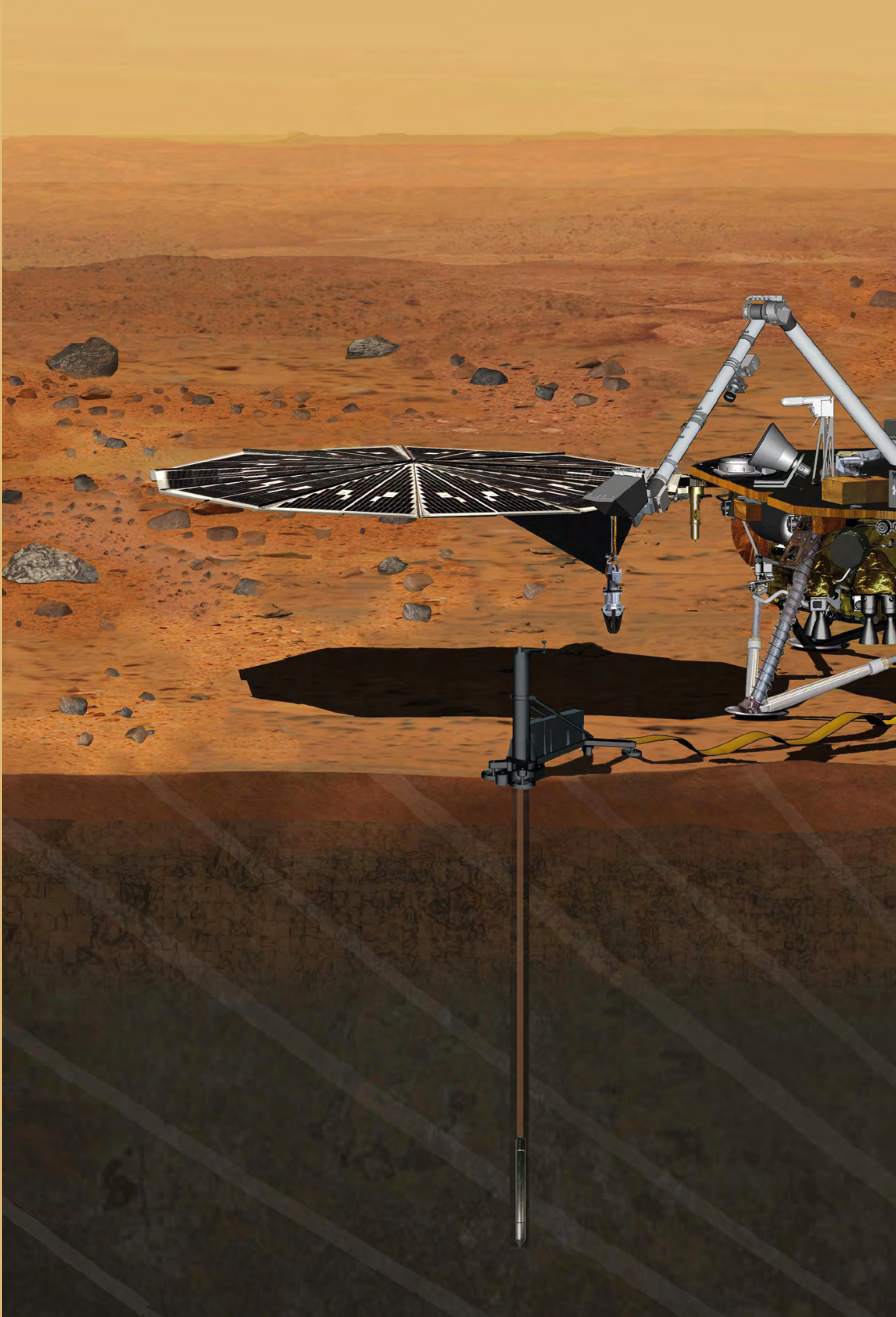

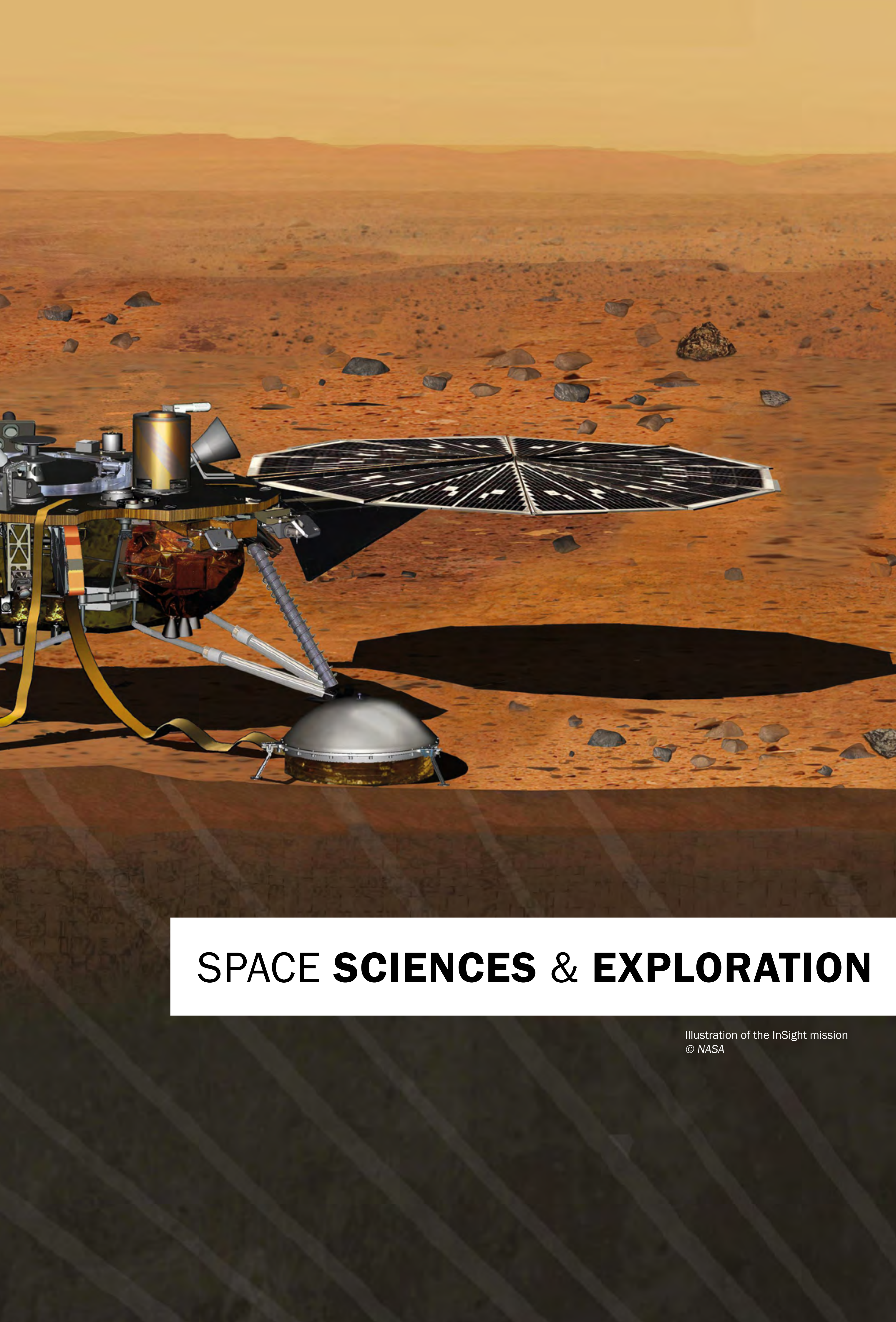

SPACE **SCIENCES** & **EXPLORATION**

Illustration of the InSight mission
© NASA

Fig.1

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Space sciences and exploration

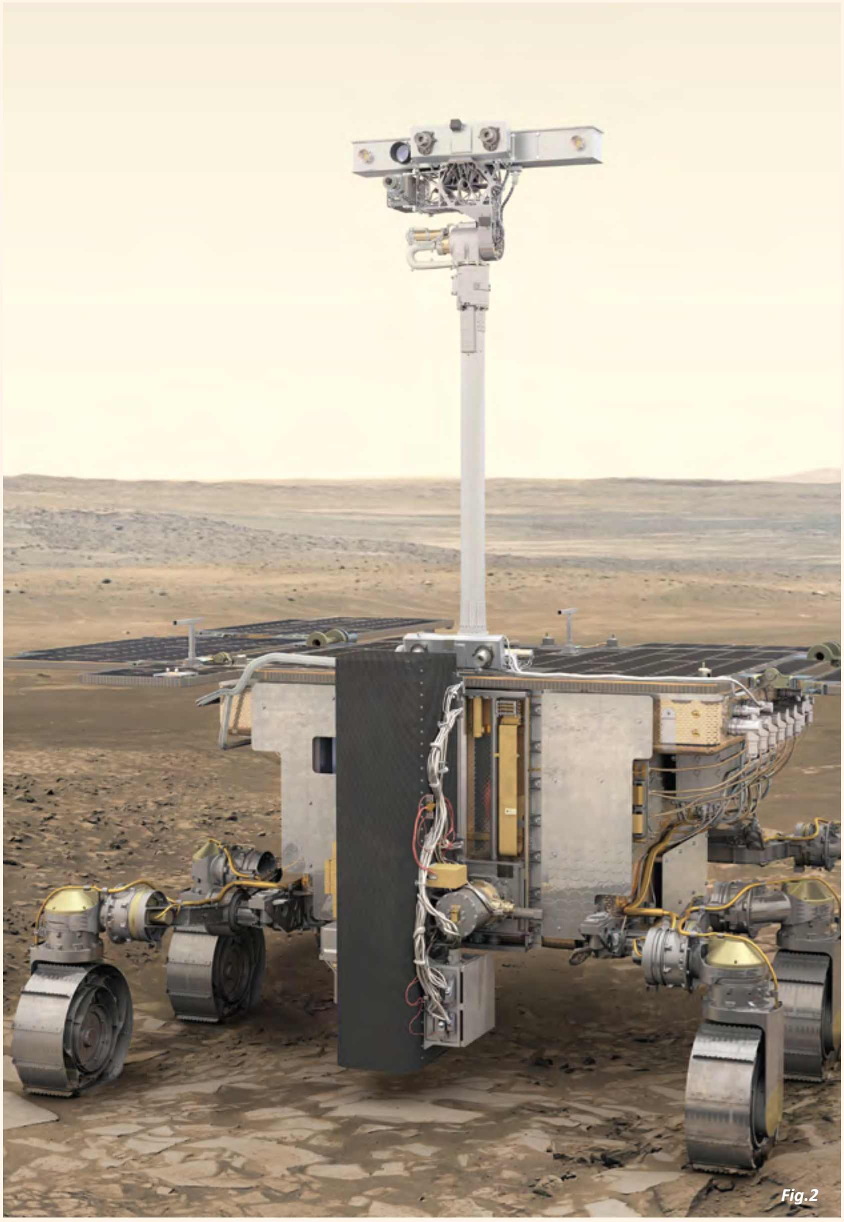


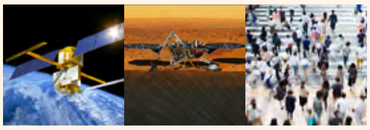
Fig.2

SPACE SCIENCES AND EXPLORATION

Space offers the scientific community many opportunities in both fundamental and applied research. Under the name of "space sciences", we group together all the disciplines of universe sciences (stellar, galactic and extragalactic astrophysics, cosmology, planetary sciences, exobiology and exoplanets, solar physics and magnetospheres), condensed-matter physics and fundamental physics when operating in microgravity. To this group we have to add life sciences whose progress is important for Mars exploration for example.

In November 2016, Thomas Pesquet began the Proxima mission and was the first French astronaut aboard the ISS in 8 years. During his 6-month mission (he returned in early June 2017), he performed many scientific experiments in both life sciences and condensed-matter physics. He notably performed the FLUIDICS experiment which is designed to study the fundamental mechanisms of wave turbulence as well as other experiments on more technological aspects such as the sloshing in space tanks. There are numerous applications for this experiment: oceanic or atmospheric waves, the Alfvén wave in solar wind, the spin wave in solid-state physics... For example, the wave height spectrum is in accordance with the theory of wave turbulence.

Thomas Pesquet also tested the AQUAPAD device, which makes it possible to rapidly determine the level of microbial contamination of drinking



water in the space station while using very little of it, an absolute necessity for long-term flights.

The scientific themes addressed in microgravity sciences can be broken down into research "for space" and "space-based". For example, the work of FUIDICS on tank sloshing or microgravity combustion studies is carried out "for space". Work on wave turbulence is "space-based", as are many basic research studies that use access to sufficient microgravity levels for long periods of time.

Recently, CNES decided to upgrade the DECLIC instrument and manufacture new inserts for new scientific experiments.

In life sciences, the disciplines involved in exploration range from psychology (human and social behaviour in a confined environment) to physiology (effects of microgravity on the cardiovascular system, the immune system, muscles and bones). On this topic, CNES has decided to produce the new version of the CARDIOSPACE instrument that will make it possible to monitor the performance of the cardiovascular system of astronauts, particularly in the context of a partnership with China. These studies are supplemented by experiments and simulation of ground microgravity during bedrest, such as those that ended in 2017 for example. In September 2018, a symposium on microgravity sciences and the adaptation of man to space will be organised in Toulouse.

In October 2016, the ROSETTA probe mission ended in a controlled landing on the comet 67P/Churyumov–Gerasimenko. The images taken by the probe until the last moments showed details at the centimetre level. The last signal was received on 30 September 2016. This was an extremely moving moment for the French scientific community and especially for everyone who took part in this project for the last 30 years. Obviously, the scientific research continues to provide even more information on the Solar System's origin, on the organic compounds on small bodies, on the origin of water and life on Earth.

Fig.3

In December 2016, the CNES Board of Directors made the decision to start the development phase of the SVOM mission. This Franco-Chinese mission, whose launch is planned for the end of 2021, will observe transient energy phenomena, particularly those associated with gravitational wave emissions. This mission will thus fully participate to the emerging era of multi-messenger astrophysics, with for example the detection in August 2017 by the FERMI and INTEGRAL satellites of a high-energy emission from gamma-ray bursts just seconds after the gravitational burst observed by LIGO and VIRGO on the ground. These observations have been supplemented by a very large number of observations by other telescopes.

The historic announcement of gravitational waves detection in 2016 from Earth has opened a new window to observe the universe, allowing us to *"see" the fusion of black holes and neutron stars, but also the violent phenomena of the beginnings of the universe, and a whole series of events still unsuspected today. This discovery in astrophysics will forever disrupt our vision of the universe. The ESA LISA mission selection in June 2017 was a major decision which puts Europe and its state members at the forefront of this discovery in astrophysics. LISA is the third Large Class Mission of the Cosmic Vision programme and will observe the gravitational waves from space in a frequency domain inaccessible from the ground.*

The path towards the observation of gravitational waves from space had been prepared for a long time and particularly by the ESA LISA PATHFINDER mission launched in December 2015. The measurements obtained in 2016 and 2017 validated the technological feasibility, demonstrating that the original specifications were exceeded by more than an order of magnitude and that the performances obtained are well above the level required for the LISA mission. The French community is deeply involved in the data processing of this mission, in order to be prepared for the future LISA mission. The French scientific community and CNES intends to play a major role in LISA.

On fundamental physics, the publication of the firsts results of MICROSCOPE in December 2017 turned this extraordinary experiment into a global standard in terms of verification of the Equivalence Principle which is based on the theory of general relativity. The measurements obtained on only 120 orbits are already 10 times more precise than those obtained from the ground until now and are sufficient to exclude some alternative theories on gravity. Through its MICROSCOPE mission, CNES is deeply supporting this research on general relativity. There is no doubt that this performance will be largely improved once all the data is processed.

On the Solar system, September 2017 saw the end of the CASSINI mission. With its data acquired for more than a decade, CASSINI revolutionised our vision of the Saturnian system and of its main satellite with the landing on Titan of the European HUYGENS spacecraft that was carrying 2 French PI instruments. The observation of geysers spraying hydrogen through the tiger stripes of Enceladus is also a major discovery. The giant planets of our Solar system, with their ice satellites system whose diversity has proved much richer than initially imagined, remain a primary objective for future planetary missions such as JUICE, which will study the moons of Jupiter as a planetary system model, a science renewed by the discoveries of numerous exoplanets for several years, some of which similar to the Earth.

On exobiology and exoplanet research, the search for potential traces of life under the ice cover on the moons Europe and Ganymede around Jupiter, or Enceladus and Titan around Saturn remains a major objective of future missions towards gas giants. Besides the planetary projects on Mars or on the comet 67P/Churyumov–Gerasimenko searching for the origin of life, the French community is involved in projects for the detection and characterisation of exoplanets. We are also involved in the ground segment of the CHEOPS mission, the first small class mission of ESA's Cosmic Vision programme which is to be launched in 2018. French community is involved in the ESA PLATO mission and we support the development of the AIRS spectrometer, a core piece of the ARIEL mission which has just been selected by ESA. This set of missions studying "new worlds" will take us beyond the era of detection to enter that of the characterisation of exoplanets, with the observation of hundreds of objects and their atmosphere to determine their habitability.

