophysical applications fits into the theme P2IO " innovations dans la science des accélérateurs et leurs applications".

III. Synergy between laboratories of P2IO

The project is strengthening a cooperation already established between the IAS and CSNSM Orsay, two laboratories of P2IO, on topics related to cosmic irradiation. Since 2010, the two teams are working on the analysis of the CSNSM collection of Antarctic micrometeorites (AMMs), as part of the ANR project COSMISME (P.I. E. Dartois).

IV. Project's impact on the LABEX visibility

Very favorable international context, with four space missions in the short / medium term: OSIRIS-REx (NASA), Hayabusa 2 (JAXA), Rosetta (ESA), New Horizons (NASA); and a long-term mission, JUICE (ESA). The construction in Orsay of an irradiation line available to the entire French community working on small bodies in the Solar System and interstellar medium dust will be fruitful for P2IO.

5. Possible valorization of the project

The project will make available an experimental setup to the community working on ion irradiation of solids. Even if initially designed to analyze samples of astrophysical interest, the INGMAR setup can be used to perform ion irradiation / implantation of any solid in a large range of temperatures, monitored in-situ by visible to IR reflectance and transmittance spectroscopy. Potentially, this setup can be used by different communities for other applications (solar cells, thin films, etc.) besides the Astrophysical context.

The INGMAR setup is already planned to be used also by students attending specific courses. A series of TP ("Travaux pratiques") within the course « Environnement spatial, implantations ioniques et spectroscopie » for students attending the M2 OSAE (Outils et Systèmes de l'Astronomie et de l'Espace) is planned for January – February 2015. More activities shall be planned in the future, once the system will be fully operational.

6. Expenses

To monitor in real time the evolution of the spectrum as a function of irradiation, without removing the sample from the vacuum chamber, we have developed an in-situ setup dedicated to this experiment (vacuum chamber, P ~10^{-7} mbar). Acquisition of the vacuum chamber and pumping has been funded by the R&D call of labex P2IO. The mounting system allows the target to be simultaneously irradiated and analyzed by bi-directional reflectance or transmission (depending on the thickness of the sample and the desired application) in the VIS-NIR. Different parts of this coupling system have been funded by the PNP (2013 and 2014) and DIM-ACAV. In the future, the installation of a cryogenic system will allow to irradiate targets at varying temperatures from 10 K to 300 K, and give us access to the entire temperature range of small body, allowing also to study the reflectance of irradiated planetary ices. This system will be almost entirely funded by the remaining P2IO budget.

Detailed budget plan of the project:

	Financements acquis	**Demandes de financement**			
		2015	**2016**	**2017**	**>2018**
PNP	14.5 k€	17 k€	13 k€	13 k€	-
R&D P2IO	74.5 k€				
TP P2IO	12 k€				
Crédits labo	2 k€				
Autres CNRS					
Ministère					
Régions : DIM-ACAV	10 k€				
CNES					
Contrat					
TOTAL	**113 k€**	17 k€	13 k€	13 k€	

Detailed expenses on P2IO R&D budget:

Element	**Expense**	**Year**
Pumping system	11.3 k€	2013
Spectroscopic adaptations and detectors	18.5 k€	2013
Vacuum chamber and mechanics	9.4 k€	2013-2014
Other optical elements	1.5 k€	2014
Computers	2.9 k€	2014
Sample holder and translation system	2.3 k€	2014
TOTAL EXPENDED	**45.9 k€**	
Cryogenic system and ice preparation	30 k€	2015
TOTAL TO BE EXPENDED	**30 k€**	