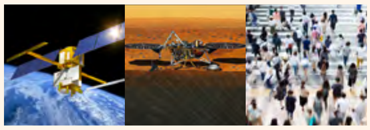
2018 sets out to be a great year for CNES with a lot of achievements towards Mars. TGO, the orbiter of ESA EXOMARS mission, ended its aerobraking phase and the measurements have begun. INSIGHT is to be launched with the SEIS instrument, a seismometer of an incredible sensitivity provided by CNES to determine the Red Planet's internal structure. For many years, France is involved in almost every missions to Mars, MARS EXPRESS, MAVEN, CURIOSITY (MSL), then INSIGHT and MARS 2020. All those missions are dedicated to search for traces of life, for the study of its climate and its evolution, for the study of its surface and its internal structure. Our commitment should continue with a Mars sample-return mission, a major issue that will certainly concentrate many efforts for the ESA's Ministerial Council in 2019.

On the way towards the Mars Sample Return mission, after HAYABUSA, CNES is developing a partnership with Japan on the MMX mission whose purpose is to bring back samples from Phobos in 2028 to improve our understanding of the formation of the Solar system and particularly on the origin of this moon.

On 25th April 2018, the 2nd version of the GAIA catalogue was released which brings unprecedented information on more than 1,7 billion stars of our Galaxy revolutionising the stellar, galactic and exoplanetary astrophysics in a way still impossible to predict today. CNES is heavily involved in the data processing of several ground segment chains.

July 2018 will see the launch of the NASA PARKER SOLAR PROBE, a mission skimming the sun that will pass as close as only a few solar radii from its surface. Several French laboratories are associated with this mission and have provided instruments for the probe. Later on, in October, BEPI-COLOMBO will start its journey to Mercury. This ESA-JAXA mission will also face extreme temperature conditions. The PHEBUS instrument has been provided by a French laboratory, with CNES support. Last but not least, the SOLAR ORBITER mission has been delayed due to satellite problems and should be launched in 2020. This unfortunate delay will give us the opportunity to present this very important solar physics mission during the next COSPAR session.

Recent successes have been achieved with CNES's balloon missions. In September 2017, the second flight of the



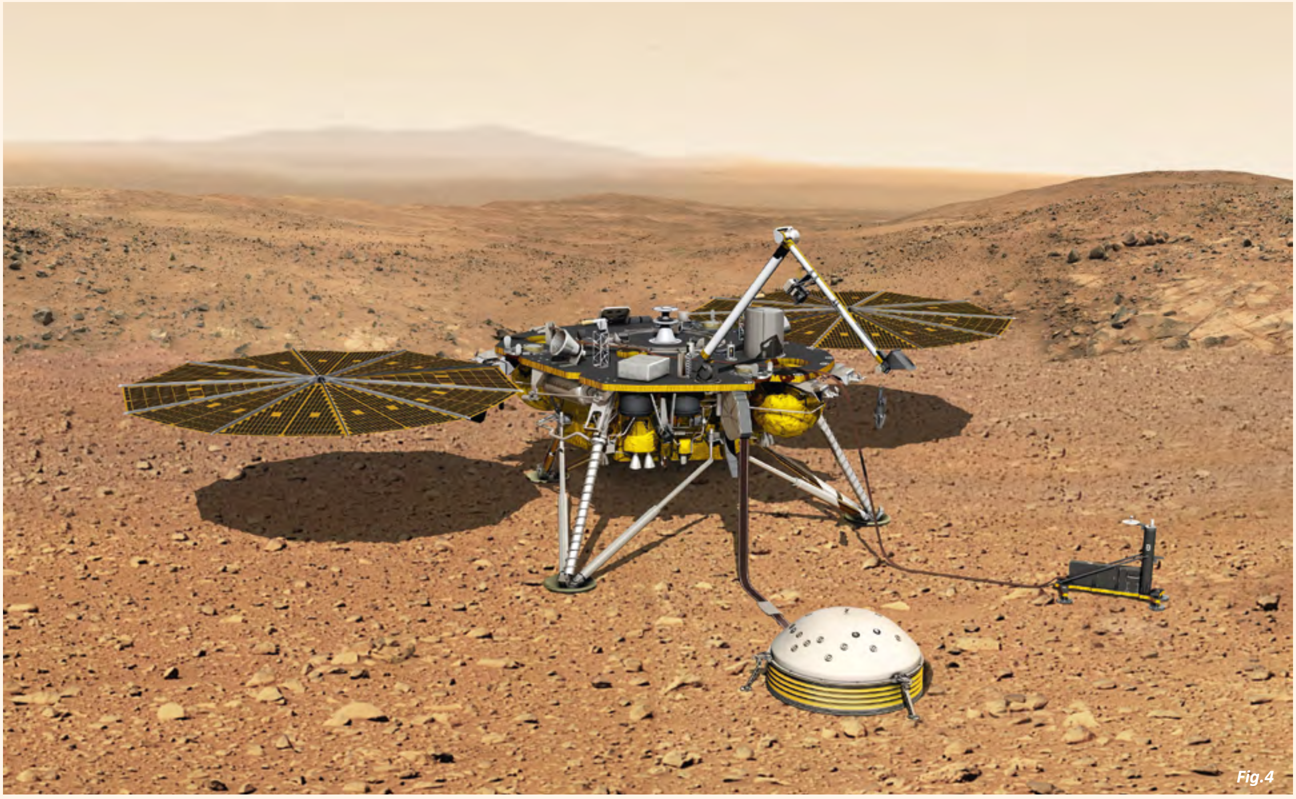


Fig.4

PILOT experiment (Polarized Instrument for Long-wavelength Observations of the Tenuous interstellar matter) made it possible to measure the polarised sub-millimetric emission of interstellar dust from our Galaxy.

To conclude, since the last report to COSPAR, there is no doubt we remain in the golden age of space sciences. The years to come will see the launch of many mission with French scientific community and CNES support. Work progresses on many missions under development, such as the future ESA's L2 mission ATHENA, for which CNES is supporting the French PIship of the X-IFU instrument, and also for EUCLID who will unveil the secrets of dark energy and dark matter. From dark matter to gravitational waves, from the Equivalence Principle to looking for traces of life on Mars or on icy moons in the far reaches of our Solar system, space research is one of the most exciting adventures of our time which uncovers little by little the secrets of the universe.

Fig.5

Fig. 1: Jean-Louis Monin
© CNES/JALBY Pierre, 2016

Fig. 2: EXOMARS rover
© ESA/ATG medialab

Fig. 3: Thermal vacuum test of the Microscope satellite *© CNES/GRIMAULT Emmanuel, 2015*

Fig. 4: Artist's view of the InSight lander (INterior exploration using Sesmic Investigations, Geodesy and Heat Transport) *© CNES/IPGP/Ill./DUCROS David, 2017*

Fig. 5: Thomas Pesquet's return
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The Cocktail bed rest study

Space environment and microgravity cause physiological changes that particularly challenge the cardiovascular, metabolic, muscle, bone, immune and neuro-vestibular functions. This can jeopardise the performance of astronauts, their healthy return to Earth and the success of a mission. With the planned exploration of celestial bodies such as the Moon and Mars, the development of efficient countermeasures is a top priority.

Since the beginning of manned space flights, numerous countermeasures were tested, including drugs, nutrition, and various physical exercise training programmes. However, none were proven to be fully effective so far.

Over the past decade, a growing interest for nutritional countermeasures has emerged. First, to prevent negative protein balance and muscle mass loss. Protein supplementations with or without the use of bicarbonate to buffer changes in blood acidity were tested. Results happened to be highly variable and not conclusive.

Very recent observations from clinical studies and studies conducted either in actual or simulated microgravity pointed towards the use of micronutrients, vitamins and other bioactive compounds from the diet. The widest range of effects was observed for a polyphenol, the resveratrol. In rats, we observed that resveratrol supplementation maintains protein balance, muscle mass, strength and mitochondrial oxidative capacity, bone mineral density and strength. It further protected whole-body insulin sensitivity, lipid trafficking and oxidation, and oxidative stress (Fig. 1).

Based on all the recent findings reported in the literature showing the wide effects of several bioactive compounds from the diet, scientists decided to test a dietary cocktail with anti-oxidant and anti-inflammatory properties as a new countermeasure, for a 60-day bed rest during a workshop on new countermeasures held by ESA in 2014. However, the ESA nutrition expert group strongly suggested performing a preliminary study to assess the efficacy of the cocktail on basic parameters known to be affected by bed rest. It was decided to use a simple outpatient protocol of step reduction to induce physical inactivity in active individuals; physical inactivity being 1 of the major factor inducing adaptation to space environment. In order to boost the metabolic challenge induced by inactivity, the last 10 days of the protocol were coupled with fructose ingestion, which is generally used to induce reversible insulin resistance in biomedical research.

SCIENTIFIC PAYLOAD

The purpose of the Cocktail bed rest study is to test a new nutritional countermeasure that consists of an anti-inflammatory and antioxidant mixture (called XXS-2A-BR2) composed of plant extracts derived from edible plants coupled with vitamin E, dietary omega-3 and selenium to prevent and/or reduce the deleterious effects induced by 60 days of antiorthostatic bed rest. Sixteen scientific protocols (PIs: G. Trudel, JP. Frippiat, J. Fielitz, A. Blaber, I. McDonald, A. Stahn, M. Tagliabue, C. Leguy, D. Thompson, S. Archer, M. Salanova, A. Chopard, M. Heer, S. Blanc, E. Caiani, R. Reynolds) have assessed the modifications in the cardiovascular, metabolism, muscle, bone, neuro sensorial, hematological and immunology systems, and the potential beneficial effects of the countermeasure on these same systems.

SCIENTIFIC HIGHLIGHTS

As for now, the main results of this scientific project have been obtained during the feasibility study. Twenty healthy active (14 000 steps/d measured by accelerometer) young men, randomised in control (n=10) and cocktail supplemented (n=10)

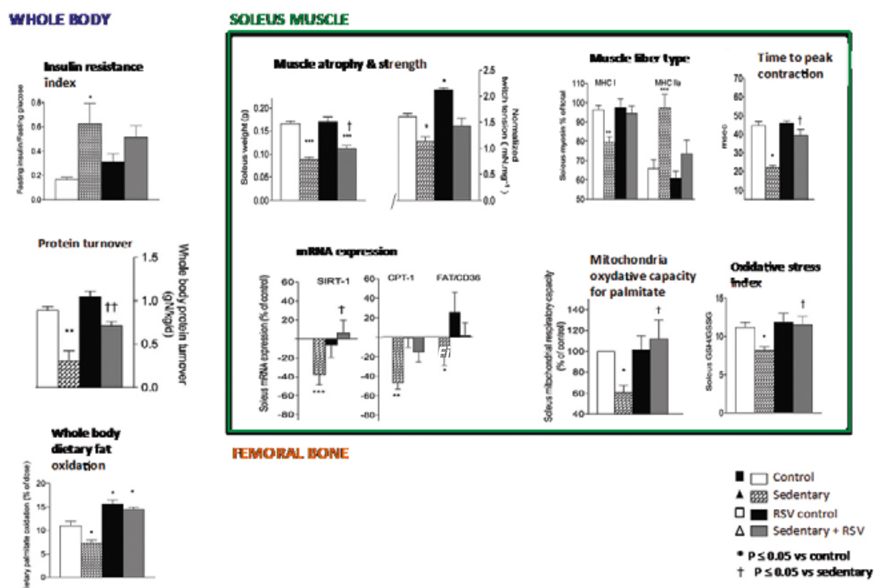

Fig.1

groups, were asked to stop exercise and drastically reduce their daily physical activities (2 800 steps/d) for 20 days. The supplemented group received a cocktail composed of polyphenols (530 mg/d), omega 3 (2.1 g/d), selenium (80 µg/d) and vitamin E (168 mg/d). Participants received a fructose supplementation during the last 10 days of the protocol to trigger the development of systemic insulin resistance.

The 20 days of deconditioning induced a reduction of about 20% in both total and type 2-myosin heavy chain cross sectional areas in the control group that was prevented in the supplemented group ($p<0.01$ and $p<0.001$ as compared to control group respectively, Fig. 2a & 2b). While insulin sensitivity was only moderately affected by the intervention in either of the 2 groups (Fig. 2c), plasma concentration of adiponectin, an insulin-sensitiser and anti-inflammatory adipokine, was still higher in the supplemented than in the control group at the end of the intervention ($p<0.05$, Fig. 2d). The supplementation also counteracted the deleterious effects of the intervention in the control group on fasting and OGTT-plasma triglycerides ($p<0.02$ at the end of the intervention, Fig. 2e), on fasting HDL ($p<0.0001$), Fig. 2f) and was associated with a greater lipid oxidation during the OGTT ($p<0.02$, Fig. 2g), greater muscle FATP1 protein content (Fig. 2h) and stable ubiquitous protein content (Fig. 2i). The supplemented group had higher blood anti-oxidant capacities than the control group at the end of the OGTT after 20 days of intervention suggesting improved anti-oxidant reserves ($p<0.01$, Fig. 2j).

Based on these positive results, it was decided by the ESA's bed rest investigators working group and ESA's nutrition group to go on with the cocktail countermeasure and test it during the 60 days bed rest study. Given the small changes observed on the blood anti-oxidant capacity, a slight modification of the cocktail was proposed through a mild increase in the quercitin fraction of the polyphenol's fractions; querticin being known to possess important anti-oxidant properties.

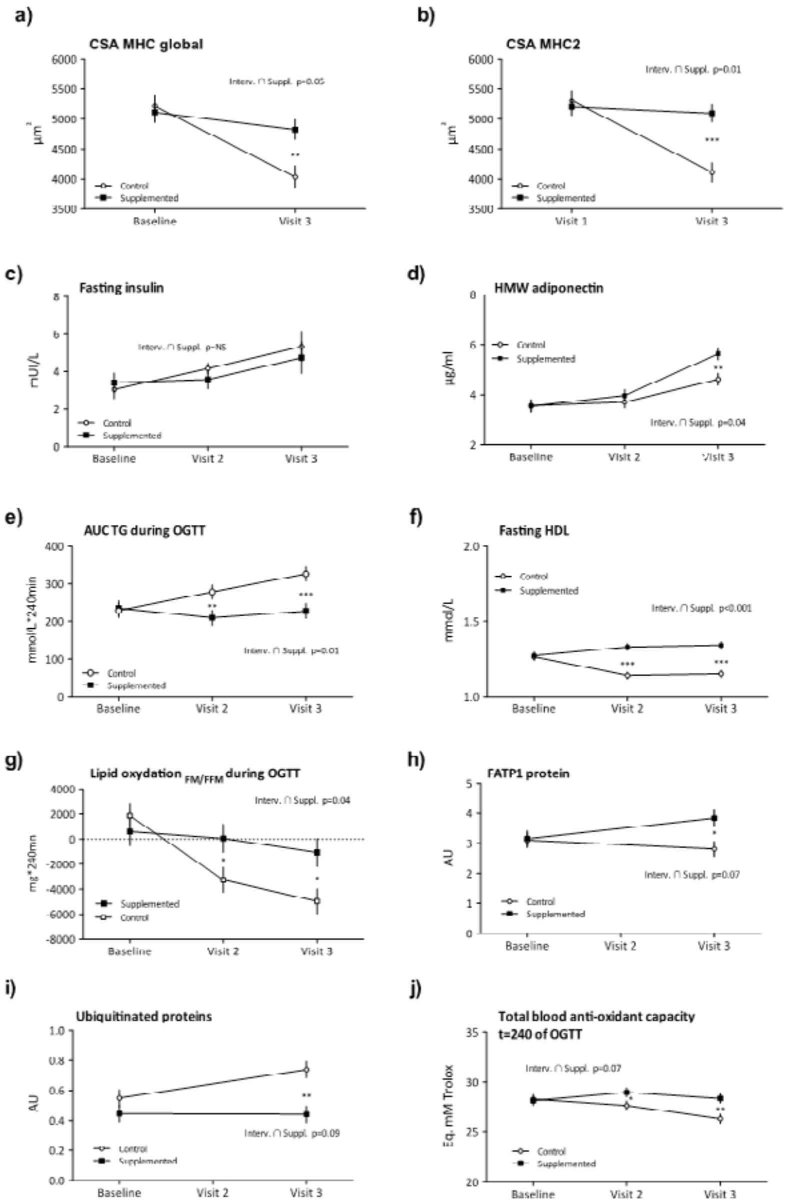

Fig.2

MISSION STATUS

The feasibility study was conducted at the Space Clinic, MEDES at the Hôpital Rangueil in Toulouse, France in September 2016. The team led by S. Blanc (CNRS, Strasbourg, France) was in charge to conduct this first trial. Data and samples have been analysed and a manuscript is in revision at the *Journal of Applied Physiology*. The most conclusive Cocktail bed rest study was conducted during 2 sessions, the first one occurred in January-March 2017 and the second one in September-December 2017. The bed rest study was also performed at the MEDES. Following an extensive and thorough recruitment and screening process, 20 young male adults (10 per session) were selected to take part in the study and provided a signed informed consent. The bed rest study was organised in 3 periods: A 15-day baseline data collection period followed by the 60 days of bed rest and a 15-day recovery period. During the bed rest period, the twenty subjects were randomly assigned to one of the 2 groups, the control group who was in strict bed rest, or in supplemented group who received the cocktail supplementation during the bed rest period. During this study, 16 independent research projects have been conducted on these 20 participants. The study has been successfully completed and all the data and samples have been collected. They are now under analysis in the 16 respective research labs.

Fig. 1: Effect of resveratrol in hind-limb suspended rats © *from Momken I. et al. (2011) Resveratrol prevents the wasting disorders of mechanical unloading by acting as a physical exercise mimetic in the rat, The FASEB Journal, 25, 3646-3660*

Fig. 2: Effects of the cocktail countermeasure to prevent the metabolic alterations induced by 10 days of reduction in daily steps alone (Visit 2) and by 10 more days of reduction in daily steps coupled with fructose supplementation (Visit 3) as compared to baseline. Results are based on analyses using linear mixed models taking into account repeated measures. The interaction between the intervention (inactivity & fructose supplementation) and the supplementation was tested. The post-hoc comparisons between the supplemented and the control groups at the end of the intervention, adjusted on fat-free-mass and on baseline values of the variable of interest, are presented below. © *from JAP (submitted)*

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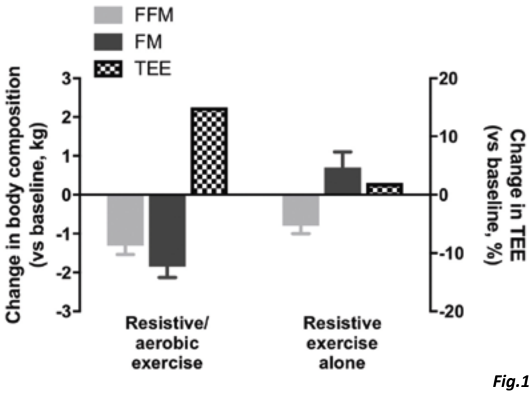
The obligatory exercise countermeasure programme during space flight: is it time for revision?

Astronauts' weight loss is a medical concern since early space flights. The underlying energy deficit is detrimental to health and may jeopardise the missions' success and a healthy return to Earth. Data obtained in both actual and simulated microgravity suggest that the obligatory exercise countermeasures programme may be partly responsible for this chronic weight loss. If validated, this hypothesis will require an in-depth revision of the countermeasures required for planetary exploration.

During short term missions on-board the shuttles and MIR, the systematic in-flight energy deficit [1, 2] is of particular concern. A meta-analysis based on 619 missions estimated an average loss of 2.4% body weight per 100 days spent in space [3], which would represent 15% body mass loss for a mission to Mars. While such energy deficits are tolerable for short-term missions because of body fat stores, a chronic negative Energy Balance (EB), *i.e.* energy intake lower than Total Energy Expenditure (TEE), is an issue [1]. Ground-based data demonstrated that chronic energy deficit exacerbates some of the deleterious physiological adaptations observed during space flights including cardiovascular deconditioning, bone loss, muscle mass and strength losses, impaired EXercise (EX) capacity, and immunity defects. All of this can jeopardise crew health and performance, and the success of the mission. Achieving EB during long term space flights is a research priority for planetary exploration.

Energy requirements during short term missions were reported to be similar to those on the ground [1] if and only if, the cost of EX countermeasure was well accounted for. EX countermeasure is a mandatory programme to prevent the adverse adaptations including the loss of fat-free mass. For longer missions, data are not available and the origin of the negative EB remains unknown. It is likely twofold, *i.e.* too low energy intake and/or too high EE. Calorie intake has been slowly increasing in astronauts on the ISS, but still does not match EE [1]. On the other hand, the EX countermeasure along with the 500 hours of Extra Vehicular Activity (EVA) performed by the astronauts induces very high EE. This high TEE needs to be balanced by greater energy intake, which is not always easy to achieve.

In 2000 P. Stein observed that 15-days Shuttle missions with high physical EX prescriptions were associated with major body mass loss and negative protein balance (index of muscle mass loss), while missions with low EX prescription were associated with stable protein balance and body mass [1]. Pre-flight fitness is another determinant; astronauts who were most trained prior to the mission lost the most, while astronauts relying on walking as EX lost the least [3]. Based on these data, he hypothesised that EX countermeasure was an important driver of weight loss in space. Over the last 10 years, we have collected supportive evidence. Data obtained in simulated microgravity conditions during bed rest studies showed that weight loss was related to the impact of EX on TEE. An EX programme combining resistive and aerobic EX with a high impact on EE induced a loss in both fat mass and fat-free mass [4], while the practice of resistive EX only with a low impact on EE maintained fat mass and prevented the loss of fat-free mass (Fig. 1). During the protocol ENERGY conducted in the ISS since 2011, we further examined the contribution of each component of TEE, *i.e.* Resting Metabolic Rate (RMR), Diet-Induced Thermogenesis (DIT) and Activity Energy Expenditure (AEE), to better understand the in-flight regulation of EB and estimate daily energy requirements. Based on preliminary data, we unexpectedly observed a large variability between individuals who can be divided into 2 groups: those who had an increase in TEE (n=5) and those who had a decrease (n=4) after 3 months on the ISS (unpublished; Fig. 2). These in-flight changes in TEE were not explained by changes in RMR or DIT but by changes in AEE. This is important because astronauts who had an increase in TEE maintained their fat-free mass as



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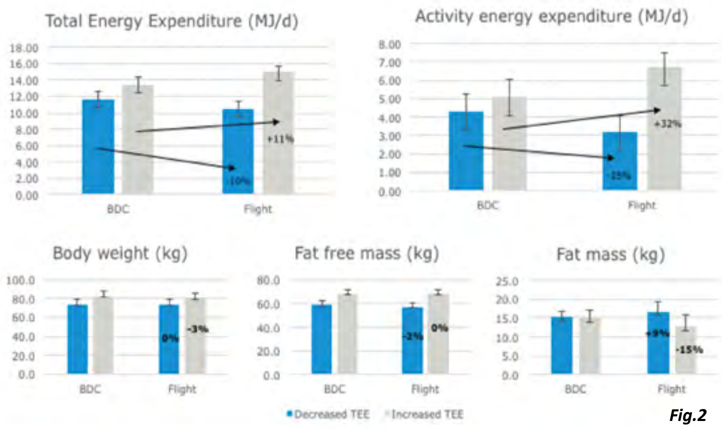

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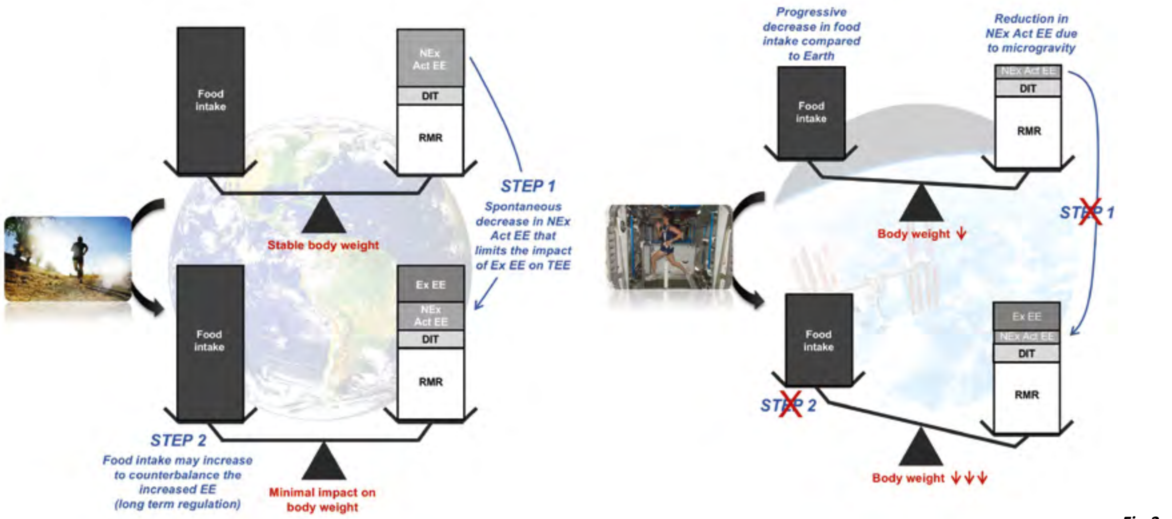

Fig.3

expected but lost fat and body mass. In contrast, astronauts who did not increase their TEE did not lose body mass, gained fat mass, and more importantly had only a minor fat-free mass loss. The changes in fat mass were further correlated with time spent doing EX. These results are in line with P. Stein's hypothesis and are the firsts for long missions. Understanding the underlying mechanisms explaining why astronauts are unable to regulate EB in presence of EX when the performance of EX has a very limited effect on body mass on Earth is key.

AEE is a complex component of TEE. It is composed of energy expended during EX and non-EX activities. On Earth, non-EX AEE represents the energy expended in any body movement during daily life activities (walking, taking the stairs, gardening, etc.). During bed rest studies, we showed that non-EX AEE, and not energy intake, is primarily used to buffer energy deficit induced by high volume of EX and represents a key component of EB control [4]. Because this component is drastically reduced in space due to the very nature of the microgravity conditions, AEE is equivalent to the energy expended during EX and EVA only. Consequently, non-EX AEE cannot be used to restore EB in response to high EX volume prescribed as countermeasure. Weight loss occurs because energy intake does not increase to match EE (Fig. 3).

While not negating the role of EX as countermeasure during space flights, these data challenge the current EX countermeasure programme, especially in the context of planetary exploration. The development of an EX countermeasure programme that has a minimum impact on TEE, while preventing muscle mass loss and the other physiological adaptations is needed. Among possibilities, a large body of data generated on Earth shows that the High Intensity Interval Training (HIIT) fulfils these needs.

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Fig. 1: F Effect of exercise countermeasure programmes combining resistive and aerobic exercise vs. resistive exercise alone on fat mass, fat-free mass and total energy expenditure during bed rest studies.

FM: fat mass; FFM: fat-free mass; TEE: total energy expenditure

Fig. 2: Changes in total energy expenditure and activity energy expenditure after 3 months on the ISS, and impact on body mass, fat-free mass and fat mass.

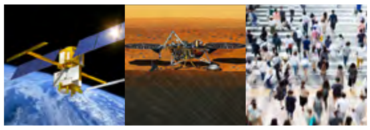
TEE: total energy expenditure; BDC: baseline data collection.

Fig. 3: General model of energy balance regulation on Earth and in space in response to exercise. EE: energy expenditure; TEE: total EE; NEx Act EE: non-exercise activity EE; Ex EE: exercise EE; DIT: diet-induced thermogenesis; RMR: resting metabolic rate.

Installation and use of the FLUIDICS instrument in the ISS by Thomas Pesquet in May 2017

The study of systems brought away from equilibrium is one of the fields of physics that particularly digs turbulent phenomena. Generally, in those systems, a stream of energy propagates in the form of random waves. But the theoretical approach of wave turbulence shows that these interactions are following very specific laws that are yet to be tested experimentally.

Fig.1



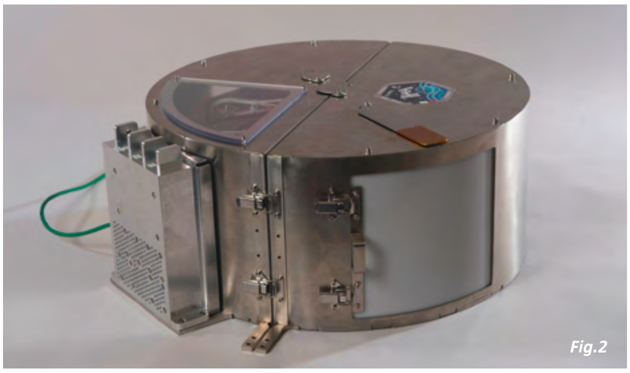
The study of the variations in the amplitude of a liquid inside a container represents the ideal model to study the waves on the surface of the ocean. However, the comparison remains difficult because experiments in containers are inevitably altered by the edges reflecting the waves. Scientists from ENS (École Normale Supérieure) and from Paris Diderot University proposed to bypass this issue by placing a sphere partially filled with liquid in microgravity. The liquid then covers the interior wall of the sphere and organise itself to create waves with various amplitude and length under the effect of imposed vibrations. In this case, these interacting waves display a random dynamic. The measurement of the height of waves, over time, then allows to verify that a relation emerge between the amplitude and the frequency of waves and that this relation is by no means affected by the agitation imposed on the environment.

The FLUIDIDCS instrument has been developed jointly with Airbus Defence and Space in Toulouse to respond to this proposal of experiment. Because with this same instrument, but different spheres, we have also been able to study, inside the International Space Station (ISS), the disturbances in the orientation of satellites caused by the sloshing of liquid-propellant inside their tank.

FLUIDICIS is composed of an oscillating arm holding 2 cameras and 2 liquid level sensors. After having assembled and tested the instrument, Thomas Pesquet successively set up the spheres corresponding to the different experiments.

The results of these technological experiments are useful to adjust the predicative models of the movement of liquid-propellant and will make it possible to better control the positioning of satellites. As for the scientific approach of these experiments, the measurements show a good agreement with the theoretical prediction of surface waves turbulence. Apart from a better understanding of the conditions surrounding the occurrence of the wave turbulence phenomenon, these results will help to better understand the complex evolution of surface waves in oceans, in which similar effects take place. This deeper understanding should lead to an improvement of the parametrisation of the exchanges between the atmosphere and the ocean within the current climates and weather models.

The number of times Thomas Pesquet performed these experiments has been increased within the allocated time and the result is a success. Thus, it has been proposed to ESA to keep the instrument in the ISS to add new experiments to the future European astronauts' programmes. And in turns, new technological and scientific experiments will take place in the ISS, both to test new types of tanks and to test the validity domain of the theory of waves turbulence.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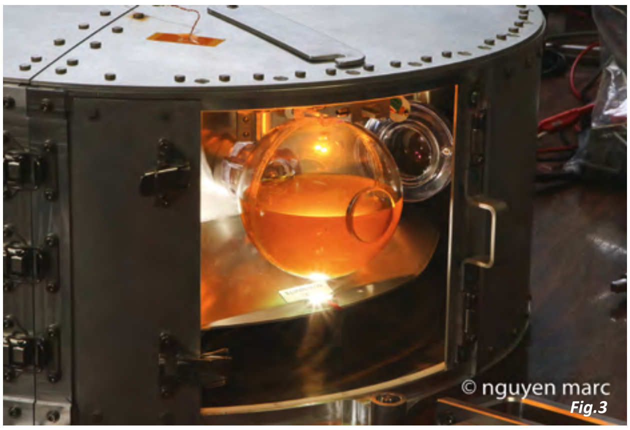

Fig.3

Fig. 1: Fluidics experience aboard the International Space Station *© ESA/NASA/, 2017*

Fig. 2: Preparation of the Fluidics experiment of the Proxima mission at Cadmos *© CNES/GRIMAULT Emmanuel, 2016*

Fig. 3: Preparation of the Fluidics experiment of the Proxima mission at Cadmos *© CNES/NGUYEN Marc, 2016*

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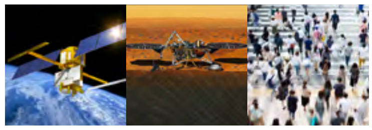
Wave turbulence in microgravity

We report experiments conducted by the ESA astronauts T. Pesquet and P. Nespoli on the International Space Station in 2017. Using a new device, "FLUIDICS" (Fluid Dynamics in Space), developed by CNES and Airbus Defence and Space, they studied turbulence of capillary waves on the surface of a fluid in a spherical container. Power spectra of wave turbulence have been found to be in good agreement with weak turbulence theory.

Wave turbulence results from the nonlinear interactions among stochastic waves [1]. The first studies have been conducted in the early 1960s motivated by wave forecasting on the ocean. However, it was soon realised that similar techniques could be used to understand nonlinear interactions between waves in many different systems, such as Alfven waves in the solar wind, radar waves in the ionosphere or at much smaller scales, sound waves in solids or liquids. The first analytical studies of wave turbulence have been performed in the early 1970s in order to predict how the distribution of the wave energy depends on their wavenumber. Besides equilibrium spectra (such as the blackbody spectrum for instance), out-of-equilibrium spectra that involve a finite energy flux in Fourier space, *i.e.* a transfer of energy from an injection scale to a dissipation scale, have been found. This out-of-equilibrium behavior is similar to the Kolmogorov cascade in fluid turbulence. Many data from astrophysical or geophysical fluid dynamics obtained using remote sensing have been analysed using the framework of wave turbulence. Several laboratory experiments, performed during the past decade have shown the limits of the theory based on weakly interacting waves. The different requirements for the validity of weak turbulence theory are indeed conflicting. It is assumed that waves propagate in a medium of infinite extension with negligible damping. Experiments of course involve a finite domain. If dissipation is small, resonant modes of the domain are excited dominantly compared to the continuous spectrum predicted by weak turbulence. A too large dissipation requires a strong forcing and is also out of the validity range of weak turbulence. There is probably an optimum dissipation in the limit of a large domain but no criterion is known in that framework. Reflection on boundaries could also affect wave turbulence. We mention below how experiments in reduced gravity can solve some of these problems.

Many laboratory experiments have been performed with surface waves on a horizontal layer of fluid. In this configuration, the dominant restoring force is gravity for large wavelength and capillarity for short wavelength. The transition between the 2 regimes occurs for the capillary length that depend on the surface tension, the fluid density and the acceleration of gravity. For simple fluids on Earth, the capillary length is a few millimetres. Energy transfer mechanisms are different for gravity and capillary waves and this makes the cascade process of the energy more difficult to understand since the mechanisms change when one crosses the capillary length [2]. The first advantage of experiments in reduced gravity is to increase the capillary length above the size of the container and thus to have capillary waves throughout the cascade. A second advantage is related to the geometry of the experiment. At low gravity, the fluid inside a spherical container wets the inner boundary and therefore takes the shape of a spherical fluid layer. Capillary waves propagate on its inner surface without meeting any lateral boundary in contrast to the configurations studied on Earth. Although the infinite medium limit assumed for weak turbulence theory is not achieved, the parasitic effect of lateral boundaries is suppressed.

Capillary waves in reduced gravity have been first studied in parabolic flights [3]. The main limitation is related to the 20 s duration of each parabola that does not allow enough statistics and could be even too short compared to the transient regime. An experimental device called FLUIDICS has been developed by Airbus Defence and Space and CNES and operated by the ESA astronaut T. Pesquet, and then by P. Nespoli, on ISS. This has allowed much longer measurements. This device has been developed to study both capillary wave turbulence and sloshing. Its schematic view is displayed in Fig. 1.



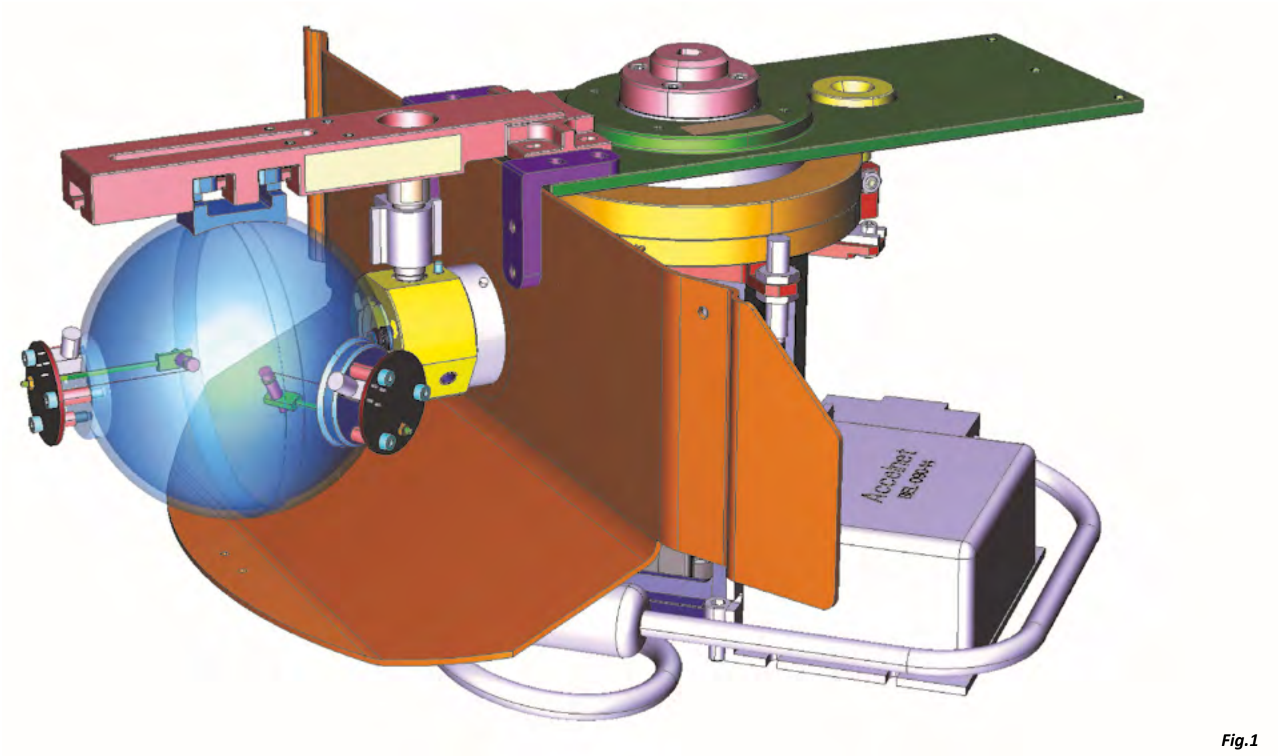


Fig.1

The sphere of inner diameter 100 mm is partly filled with water (30% in volume). The depth of the spherical fluid layer is 5.6 mm. The sphere is driven in an oscillatory rotating motion by a lever and the surface deformation of water is measured by 2 capacitive wires. The power spectrum of the fluctuations of the surface in the turbulent regime is displayed in Fig. 2. Although the excitation is sinusoidal, a continuous spectrum is generated by non-linear interactions that trigger energy transfers between waves of different frequencies. The slope of the spectrum is found to be in good agreement with the prediction of weak turbulence theory.

To conclude, reduced gravity provides better experimental configurations to study capillary wave turbulence than laboratory experiments on Earth. Spatial correlations and probability density functions of the fluctuations of the fluid surface will be studied soon. Using higher frequency forcing will also allow us to test whether scales larger than the one of the forcing are in statistical equilibrium [4]. This work will be pursued by next ESA astronauts. A more technological study has also been performed on ISS with FLUIDICS instrument to benchmark numerical models for a better prediction of slosh dynamics in liquid propellant tanks and their effect on spacecraft trajectories during their manoeuvres [5].

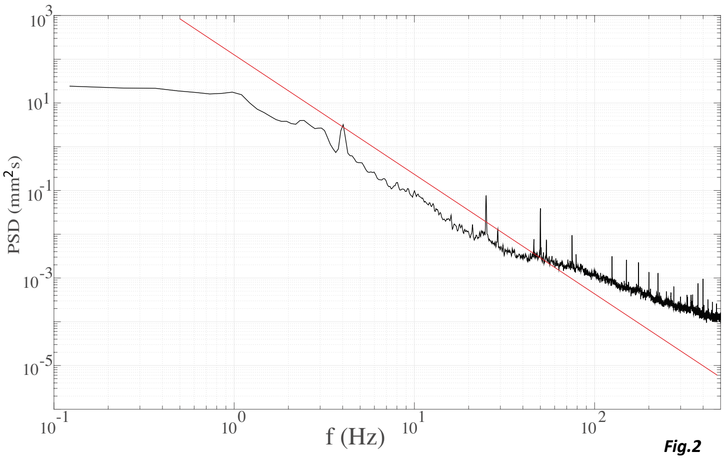


Fig.2

Fig. 1: Schematic view of the experiment: a sphere partly filled with fluid is fixed at the end of a lever that is rotated in order to generate waves on the fluid inner surface. The fluid motions are visualised using two cameras and its height is measured by two capacitive gauges. *© Airbus Defence and Space*

Fig. 2: Power spectrum of the fluid surface fluctuations: the container is driven in an oscillatory rotating motion with amplitude 0.04 rad and frequency 2 Hz. A continuous spectrum is generated by energy transfers between random waves. Straight line: theoretical prediction in the weak turbulence regime. *© LPS, Ecole Normale Supérieure & MSC, Univ. Paris Diderot*

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INSIGHT, geophysical science on the surface of Mars

INSIGHT (INterior exploration using Seismic Investigations, Geodesy and Heat Transport) is a mission from NASA's discovery programme. A lander will deploy geophysical instruments on the surface of Mars to study the planet's deep interior and gain new understanding of how rocky planets form.

INSIGHT aims to study Mars' deep interior structure using a seismometer deployed from a fixed lander to better understand the mechanisms that shaped the rocky planets in our Solar system. Using the SEIS seismometer (Seismic Experiment for Interior Structures), it will measure Mars' tectonic activity to learn more about its structure, for example the size of its core, the thickness of its mantle and crust. Meteorite impacts will also be analysed by measuring seismic waves. The Heat Flow and Physical Properties Package (HP3) will gauge the planet's cooling rate in order to retrace its thermal history. And the RISE instrument (Rotation and Interior Structure Experiment) will acquire precise measurements of the Red Planet's rotation. INSIGHT includes also a suite of environment sensors (APSS-Auxiliary Payload Sensor Suite) including pressure / infrasound sensors, magnetometer and wind sensor.

INSIGHT will land on Mars on 26 November 2018 for a 2-year mission. CNES is overseeing development of the SEIS instrument in partnership with the Paris Institute of Earth Physics (IPGP), SODERN (ArianeGroup), the Swiss Federal Institute of Technology (ETH), the Max Planck Institute for Solar System Research (MPS), Imperial College London and the Jet Propulsion Laboratory (JPL). INSIGHT is the 12th mission of the Discovery Programme.

Fig.1

SCIENTIFIC PAYLOAD

INSTRUMENT	OBJECTIVE	PI LABORATORY
SEIS (Seismic Experiment for Interior Structures)	Seismometer to measure tectonic activity: Mars quakes, meteorite impacts, Phobos gravity waves.	CNES overall responsibility with IPGP, SODERN, the Swiss Federal Institute of Technology (ETH), the Max Planck Institute for Solar System Research (MPS), Imperial College London and the Jet Propulsion Laboratory (JPL)
HP3 (Heat Flow and Physical Properties Package)	Instrument to gauge the planet's cooling rate	DLR-Berlin
RISE (Rotation and Interior Structure Experiment)	Instrument to measure the planet's rotation	JPL, Royal Obs. of Belgium (ORB)

SCIENTIFIC OBJECTIVES

INSIGHT's primary objective is to uncover how a rocky body forms and evolves to become a planet by studying the size, thickness, density and overall structure of the Red Planet's core, mantle and crust, as well as the rate at which heat escapes from the planet's interior. Generally, a rocky body begins its formation through a process called accretion. As the body increases in size, its interior heats up and melts. As it subsequently cools and recrystallises, it evolves into what we know today as a terrestrial planet, containing a core, a mantle and a crust. While all the terrestrial planets are by no means uniform, they share similar structures and their bulk compositions are roughly the same due to the fact that they were formed from the same nebulous material. Each of the terrestrial planets reached its current formation and structure through a process known as differentiation, which is poorly

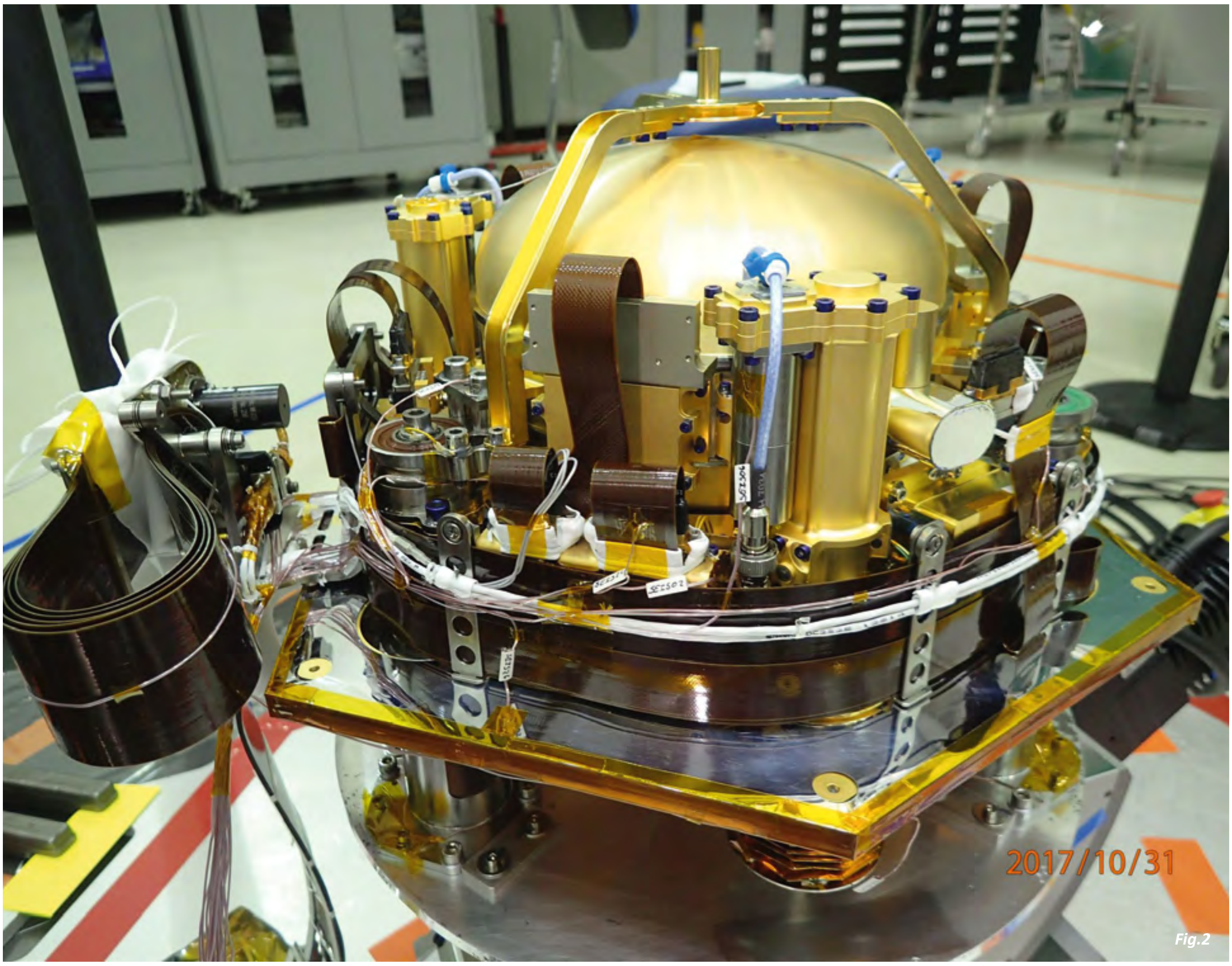


Fig.2

understood. INSIGHT's goal is to solve the mystery of differentiation in planetary formation - and to bridge the gap of understanding what lies between accretion and the final formation of a terrestrial planet's core, mantle, and crust.

The mission's secondary objective is to conduct an in-depth study of tectonic activity and meteorite impacts on Mars, both of which could provide valuable knowledge about such processes on Earth.
To achieve each of these objectives, INSIGHT will conduct 6 investigations on and below the surface of Mars to uncover the evolutionary history that shaped all of the rocky planets in the inner solar system. These investigations will:

- Determine the size, composition, physical state (liquid/solid) of the Martian core
- Determine the thickness and structure of the Martian crust
- Determine the composition and structure of the Martian mantle
- Determine the thermal state of Mars' interior
- Measure the magnitude, rate and geographical distribution of Mars' internal seismic activity
- Measure the rate of meteorite impacts on the surface of Mars

MISSION STATUS

INSIGHT key dates:

- Launch: 5 May 2018 (start of the 30 days' launch window)
- Landing: 26 November 2018 (at 19-20 h UT)
- Surface operations: 720 days / 700 sols
- Instrument deployment: 60 sols (including 20 sols' margin)
- Start of science operations: late January 2019
- Data volume over one Martian year: More than 29 Gb (processed seismic data posted on the Web in 2 weeks; remaining science data less than 3 months, no proprietary period)
- End of nominal Mission: October 2020

Fig. 1: The SEIS FM experiment with the WTS (Wind & Thermal Shield) white dome deployed during a thermal vacuum test at Lockheed Martin in November 2017 © *Lockheed Martin.*

Fig. 2: The SEIS FM experiment during integration and tests at Lockheed Martin last October © *Lockheed Martin.*

MSL/CURIOSITY, a rover exploring Mars

On 6 August 2012, the CURIOSITY rover landed on Mars to determine if the Red Planet could have once harboured life. CNES is closely involved in this mission led by NASA, which has been extended beyond its 22 months' nominal mission.

Was Mars once habitable? That is the main question the Mars Science Laboratory (MSL) mission of NASA's Mars exploration programme is attempting to answer with the CURIOSITY rover operating on the planet's surface. Since its landing in Gale Crater, this 900-kg robotic explorer has conducted a series of analyses aimed at assessing Mars' habitability, estimating its biological potential and characterising its geology.

To accomplish its task, CURIOSITY has a robotic arm equipped with in-situ instruments to survey the soil and rocks, together with a drill and a scoop to pick up samples for further analysis by its SAM (Sample Analysis at Mars) and CHEMIN (CHEmistry & MINeralogy) mini-laboratories. The rover is also equipped with 8 other instruments.

CNES' contribution to the MSL mission is twofold. First, it is overseeing the French instruments SAM and CHEMCAM (CHEMistry CAMera), in which the LATMOS-CNRS and the IRAP-CNRS are involved. Second, CNES is responsible for developing and running the French Instruments Mars Operations Centre (FIMOC) in Toulouse, which operates CHEMCAM and SAM, and exploits the data they gather.

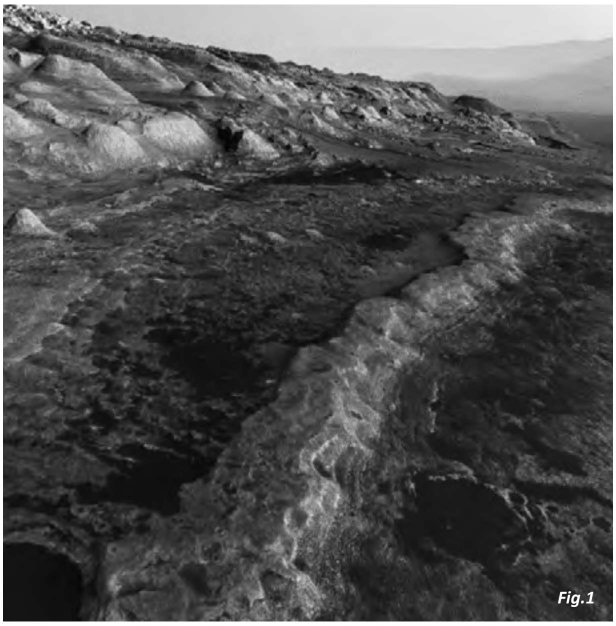
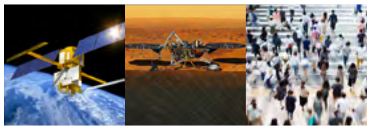


Fig.1

SCIENTIFIC PAYLOAD & FRENCH CONTRIBUTION:

INSTRUMENT	OBJECTIVE	PI LABORATORY
CHEMCAM (CHEMistry CAMera)	It analyses by UV-Vis-NIR optical spectrometry the plasma light emitted by Martian rocks shot with a laser (from a distance of 1 to 9 m). It is composed of the following 2 units: The Mast Unit (mounted on the rover mast) is constituted of a laser, a telescope, and a camera (RMI: Remote Micro Imager). The Body Unit (mounted on the rover's body) is constituted of 3 spectrometers, the power and on-board management electronics. The 2 units are connected by electric cables and optical fibre.	The PI is Roger Wiens from Los Alamos National Laboratory. The Mast Unit suite is supplied by IRAP-CNRS. The Co-PI is Sylvestre Maurice from IRAP. The Body Unit is supplied by Los Alamos National Laboratory (USA). The Optical fibre is supplied by JPL (USA).
SAM (Sample Analysis at Mars)	SAM performs mineralogical and atmospheric analyses; it detects a wide range of organic compounds and performs organic stable isotopes and noble gas analyses. This instrument suite is composed of the following instruments: QMS (Quadrupole Mass Spectrometer), GC (Gas Chromatograph), TLS (Tunable Laser Spectrometer).	Its PI is Paul Mahaffy from GSFC-NASA. QMS is supplied by GSFC-NASA GC is supplied by LATMOS-CNRS. M. Cabane & C. Szopa are the lead Co-I at LATMOS TLS is supplied by the JPL-NASA.



SCIENTIFIC HIGHLIGHTS

CURIOSITY has already determined that conditions on Mars were once conducive to life and discovered an ancient river bed.

Using CHEMCAM experiment, the detection of hydrous manganese and iron oxides with variable phosphorous and magnesium contents in the lacustrine sediments of Murray formation suggests a complex process which may trace a shallow lacustrine environment [1].

A Chemical Alteration Index (CAI) used with CHEMCAM data show that this index increases with altitude on Murray formation suggesting an increase of the alteration by water when approaching the Clay-bearing unit [2].

SAM has analysed 12 samples during the 6 years of the mission. The instrument already has samples in some of its oven that may be analysed when needed. SAM is regularly monitoring the atmosphere and has detected methane at 3 occasions at concentration of 2 to 10 ppbv. Furthermore, a background level of methane is constantly measured at a level around 0.4 ppbv. This low level of methane varies with the season with a maximum of 0.7 ppbv in Northern Summer. No definitive interpretation has been given on this regular variation which does not seems to be explained by the Martian atmospheric cycle of condensation-sublimation of CO_2 in the poles.

MISSION STATUS

CURIOSITY has now driven more than 18 km and is currently on top of the Vera Rubin Ridge. Observations from orbit led to think that this ridge is enriched in iron oxides; its exploration is in progress.
At the moment, CHEMCAM has taken more than 500 000 spectra, which corresponds to almost 15 000 observation points on 1 800 Martian targets during the mission.

Late in 2016, the drilling system started to malfunction. It took more than a year for JPL to set up a new procedure to use the drill safely. A first drill has been performed in January but it was not deep enough to collect samples. It is planned to make other tests using the drill with percussion mode.

A second extended mission of one year up to September 2019 is considered, then a full extension of 3 years will be decided in Spring 2019 for 2020-2022. If this full extension is confirmed, CURIOSITY has the objective to attend the clay-bearing unit follow by the sulphate-bearing unit, driving a total of more than 25 km. The wheels are damaged by the sharp rocks of Mars, but JPL assesses that CURIOSITY will be able to drive the last 7 km without critically damaging one of its wheels.

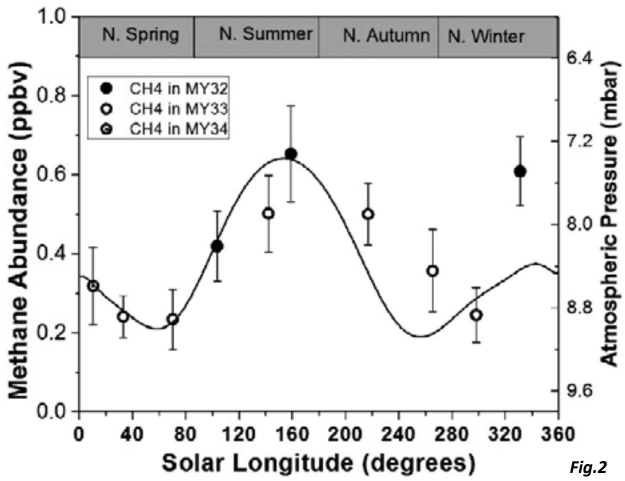


Fig.2

Fig. 1: The Vera Rubin ridge seen by HiRISE. This ridge has been observed from orbit and revealed the presence of hematite mineral, a ferric oxide mineral. Similar hematite has been observed by Opportunity in the form of small spherule. In September 2017, CURIOSITY arrived on top of the ridge. © *NASA/JPL*

Fig. 2: Methane low level variation with seasons (Webster *et al.*, Science, 2018)

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MSL/CHEMCAM: 2 000 sols within Gale Crater, Mars

CHEMCAM is the first laser-induced breakdown spectroscopy (LIBS) instrument for planetary science. It is part of the CURIOSITY Mars rover that landed in Gale crater in 2012 that measures bulk chemistry at remote distances in synergy with the 9 other rover instruments. Over the course of 2 000 sols (1 sol = 1 Mars day) more than 1 800 unique targets were analysed, revealing the composition of sediment sources, evolved igneous rocks, vein minerals, hydrated soils, and signatures of minor elements.

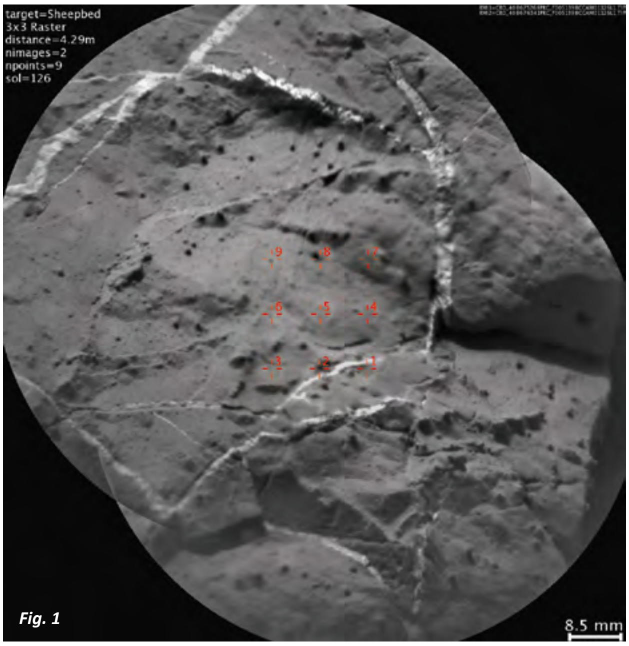
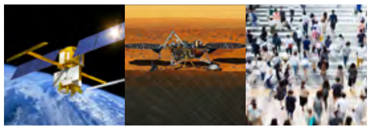


Fig. 1

The MSL mission of the NASA Mars programme is managed by Caltech-JPL. In August 2012 the CURIOSITY rover landed in Gale crater, which is partly filled with sediments. The mission objectives are to explore the sedimentary layers, which are proxies of the successive geological epochs, to evaluate the habitability of that site, and to monitor its current environment. As it progresses, CURIOSITY characterises several sedimentary deposits, some being undetectable from orbit by remote sensing, in an intricate setting resulting from a succession of fluvial, lacustrine, and aeolian episodes (deposits, erosion, weathering) [1]. The past habitability of Mars was established at Yellowknife Bay, a fluvio-lacustrine deposit where the chemical alteration of the clays was limited. A thorough stratigraphy is now being established by the rover from this lowest elevation point explored up to the flanks of the eroded mound at the centre of the crater, Aeolis Mons (or Mount Sharp).

CHEMCAM is a French-US instrument using Laser-Induced Breakdown Spectroscopy (LIBS). It measures the composition of rocks and soils within 2 to 7 m of the rover for major elements (Si, Ti, Al, Fe, Mg, Ca, Na, K), hydrogen, and non-metallic elements when they are sufficiently abundant (F, Cl, P, S), as well as minor or trace elements (Li, Rb, Sr, Ba, Cr, Mn, Ni, and Zn). In addition, CHEMCAM includes a high resolution panchromatic camera, which is used to identify the context of LIBS data (crystals, veins, nodules, grains, cement) and to make high-resolution long distance imaging a few kilometres away (ridges, lineae slopes, preserved alluvial fans, yardangs). CHEMCAM is also used in a solar-induced passive mode either to look for the reflectance of minerals (olivine, hematite) or for temporal studies of atmospheric species (O_2, CO_2). Several geological formations have been studied with CHEMCAM, as well as various outcrops, conglomerates, and soils that attest the fluvial, lacustrine, and aeolian past activities in this region of Mars. CHEMCAM contributed significantly to understanding the geochemical diversity of the landing site (Mg-rich clays, K-rich facies, Ca-rich veins, Mn-rich varnishes, Si-rich alteration halos), reflecting several sources of sediments (in space or time), and the diversity of alteration and diagenesis mechanisms that formed these rocks [2].



In support of the in-situ investigation on Mars, laboratory experiments are conducted at LANL and IRAP (respectively Los Alamos, NM, USA and Toulouse, France) to extend the database of reference spectra, and for specific studies such as the laser interaction with soil grains.

As the rover progresses, the soil composition is regularly characterised with CHEMCAM revealing 2 to 3 components, one with fine-grained hydrated mafic composition and another one with more felsic composition in gravel derived from local rocks [3]. This felsic (Si-, Al-, Na-, K-rich) signature was also seen early in the mission by CHEMCAM in igneous float rocks and conglomerate clasts that were interpreted as samples transported from the crater rim or beyond representing a somewhat evolved crust with alkaline magmatism [4].

CURIOSITY explored the active Bagnold Dunes where the entire rover payload was used to document the subtle compositional differences with the standard soil in the crater, as well as the grain size distribution and the grain motions.

Many precipitate-filled veins are present almost everywhere along the rover traverse. They prove the past occurrence of a subsurface aqueous circulation, which involved water percolation and evaporation, leaving S-rich deposits that were remobilised into the veins that crisscross the sediments (Fig. 1). CHEMCAM showed that those light-toned veins are made of a slightly hydrated calcium sulphate known as bassanite [5]. More generally, the capability of CHEMCAM to investigate the bedrock at submillimetre scales is appropriate to study the small diagenetic figures.

More clays were found in the Murray Buttes region as the rover reached Mount Sharp, and it is known from orbital observations that other clay-rich units will be encountered by the rover with the next few kilometres to come. The paleo-lacustrine mudstone terranes of the Murray Formation are made of relatively Si-, Al-, and alkali-rich sediments suggesting significant weathering in an open system with liquid water [6]. The capability of CHEMCAM to make many measurements is important for studying the chemical diversity of such an area, as shown in Fig. 2 (bars plotted at each observation point show varied chemistry despite a homogeneous-looking surface), and nicely complements the observations made by the other instruments of the payload.

In parallel to CHEMCAM operations on Mars, the next-generation instrument, SuperCam, is being built: in addition to LIBS and imaging, SuperCam will perform Raman and infrared spectroscopy, and will record laser impact sounds; it is one of the payload instruments of the NASA mission Mars2020 that will land at the surface of Mars in 2021.

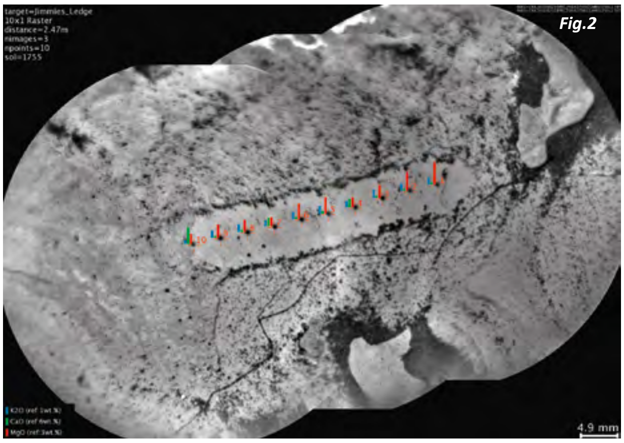


Fig. 1: Sheepbed mudstone crosscut by basanite veins in Yellowknife Bay and sampled by CHEMCAM (points 1 to 9) on mission day 126 © *NASA/JPL-Caltech/CNES/CNRS/LANL/IRAP/IAS/LPGN).*

Fig. 2: Jimmies_Ledge bedrock in the Murray Formation, sampled with 10 CHEMCAM points on mission day 1755. The image shows the dust blown away by the laser impacts on this smooth rock and the compositional variations in Mg, Ca, and K © *NASA/JPL-Caltech/CNES/CNRS/LANL/IRAP/IAS/LPGN).*

Fig. 3: CURIOSITY self-portrait at the Vera Rubin Ridge on mission day 1943. The CHEMCAM telescope is visible at the top of the rover mast (© *NASA/JPL-Caltech/MSSS*). Link to high resolution image: https://photojournal.jpl.nasa.gov/catalog/PIA22207.

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The chemistry of Gale Crater (Mars) as seen by the SAM instrument on board the CURIOSITY rover

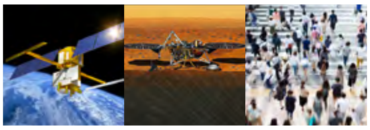
The SAM instrument on board the CURIOSITY rover analyses the chemical composition of the atmosphere, soil and rocks in Gale crater (Mars) for 6 years. For the last Martian years, the instrument continued its harvest of results by improving our understanding of the seasonal variability of the atmospheric composition, contributing to characterise the chemical stratigraphy of Mount Sharp, and by confirming the presence of organic materials at the surface of the planet.

On the way to Gale crater, the CURIOSITY rover analyses the chemical composition of rocks and soil, and surface atmosphere. If several instruments on board the rover provide precious information about the elemental composition of the minerals, SAM is the only experiment which is capable of characterising the content in volatile molecules in the different component of the surface. To this end, it uses a suite of 3 complementary instruments developed by a consortium of NASA and French laboratories. These instruments analyse either directly the atmospheric gases, or volatile species released by the solid samples collected by the robotic arm of the rover. These volatiles are produced by the sampler preparation system of SAM, when the samples are heated up to about 850 °C, or when they are submitted to chemical reactions in contact with a liquid reactant [1]. After almost 6 years operating on Mars, SAM is still in good health and analysed the composition of the hematite rich rocks of the Vera Rubin Ridge where the rover was present in march 2018, and the clays and sulfates rich layers the rover should explore in the years to come.

For the last 2 years, the data collected with SAM allowed to significantly improve our knowledge about the ancient environment of Gale crater and its relevance to a habitable place, and we present here the key results that were obtained.

Regarding the solid samples, a systematic analysis of the major gaseous species released by the 11 different samples delivered by the rover arm to SAM was achieved with the mass spectrometer as a function of the sample temperature [2]. This evolved gas analysis gives information about the mineralogy of rocks and their content in volatile species. This systematic study showed the presence of nitrate in all the samples that were analysed through the detection of NO. This mineral is of high interest as it fixes nitrogen atom in the soil that can be assimilated by living organisms on Earth. In addition to nitrates, the detection of CO_2 released by the samples at different temperatures and especially at temperatures for which O_2 is also released (Fig. 1) strongly suggests the presence of CO_2 adsorbed on the grains, carbonates that decompose at high temperature, and also organic molecules that would be oxidised by O_2. Even if this last conclusion cannot be strictly confirmed, it strengthens the first detection ever of organic molecules indigenous to Mars with SAM a couple of years ago [3], and it suggests that organic molecules could be widespread on Mars despite the harsh conditions of the Mars surface for the organic materials. The presence of both nitrates and organic materials in the Martian soil analysed also strengthens the potential for habitability of Gale crater as these 2 species are known to be used by heterotrophic organisms to build their own material on Earth.

Regarding the atmosphere, SAM was able to finely quantify the amount of noble gases and their isotopic ratio, with a significant improvement for Xe comparatively to those achieved with the Viking probe GCMS instrument. The SAM team compared



the current atmospheric isotopic ratios of Xe and Kr to those measured in the gases trapped in Martian meteorites which are supposed to be representative of the ratios that existed at the period when the meteoritic material was ejected from Mars [4]. From this comparison, it can be seen that the lightest isotopes are present in excess in the current Mars atmosphere (Fig. 2). By considering the different processes that could be involved in the production of this excess of light isotopes, it appears that spallation and neutron capture are among the contributing mechanisms. The evidence of the existence of these processes could help to better constrain the interaction between the mars atmosphere and the solar wind. It could also be a first step in the determination of the age of trapped atmosphere components in Martian meteorites. The measurement of the Mars atmosphere composition to be done with SAM in the future should not bring a significant improvement to these noble gases isotopes study. They will rather focus on the seasonal variation of the major atmospheric gases, and the question of atmospheric methane, at the time when the TGO probe is now fully operational to look for the presence of methane in the atmosphere from the Mars orbit.

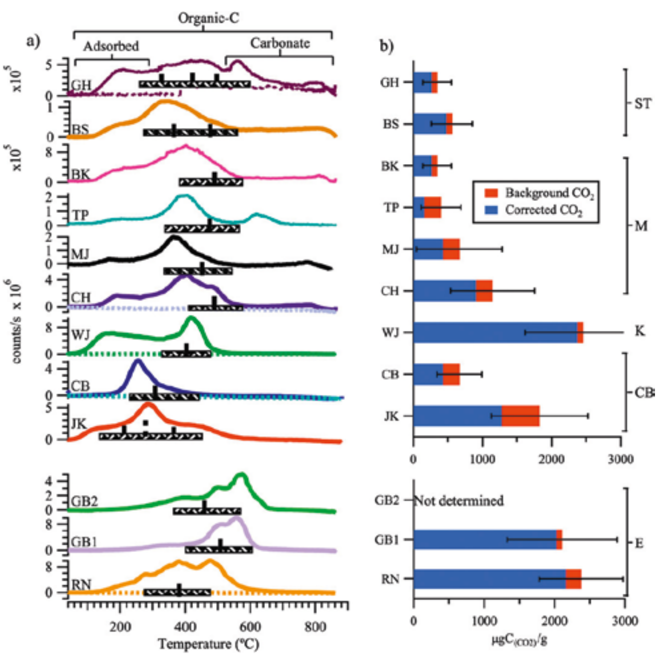


Fig.1

Fig. 1: (a) Evolved CO_2 (m/z 44) (c/s) versus temperature as detected by SAM-EGA. Temperature ranges of possible CO_2 sources are indicated in brackets. Cross-hatched bars indicate temperature range of O_2 evolution (b) Carbon content (μgC$_{(CO_2)}$/g) derived from evolved CO_2. CO_2 contribution from sample in blue with estimated contribution from background in orange © *Wiley.*

Fig. 2: Martian meteorite, fractionated solar wind, and average SAM Xe data plotted as δ-values referenced to the solar wind (SW) composition, and corrections for hypothetical atmospheric spallation and *n*-capture ^{127}I(n,γβ−)^{128}Xe and 130Ba(*n*,γβ−)^{131}Xe components © *from Conrad P.G., et al. (2016)*

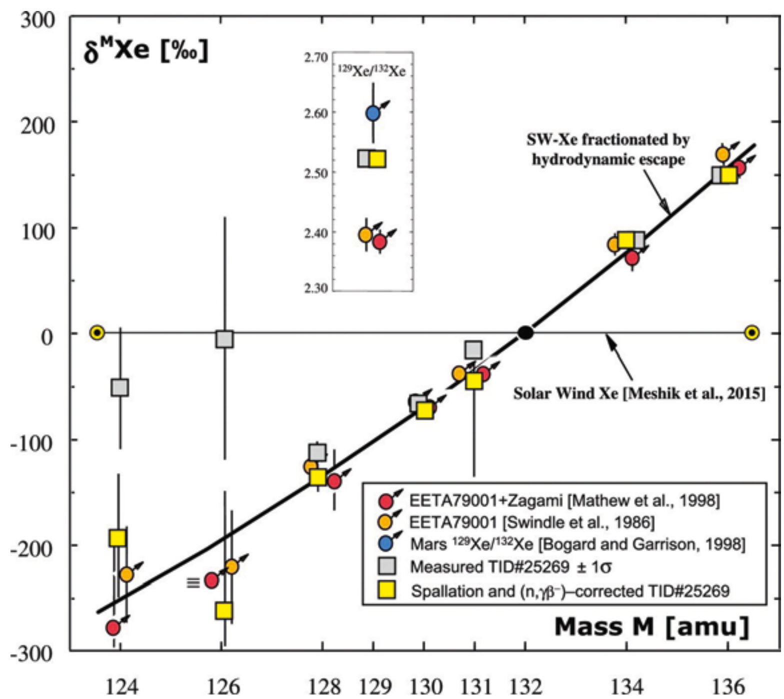


Fig.2

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Recent MAVEN results from the SWEA instrument at Mars: consequence for the hydrogen exosphere

Foreshock electrons produced at the bow shock of Mars by a mirror reflection of a portion of the incident solar wind show a flux fall off with the distance from the shock. This attenuation, unobserved at the terrestrial foreshock, has been recently explained by the impact of backstreaming electrons on Mars exospheric neutral hydrogen. The important consequence is that foreshock electrons can be used to put constraint on the exospheric hydrogen profile of Mars especially at high altitudes.

A recent study mostly based on the data from the electron spectrometer SWEA on board the NASA spacecraft MAVEN orbiting Mars since the end of 2014 revealed that observations of this instrument obtained in the region upstream from the planetary bow shock could provide a new method to investigate the hydrogen exosphere especially at large distances from the planet [1]. A previous study [2] had already shown that the entire bow shock surface of Mars forms a source for backstreaming electrons, flowing mainly along the magnetic field in the direction opposite to the flow of the incident solar wind in the region called the foreshock, with energies reaching up to ~2 keV. The backstreaming electrons appear as ring-beams in velocity space strongly indicating that the magnetic mirroring of a portion of solar wind electrons taking place at the shock is a plausible mechanism for their production. In addition, the study shows that the electron flux falls off with distance from the shock.

Fig. 1 displays one example of such observation. The upper panel shows the electron fluxes for different energy ranges compared to the magnetic field observations and geometrical parameters when MAVEN is located within the foreshock region after crossing the bow shock. At first glance, electron beams from tens to several hundreds of eV emanating from shock are expected to propagate at a considerable distance beyond MAVEN's orbit before the effects of scattering by magnetic field fluctuations become measurable. There is no evidence in the MAVEN wave data for plasma waves that could efficiently scatter the electron beams. The recent analysis by Mazelle *et al.* [1] provides evidence that the observed foreshock electron flux decrease with distance above some tens of eV is due to collisions with the extended exospheric neutral hydrogen of Mars.

Because of Mars' lack of a global magnetic field, the solar wind can directly interact with the upper atmosphere inducing ion escape via ionization, sputtering and pickup processes. In the later process, which is one of the important mechanisms driving the atmospheric loss of Mars, neutral atoms are ionized and "picked up" by the solar wind embedded magnetic field. Several sources of ionization are possible. In the exosphere, upstream of the bow shock, photoionization and charge exchange are the dominant mechanisms, with ionization through electron impact providing a minor contribution.

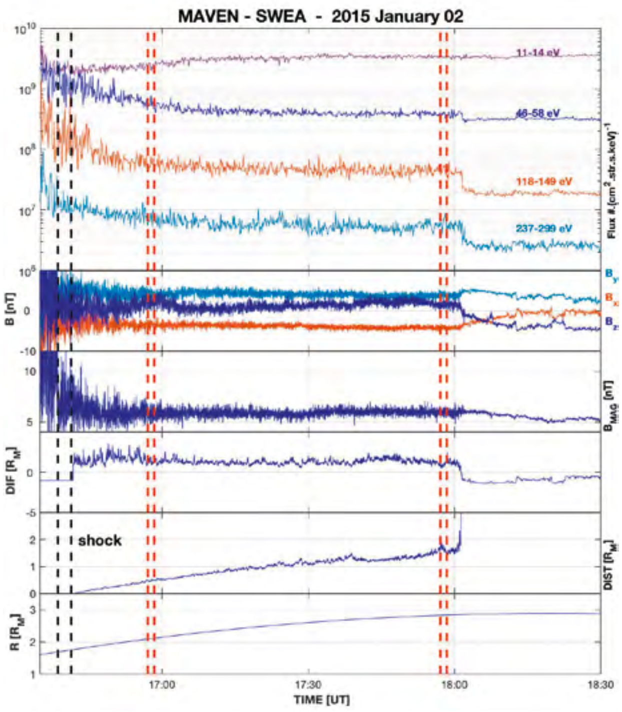

Fig.1

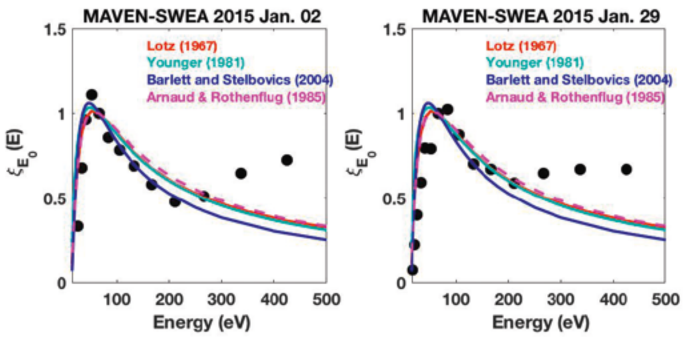

Fig.2

Fig. 1: Top to bottom panels respectively show the electron flux for 4 selected energy ranges, the MSO-IMF components, the magnetic field magnitude, the distance DIST along the ambient IMF of MAVEN to the shock, the foreshock depth DIF and the planetocentric distance R of MAVEN © *Wiley AGU.*

Fig. 2: Open circles indicate $\xi E_0(E)$ ratio versus energy E using E_0 = 52.1 eV (see text for explanation). The continuous lines show the ratio of HI-electron impact cross sections $\sigma(E)/\sigma(E_0)$ from various sources showing the very good agreement for the peak energy © *Wiley AGU.*

In this mechanism, free electrons collide with neutral atoms, and if the energy of the former is higher than the ionization threshold of the latter, an ion can be produced. The collision cross-section indicates the relevance of the impact process and it is expected that the solar wind electron impact neutral ionization remains weak upstream of the bow shock. With a temperature of ~10 eV, most of the solar wind electron flux remains below the level for which the cross section for electron impact ionization for hydrogen peaks (~50 eV). At first glance, the exospheric neutral atoms impact with foreshock electrons may appear quite minor as the foreshock electron density is significantly much smaller comparatively to the solar wind electron density. Nevertheless, the flux of foreshock electrons with an energy above the ionization threshold exceeds that of the solar wind and is significantly enhanced up to a few hundreds of eV in the energy range where electron impact ionization is important.

Quantitative arguments can be developed in support of foreshock electrons impact with exospheric hydrogen. First it is possible to fit the observed decrease of the flux from simple analytical calculations. By considering a mono-energetic beam of electrons with energy E emanating from the shock and colliding with a neutral exospheric atomic hydrogen, the variation of electron flux $F_E(x)$ at a distance x from the shock as the electrons propagating through the exosphere can be governed by the following expression:

$$dFE(x)/dx = -n_H(r(x)) \times \sigma(E) \times F_E(x)$$

where $n_H(r(x))$ is the atomic hydrogen density profile and σ(E) the collision electron cross-section. It is implicitly assumed that the exospheric hydrogen is at rest and the electrons propagate along the magnetic field direction x. Integrating between 2 positions x_1 and x_2 using a bow shock model and assuming an analytical profile for nH as a simple power law with an index very close to an independent determination, it is then straightforward to derive an expression of FE(x) which has been shown to fit well the observations [1]. Pursuing the analysis further and to better adjust a comparison with the observations, the dependence upon the bow shock and hydrogen profile models are then eliminated. For this purpose, for 2 arbitrary energy values E_0 and E and the following ratio is derived at 2 different positions x_1 and x_2:

$$\xi E_0(E) = \ln(FE(x_1)/FE(x_2)) / \ln(FE_0(x1)/FE_0(x2)) = \sigma(E)/\sigma(E_0)$$

Hence, this ratio is solely dependent upon the electron flux levels, and therefore can be directly obtained from observations. The right-hand term can also be determined from ionization cross-section Tables. Fig. 2 shows the result obtained for E_0=52.1 eV, a numerical value corresponding to the maximum electron-hydrogen impact cross-section. However, the results are only weakly sensitive to the choice of E_0. An excellent agreement is obtained close to the maximum enforcing the above interpretation.

These results may have important implications on the pickup ion production rate at distance far from the planet centre. Also, additional pick-up ion production rate due to the electron impact inside the electron foreshock is an important element in our comprehensive understanding of the Martian upstream region variability at small time scales compared to seasonal effects on much larger time scales reported e.g. by Romanelli *et al.* (2016) [3]. Moreover, the experimental flux attenuation fitted profiles could be used as a new tool to constraint the exospheric hydrogen density profiles.

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EXOMARS: two Martian missions for exobiology

Has life ever existed on Mars? ESA planned 2 missions to find it out, one in 2016, and the other in 2020. The later will land a rover – a real laboratory on wheels – on the Red Planet's surface.

Fig.1

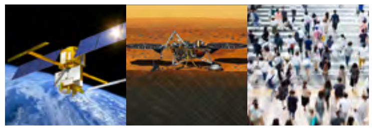
This name comes from the contraction of 2 words: "Exo" standing for "exobiology", the science looking for traces of extra-terrestrial life forms, and obviously, "Mars". These missions are directed by ESA in collaboration with the Russian space agency Roscosmos.

CNES is coordinating the contribution to this mission of several French laboratories to the provision of the instruments as well as the scientific processing of the data collected.

EXOMARS must achieve 4 technological objectives:
i) landing a rover equipped with scientific instruments on Mars' surface;
ii) ensuring the rover's progression over several kilometres on Mars' surface;
iii) collecting samples from the Martian underground likely to contain preserved organic matter;
iv) packing those samples so that they can be analysed by various instruments.

Added to these are scientific objectives such as:
i) detecting the presence of gases and measuring the concentration of volatile compounds present in trace amounts in Mars' atmosphere;
ii) searching in samples taken in the Martian underground traces of a present or past Martian life form;
iii) characterising the structure of Mars' underground.

The French teams are in charge of 2 instruments of the European rover. WISDOM is a radar studying the underground in order to characterise the structure and detect the presence of ice. MicrOmega is a spectrometer and imager capable of taking images in the visible and the infrared spectrum, to study the mineralogical composition of the samples collected. Some laboratories also contribute to the development of 3 other instruments (MOMA, RLS and CLUPI) under the responsibility of other country members of ESA. CNES works with ESA to provide software for the visual navigation of the rover in 2020.



EXOMARS 2016

Launched on 19 October 2016 with a Russian rocket Proton, the first mission put into orbit a satellite, the Trace Gas Orbiter (TGO), which will study Mars' atmosphere and evolution and will also be used as a communication relay between the Earth on the various missions operating on the planet's surface. Since April 2018, the TGO begins its science mission to look for gases present in Mars' atmosphere such as hydrocarbons.

In addition to the 4 instruments, it is equipped with 2 radio transmitters and receivers provided by NASA (Electra) which will be used to relay the instructions and data between the Earth and the operating European and US rovers.

Several French laboratories are working closely with their Russian counterparts of the Russian Space Research Institute (IKI, Институт Космических Исследований) for the ACS (Atmospheric Chemistry Suite). LATMOS (France) contributed to the design and production of the instrument and coordinates the involvement of French laboratories in the interpretation of data.

Moreover, ESA selected scientists to contribute to the use of the data collected by the various instruments. Scientists from the Laboratory of Dynamic Meteorology (LMD) will combine the observations of the TGO instruments with atmospheric models and data from other Martian mission. Scientists from the Laboratory of Planetology and Geodynamics (LPG) will use the data from the CASSIS Camera in combination with the data from other instruments and other missions to understand the dynamic phenomena that occur on the planet's surface (accumulation, erosion, transformation). Finally, the Geosciences Laboratory Paris Sud (GEOPS) will use the data from NOMAD and ACS by combining them with the images from CASSIS to determine the connections between the volatile compounds condensed on the surfaces and their behaviour in the atmosphere.

EXOMARS 2020

The second mission, EXOMARS 2020, which will land a Russian platform and a European rover on Mars' surface, will be launched from Baïkonour with a Proton rocket between the 24 July and the 12 August 2020 and will reach its destination in March 2021.

The Surface Platform is provided by IKI and Roscosmos. This platform of 827 kg carries 10 Russian instruments as well as 2 European instruments and will monitor its environment for a Martian year (687 Earth days). There is no direct French contribution to these scientific instruments.

The European rover of 310 kg will be equipped with 9 scientific instruments dedicated to the study of the Martian ground and underground. With a drill able to collect samples down to a depth of 2 metres, this rover will collect samples and analyse them with its instruments. At this depth, organic matter that could have formed billions of years ago is protected from cosmic radiation showering on the planet's surface and oxidising compounds that form on its surface.

The French contributed in 5 out 9 instruments that compose the "PASTEUR" payload.

The WISDOM radar (Water Ice and Subsurface Deposit Observation on Mars) from LATMOS will test the soil at a depth of approximately 5 metres to detect sedimentary layers and identify buried rock boulders or ice. Beyond the science, this will be used to determine the appropriate drilling locations and depths. Data will be coordinated with ADRON (IKI) which seeks the water present a few centimetres below the surface as well as hydrated minerals.

The drill will collect samples at a maximum depth of 2 metres. These core rocks, of approximately 1 cm in diameter and 2 cm length, will be crushed, transported and brought to the analytical instruments. The CLUPI camera (Close-Up Imager), to which contributed the Centre of Molecular Biophysics of Orleans (CBM), equipped with a high magnification lens, will take images of the drilling site, the dust and of the cores after it has been placed in the container.

The surface of the crushed material will first be examined by MicrOmega (Astrophysical Space Institute of Orsay-IAS). This infrared and visible microscope will identify the minerals and detect the potential presence of organic molecules. The most interesting areas will be analysed using the RLS (Raman Laser Spectrometer), with a contribution of the Institute for Research in Astrophysics and Planetology of Toulouse (IRAP). This analysis will complete the mineralogical data and will specify the composition of the organic matter potentially detected. If the sample proves to be scientifically interesting, a small part will be directed to MOMA (Mars Organic Molecule Analyser). This instrument consists of 3 complementary elements. The mass spectrometer will identify ions and organic molecules from the other 2 elements. The LIBS system (Laser-Induced Breakdown Spectroscopy) uses a laser to produce ions that are directed towards the mass spectrometer. An oven system can bring a small aliquot of crushed material at high temperature in the presence or absence of a chemical solvent in order to vapourise the organic matter, then it can direct it towards the gas chromatograph (contribution of the Inter-University Laboratory of Atmosphere Sciences -LISA- of Creteil), then to the mass spectrometer.

The 2 EXOMARS missions attain a critical phase. The TGO mission will indeed begin its scientific mission and provide, with an unmatched sensitivity, a global cartography of the detailed composition of the Martian atmosphere. The mission EXOMARS 2020 enters the delivery phase of the flight instruments as well as their assembly on the different elements of the mission. The schedule is speeding up for both the TGO, with the exploitation of the first data, and for EXOMARS 2020, with the preparation of the calibration and interpretation work that will mobilise the laboratories after the end of the assembly, integration and testing of their instruments on the EXOMARS rover.

Fig. 1: Trace Gas Orbiter aerobraking. With aerobraking, the spacecrafts's solar array experiences tiny amounts of drag owing to the wisps of martian atmosphere at very high altitudes, which slows the spacecraft and lowers its orbit © *ESA/ATG medialab*

BEPI-COLOMBO, two probes exploring Mercury

Mercury is the least well-known of the planets in our solar system. This is largely because its proximity to the Sun is a real challenge for space exploration. To uncover the secrets of this mysterious world about which planetologists still have much to learn, the European BEPI-COLOMBO mission will launch 2 probes in October 2018 - MPO (Mercury Planetary Orbiter) and MMO (Mercury Magnetospheric Orbiter) - for a final insertion into orbit around Mercury late 2025.

BEPI-COLOMBO is the first mission in total collaboration between ESA and JAXA for the interdisciplinary study of Mercury. Mercury, the closest planet to the Sun, is known since Antiquity, but direct observation of Mercury was only performed by the MARINER 10 probe in 1974-75 and by the American probe MESSENGER launched in August 2004 whose mission ended in April 2015 by falling down on Mercury.

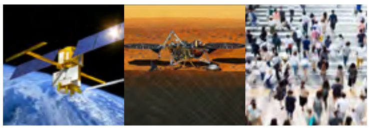
MPO will map the entire surface of the planet, will study its inner composition and structure and its immediate environment (atmosphere and ionosphere), while MMO will analyse its magnetic field and magnetosphere. Data gathered will provide new insights into the formation and evolution of 'inner' planets—planets orbiting close to their star—like most of the known exoplanets.

The MPO probe is being developed by the European Space Agency (ESA) and the MMO probe by the Japan Aerospace eXploration Agency (JAXA). CNES is overseeing development of the French contributions to the instruments on BEPI-COLOMBO for all of the research laboratories involved in the mission—8 in all (IAS, IPGP, IRAP, LAM, LATMOS, LESIA, LPC2E and LPP) who are helping to design 6 of the 16 instruments.

SCIENTIFIC PAYLOAD

The allocations of the payload of MPO are a mass limited to 85 kg and a power of 100 W. The MPO orbiter payload is constituted of:

INSTRUMENT	NAME	PI	LABORATORY	FRENCH CONTRIBUTION	CONTRIBUTOR INSTITUTE
Probing of Hermean Exosphere By Ultraviolet Spectroscopy	**PHEBUS**	**E. Quemerais**	**LATMOS (France)**	**Provision of the instrument**	**IKI** **Tohoku University**
Laser Altimeter	BELA	N. Thomas H. Hussmann	Bern Univ. (Suisse) DLR (Germany)	**Rejecter Filter study** **Thermal Model**	**LAM** **IPGP**
Search for Exosphere Refilling and Emitted Neutral Abundances	SERENA : 4 instruments **ELENA,** STROFIO, **PICAM** & MIPA	S. Orsini	INAF-IAPS (Italy)	**ELENA** (Emitted Low-Energy Neutral Atoms) **High Voltage convertor** **PICAM** (Planetary Ion Camera) **ToF detector & imager** **PICAM calibration**	**IRAP** **LATMOS**
Spectrometers and Imagers for MPO BEPI-COLOMBO Integrated Observatory	SIMBIO-SYS 3 imagers STC, HRIC, **VIHI**	G. Cremonese	INAF (Italy)	**Main Electronic Box** **Optics & radiometric Calibration of Simbio-Sys** **VIHI** (Visual and Infrared Hyper-spectral Imager) **detector & electronics**	**IAS** **IAS** **LESIA**



The MMO orbiter payload is constituted of a set of instruments for plasma, field, and particle measurement to study the processes coupling Mercury's surface, magnetosphere, and solar wind. The allocations of this payload are a mass limited to 45 kg and a power of 53 W. The different instrument sub-systems are:

INSTRUMENTS	NAME	PI	LABORATORY	FRENCH CONTRIBUTION	CONTRIBUTOR INSTITUTE
Mercury Plasma Wave Instrument	**PWI** 5 sensors: WPANT, SC, **AM2P,** MEFISTO, **SORBET**	Y. Kasaba	Tohoku University (Japan)	**Provision of SC** (Search Coil magnetometer) **Provision of AM2P** (Active Measurement of Mercury's Plasma) **Provision of SORBET** (Spectroscopie des Ondes Radio et du Bruit Electrostatique Thermique)	**LPP** **LPC2E** **LESIA**
Mercury Plasma Particle Experiment	**MPPE** 5 sensors: **MEA,** **MSA**, SWA, HEP-e HEP-i	Y. Saito	ISAS (Japan)	**Provision of MEA** (Mercury Electron Analyzers) **Provision of « Top Hat » type electrostatic analyser of MSA** (Mass Spectrum Analyzer)	**IRAP** **LPP**


Fig.1

SCIENTIFIC OBJECTIVES

Mercury has a unique structure *i.e.* a very big core (3/4 of the planet's radius). This could be linked to its intrinsic magnetic field. Detailed observations of its interior and surface reveal that the planet formed in the region nearer to the Sun.

BEPI-COLOMBO will provide the first opportunity to compare the planetary magnetic field structure of a telluric planet to the Earth's one.
Indeed, the only telluric planets with an intrinsic magnetic field are the Earth and Mercury. The detailed observation of Mercury's magnetic field and its magnetosphere will lead to the first comparative studies with the Earth.

Thanks to BEPI-COLOMBO mission, Mercury's interior, surface, exosphere, magnetosphere, and environment will be thoroughly studied and a new frontier to solar system science will be open. MPO probe is dedicated to the study of the surface and the interior of Mercury (surface geology, geomorphology, geophysics, volcanism, global tectonics, age of the surface, composition of Mercury's surface) as well as its exosphere.

The MMO probe's instruments will allow to study the magnetic field, the magnetosphere, the inner interplanetary space, the radiations and particles in Mercury's environment and the exosphere. The comparison of the magnetic field and the magnetosphere to those of the Earth will supply a new vision of the magnetosphere's dynamics and physical processes.

Thanks to the MPO instruments coupled with the MMO instruments, coordinated measurements of the planetary magnetic field will be conducted and will therefore solve one of the main limitation of MESSENGER observations, the possibility to disentangle temporal and spatial variabilities in an environment much more dynamic than the Earth magnetosphere, as shown by MESSENGER.

MISSION STATUS

The overall test campaigns of thermal, mechanical, acoustics and vibration testing have been successfully achieved. The shipment to Kourou took place by the end of April.

The launch window for BEPI-COLOMBO by an Ariane 5 opens on 5 October until the end of November 2018 for an arrival at Mercury around December 2025.

Fig. 1: The full BEPI-COLOMBO stack seen in ESA's test centre in May 2017 *© ESA–C. Carreau, CC BY-SA 3.0 IGO*

PARKER SOLAR PROBE, exploring the Sun's corona

The U.S. PARKER SOLAR PROBE mission will begin its journey to the Sun in 2018. It aims at becoming the first spacecraft to venture into our star's outer atmosphere. The first perihelion will reach 35 solar radii in Autumn 2018 and the closest approach, within 9 solar radii from the surface, is scheduled to arrive in 2024.

Once lofted into space by a Delta IV Heavy launcher, PSP will need 7 gravity assists from Venus to reach the Sun's corona. These successive gravitational boosts will make it the fastest spacecraft of all time. It will also be the first to study in-situ the solar wind so close to the Sun with its 4 suites of instruments. The solar wind is the stream of ions and electrons that our star ejects at high speed into interplanetary space. PSP will pass several times within less than 7 million km from the Sun's surface, where it will be exposed to temperatures reaching 1 400 °C.

French research laboratories - the LPC2E (environmental and space physics and chemistry laboratory), the LESIA (space and astrophysics instrumentation research laboratory), the IRAP (astrophysics and planetology research institute), the LPP (plasma physics laboratory) - are contributing to PSP's instruments, with support from CNES. The PROMES (PROcesses, Materials and Solar Energy Laboratory), which operates the solar furnace in Odeillo in the French Pyrenees, is also working on the mission, studying the behaviour at high temperatures of the parts of the science instruments that will not be protected by the probe's solar shield.

The PSP mission is being coordinated with the European SOLAR ORBITER mission as part of the joint HELEX programme (HELiophysics EXplorers).

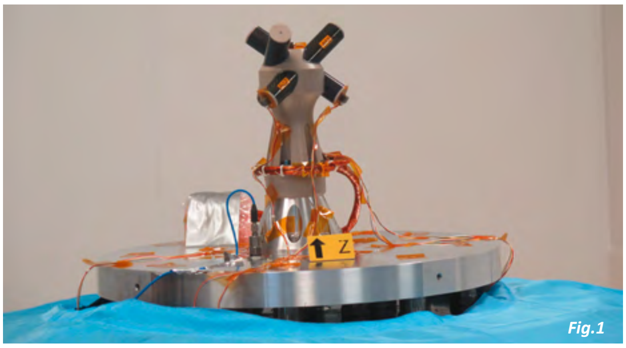
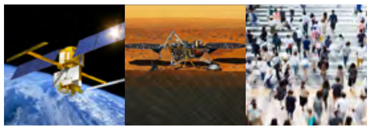


Fig.1

Scientific payload

INSTRUMENT	OBJECTIVE	FRENCH LABORATORY INVOLVED
SWEAP (Solar Wind Electrons Alphas and Protons Investigation)	Counting of the most abundant particles in the solar wind and determining their properties (density, velocity, temperature).	LPP, IRAP
WISPR (Wide-field Imager)	Imaging of the solar corona and inner heliosphere and the transient processes occurring there.	
FIELDS (Fields Experiment)	Measuring the electric and magnetic fields, pointing flux, plasma density, spacecraft potential and radio emissions.	LPC2E, LESIA
ISIS (Integrated Science Investigation of the Sun)	Measuring the most energetic particles in the solar wind.	

France is involved in 2 of the 4 instrument suites of PSP. The IRAP and LPP laboratories provide expertise on the definitions and analyses of the SWEAP observations. The LPP contributes to the electron spectrometer of the SWEAP instrument suit by providing the integrated detection electronics. The LPC2E and LESIA are involved in the FIELDS experiment for their expertise and contributes also to the instrumentation. The LESIA has participated to the design of the radio receiver while the LPC2E has provided the search coil magnetometer (SCM), a sensor measuring the variations of magnetic fields as fast as a microsecond. SCM will be located on the boom of the spacecraft and is the only European sensor on board PSP.



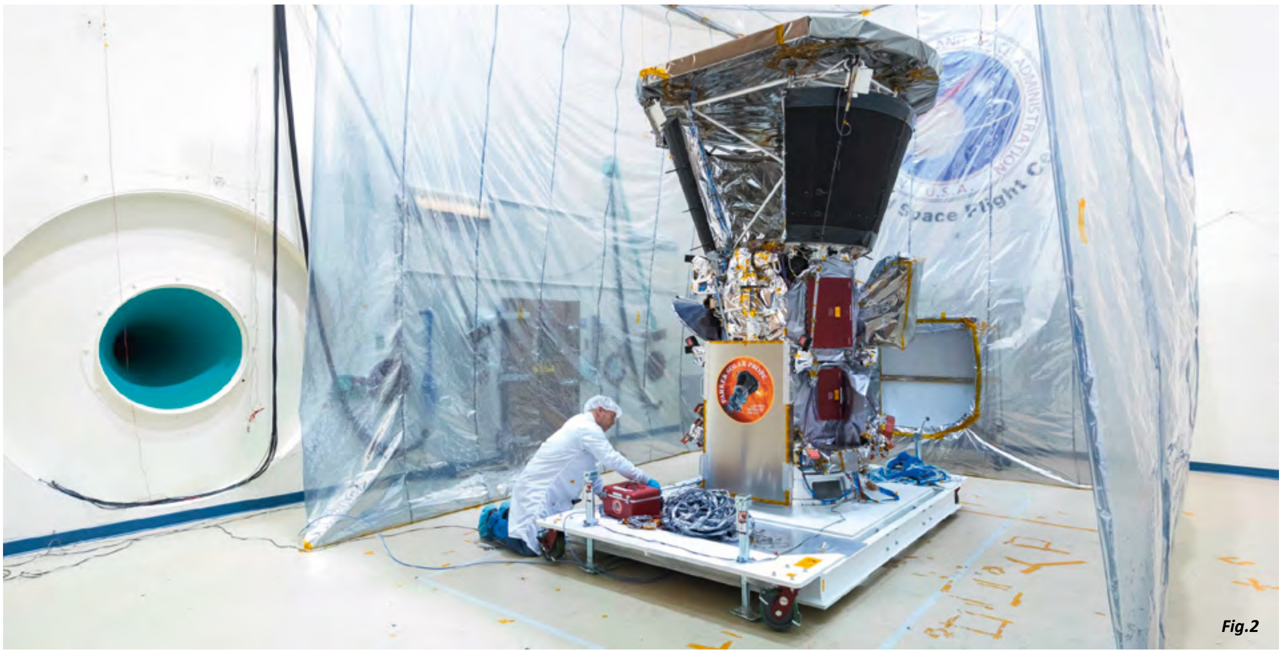


Fig.2

Scientific objectives

The Sun is well noticed in daily life because it shines. However, it also fills the interplanetary space with plasma, a state of matter similar to gas but where particles are electrically charged and that constitutes 99% of the known matter in universe. The corona, the outermost region of the Sun's atmosphere, is where this solar plasma also named solar wind starts its journey. This place exhibits several remarkable features:

- Temperatures there reach 1 million degrees centigrade, more than 100 times hotter than at the Sun's surface which is near 6 000 °C.
- It is the source of the solar wind, this stream of ions and electrons ejected at high speed into interplanetary space, and that reaches each body of the solar system.
- It is a place of violent processes, such as flares and coronal mass ejections, which next propagate in the heliosphere and eventually reach the Earth where they can cause damages on our technologies.

Most of the stars have a corona, and there are good chances that answering questions in the solar case will apply to other stars as well. Since the discovery of the solar corona in the 1940s, scientists have learned a great deal about the solar wind and the Sun itself, but they still don't understand the mechanisms going on inside the corona. The solar surface, the photosphere, is the energy supplier, but how this energy propagates towards and is deposited in the corona remains a mystery. Does it come from waves generated in the photosphere or below, and that then dissipates in the corona? Or, as suggested by Eugene Parker, from nano-flares which are ubiquitous and energetics small reconfigurations of the magnetic field?

Measuring directly the properties of the outer corona will tell us a lot about the processes at play.
Another important question that is related is the acceleration of the solar wind, which occurs mostly within 15 solar radii. Particles are constantly ejected from the Sun at a speed of several hundreds of km/s. During this process, some particles are heated more than others. The properties of the solar wind are also strongly variable, and its evolution during its trip in the interplanetary space is not as predictable. Going as close as possible to the acceleration region will help us understand the reasons and consequences of these observations. Last but not least, the solar wind is a natural laboratory to study turbulence, one of the most fascinating problems in physics.

Finally, because our societies are always more dependent on technologies, they become more and more vulnerable to perturbations coming from space. This has given birth to a relatively new science field, termed space weather, which aims at predicting when strong perturbations from space can affect our activities. Going close to the Sun, where these perturbations have their origin, will help us to understand them better. Because PSP will not image the Sun directly, its science will be complemented by the European SOLAR ORBITER mission that will both measure properties of the solar wind at different distances from PSP, image and analyse the solar atmosphere with magnetograph, telescopes and spectrometers.

Mission status

PSP will be launched from the NASA's Kennedy Space Centre in Florida between 31 July and 19 August 2018. All instruments have been delivered and integrated on the spacecraft. Environmental tests, where spacecraft and instruments experience the harsh conditions of space, including near-vacuum conditions and severe hot and cold temperatures, are performed at the NASA's Goddard Space Flight Centre in Greenbelt. Once ready, the spacecraft will be packed and shipped to Florida for its launch aboard a Delta IV Heavy launch vehicle. All instrument teams are now preparing for the analysis of the first data to come.

Fig. 1:The Search-Coil Magnetometer for PSP/FIELDS prepared for vibration tests © *LPC2E*

Fig. 2: PARKER SOLAR PROBE being tested *© Johns Hopkins Applied Physics Laboratory*

GAIA, a satellite mapping the galaxy

Our galaxy, the Milky Way, looks large, peaceful and mature at first glance. But it was probably not the case in the past – and it might not always be so in the future. Astronomers guess that like other galaxies, our cosmic motherland had a tumultuous youth, including intense star formation epoch and accretion of smaller galaxies passing by – which could still occur in the future.

These remarkable events should have left their imprints in the Galaxy, as specific layers in rocks and sediments indicate past events on Earth. Clusters of stars travelling together in unison on a track distinct from those of their neighbours could be former members of an alien galaxy, once absorbed by the Milky Way. Age, chemical composition, temperature, colours of stars are other key insights of the past activity of the Galaxy. And by extrapolation, its future can also be inferred!

The mission that ESA and its Member States decided to carry on by 2000 is to record the position, the velocity and the main physical and chemical parameters of as many stars as possible throughout the Galaxy with a considerable accuracy (about 10 micro-arcseconds, the size of a coin on the Moon as seen from Earth). This mission, GAIA, is about to be accomplished.

The GAIA satellite, a technological jewel, was launched on 19 December 2013, and has since been continuously scanning the whole sky. Light from any source with a G-magnitude up to 20.7 crossing the field of view of its 2 telescopes is recorded by its instruments. About 2 billion stars of the Milky Way and of the Small and the Large Magellanic Clouds are being repeatedly measured, about 80 times on average during the 5-year mission. In addition, tens to hundreds of thousands asteroids, brown dwarfs, exoplanets, and distant quasars will take place in the final catalogues.

Computing highly reliable and accurate parameters for billions of sources from GAIA's Petabytes of raw data – hundreds of billions transit dates and pixel signals – was the second mission's challenge. Any bias – relativistic effects, starlight absorption by foregrounds, telescopes misalignment, detectors' response, etc. – needs correction. Complex software then classifies the sources and derive their parameters. Designed, implemented and operated by the DPAC, a vast consortium of European research institutes and space agencies, they are running on 6 dedicated high power computing centres, including one at CNES premises in Toulouse, France.

SCIENTIFIC PAYLOAD

INSTRUMENT	OBJECTIVE	PRINCIPAL INVESTIGATORS LABORATORIES
Astrometer	Positions and proper motions	NA
Blue and Red Photometers	Physical parameters	NA
Radial Velocity Spectrometer	Chemical composition; Radial Velocities	NA

The GAIA satellite, including its scientific payload, was designed and built by Airbus Defence and Space in Toulouse for ESA. It includes 2 one-metre class telescopes feeding the instruments. The spinning satellite sees light from celestial objects crossing consecutively the different instruments 'detectors. The payload is designed and operated in order to reach a record-breaking thermoelastic stability.

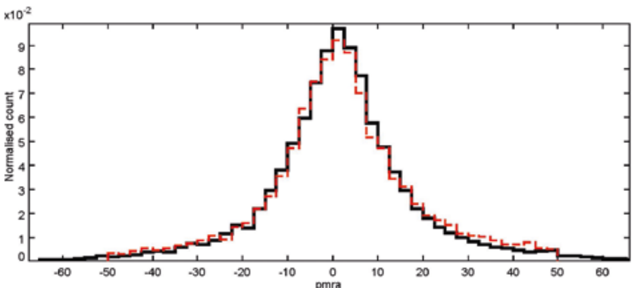


Fig.1a

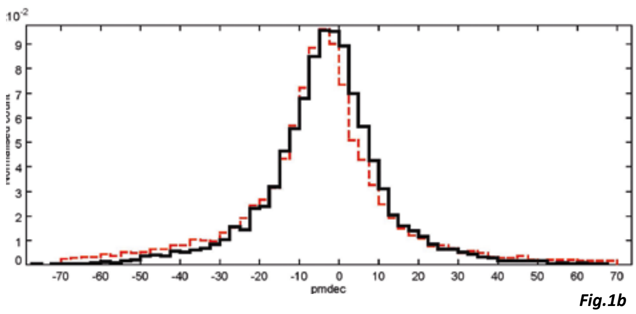
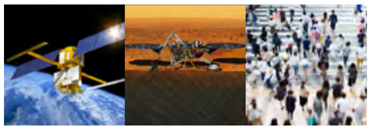


Fig.1b



DPAC involves about 100 scientific institutes and space agencies. Nice and Paris Observatories, as well as CNES, are some of the major DPAC players; UTINAM from Besançon, LAB from Bordeaux, LUPM from Montpellier and Strasbourg Observatory also contribute to DPAC.

SCIENTIFIC HIGHLIGHTS

Highly accurate star positions and parameters were, are and will remain the basement of astronomy. Almost all branches of the discipline, including large scale tests of physical laws, are being fed by GAIA. The first September 2016 GAIA catalogue (so called GDR1), although preliminary, triggered hundreds of scientific publications in a few months.

Detecting Near-Earth Asteroids (NEAs) and assessing reliable levels of associated risks are not only a scientific goal but also a societal challenge. Using GDR1 stars positions as calibrators to improve previous orbit estimates for asteroids, a Nice Observatory's team showed how GAIA, even without the direct asteroids observations only due for the following data releases, could already improve our knowledge of the current NEAs trajectories by one order of magnitude [1].

Possible Sun-stellar encounters were analysed from GDR1. Compared with previous estimates from Hipparcos data, less stars were found on close sun-encounter tracks, but one of them is now expected to pass very close to the Sun in about 1.3 million years from now, and might seriously disrupt the Oort cloud of comets and asteroids [2].

Galactic studies extensively use the so called Besançon model, a reference simulation of the Milky Way. As the considerable accuracy of GDR1 allows to track tiny deviations between the model and the data, both the GDR1 and the RAVE ground-based survey were combined to put the improved model to test. For any of the different criteria and star populations used for the comparison, data and the model remarkably fit (Fig. 1), improving even further the confidence in the model [3].

GAIA also opens the door for original extragalactic studies. Gravitational waves emitted by distant supermassive black holes binary systems should imprint apparent oscillations on star positions as the waves travel through our Galaxy (Fig. 2). Detecting these weak patterns requires a large number of stars repeatedly observed with a high accuracy. A recent study demonstrated how the GAIA final catalogue will be ideal for detecting and characterising such gravitational waves [4].

MISSION STATUS

GAIA has been working as planned since its launch end of 2013. The initial 5-year mission has already been extended for 2 additional years and might be further extended. Science ready data processed by DPAC are planned to be gradually released to the international scientific community. After the 2016 GDR1, the April 2018 GDR2 provides 3D positions, proper motions and mean Green/Red/Blue magnitudes for about 1.3 billion single stars, time-light curves, radial velocities and physical parameters for subsets of them, and dated positions for about 13 000 known asteroids. Further releases, planned in 2020 and beyond will totally fill the still missing parameters and improve the accuracy of the first releases.

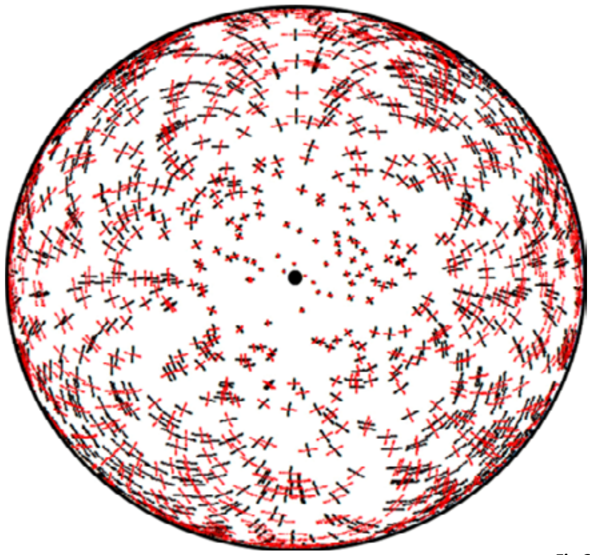


Fig.2

Fig. 1a: Histograms of GDR1 proper motions along the right ascension for stars with metallicity between -0.8 and -0.4 dex, which is dominated by the main galactic thick disk. Data are shown as black lines, and the best-fit model is shown as red lines. (from Robin, A, *et al.*)

Fig. 1b: Histograms of GDR1 proper motions along the declination for stars with metallicity between -0.8 and -0.4 dex, which is dominated by the main galactic thick disk. Data are shown as black lines, and the best-fit model is shown as red lines. (from Robin, A, *et al.*)

Fig. 2: Orthographic projection of the Galactic Northern hemisphere with 10^3 stars (simulation). A gravitational wave (GW) from the North pole (black dot) causes stars to oscillate at the GW frequency. The black (red) lines show movement tracks for a linearly plus (cross) polarised GW. For illustration purpose, the GW has an unphysically large strain amplitude of A = 0.1. (from Moore, C.J., *et al.*)

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GAIA radial velocity spectrometer: the first data release

ESA's GAIA mission is carrying out an unprecedented census of stars in the Milky Way, aiming to reveal the process of formation and evolution of our Galaxy [1]. The mission was launched on 19 December 2013 and started operations on 25 July 2014. Initially planned for 5 years, GAIA was extended for 1.5 more years in November 2017. The second GAIA Data Release (DR2) [2], issued on 25 April 2018, includes the first catalogue of radial velocities obtained with the on board Radial Velocity Spectrograph (RVS) [3].

GAIA continuously scans the sky with its 2 telescopes, collecting data of any source (mostly stars) detected by the on board system. The data are obtained with 3 instruments: astrometric data are dedicated to the measure of positions, distance and proper motions; photometric data to the determination of stellar physical properties (temperature, mass, radius); and spectroscopic data, obtained with the RVS, to the measure of stellar radial velocities, VR. Combining VR (line-of-sight component of the velocity vector) with the astrometric measurements of proper motion (tangential components of the velocity vector) allows determination of the (3D) star motion.

The first GAIA data release in September 2016, based on 14 months of data, includes the positions on the sky of 1 billion stars, as well as parallax and proper-motion estimates for a subset of 2 million bright stars. GAIA DR2, based on 22 months of data, contains the positions, parallaxes, proper motions and broad-band photometry of over 1.3 billion stars. It also includes the first release of radial velocities obtained from the RVS spectra of a sample of 7.2 million GAIA stars.

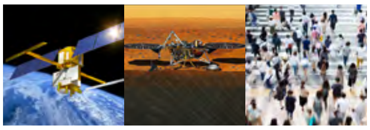
The RVS is a slitless spectrometer providing medium resolving power (R ~ 11,500) in the wavelength range [845–872] nm. When GAIA scans the sky, starlight enters the RVS after the astrometric and photometric instruments. Only stars brighter than the magnitude limit Grvs~16 (where Grvs ~ V−1) are candidates to have an RVS observation.

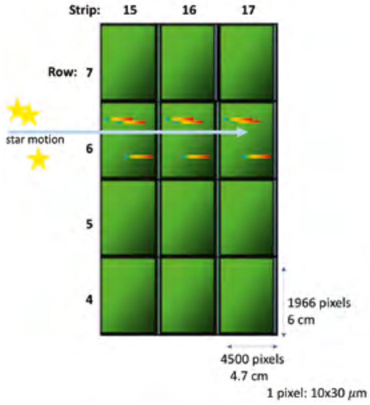
The RVS focal plane is shown in the left panel of Fig. 1 (for the complete GAIA focal plane, see GAIA Collaboration *et al.* [1]), with 12 CCDs laid out in 3 strips and 4 rows. Both GAIA-telescope fields of view are projected simultaneously onto the focal plane. The on board software identifies the pixels containing spectral information, and only the pixels in these windows are read out and telemetered. During each transit (observation), the star crosses all 3 CCDs on the row (on one) row, and 3 spectra are acquired. The spectral-dispersion direction is in the star-motion direction (Fig. 1). The 1296-pixel length of the windows in the spectral direction can lead to overlapping spectra even in modestly crowded sky regions. On average, 40% of the spectra are overlapped.

The exposure time is fixed at 4.42 sec by the scanning requirements. For faint stars, individual spectra have low S/N, and many observations are required to obtain a combined spectrum with sufficient S/N to determine VR. There will be typically 40 RVS observations per star by the end of the nominal mission. In DR2, the typical number was 4–8 per star, and only stars brighter than Grvs ~ 12 had high-enough S/N to be processed by the pipeline and have their VR calculated (fainter stars will await future releases).

The processing of GAIA data is iterative: each data release includes new data, as well as a complete reprocessing of data from the beginning of the mission, with improved calibrations and algorithms. To produce the DR2 radial velocities, 280 million spectra were treated, which represented a major challenge. The processing is managed by a top-level software system called SAGA on a 1100-core and 7.5-TB memory Hadoop cluster system. The processing took 630 000 hours CPU time and needed 290 TB disk space.

The spectroscopic pipeline [4] has 4 main tasks: i) clean and reduce the spectra; ii) calibrate the RVS instrument, including wavelength, stray light, line-spread function, bias non-uniformity, and photometric zero point; iii) extract the radial velocities;





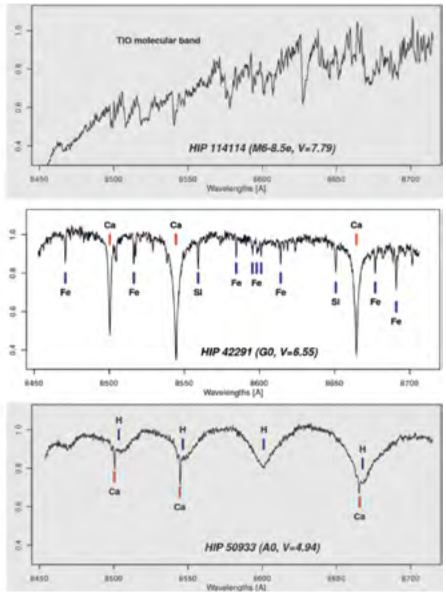


Fig.1

and iv) verify the accuracy and precision of the results. The VR of a star in DR2 is the median value of the radial velocities measured (for successive RVS observations) in the different RVS observations, each obtained through a fit of the RVS spectrum relative to an appropriate synthetic template spectrum. An additional task of the spectroscopic pipeline was to provide first-order estimates of the stellar atmospheric parameters required to select such template spectra. For the hottest (Teff ≥ 7000 K; Fig.1; right panel; bottom) and coolest (Teff ≤ 3500 K; Fig. 1; right panel; top) stars, the accuracy and precision of the stellar parameter estimates are not sufficient to allow (the) selection of appropriate templates. The radial velocities obtained for these stars were not published in DR2. Fig. 1 (right panel, central spectrum) also shows the spectrum of a medium-temperature (a solar-type) star.

DR2 contains the radial velocities of 7.2 million intermediate-temperature stars distributed over the entire celestial sphere. This is the largest existing VR catalogue and the only one covering the full sky. Fig. 2 (upper panel) shows the distribution of GAIA stars with a VR measurement over the celestial sphere, the large majority of which belong to the Milky Way. The corresponding VR distribution is shown in the medium panel of Fig. 2, where we can see the line-of-sight-projected differential rotation of the stars of the Galaxy with respect to the Sun. The bottom panel in Fig. 2 shows the overall precision of the VR measurements as a function of star magnitude. The pre-launch requirement on the end-of mission precision of 1 km/s is indicated as a dotted line; it is met, already in this first release, for the stars brighter than Grvs~ 11.5.

Future releases will contain radial velocities of fainter, cooler and hotter stars than included in DR2, rotational velocities for the brightest stars, and the combined spectra. By the final release, we expect to publish the VR of ~150 million stars, after having processed 35-50 billion spectra.

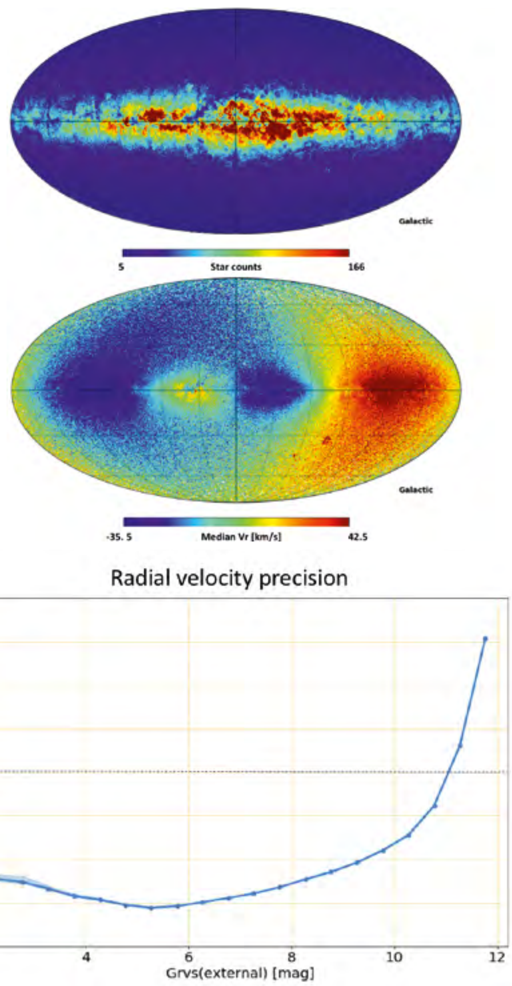


Fig.2

Fig. 1: Left panel: The RVS focal plane. The star images move in the along-scan direction (horizontal arrow). At each transit, 3 spectra are acquired. Star spectra may overlap. Right panel: RVS spectra of 3 stars: a cool (top), an intermediate-temperature (centre) and a hot (bottom) stellar spectra. © *from Katz et al. [5].*

Fig. 2: The DR2 radial velocities. Top: Distribution on the sky of GAIA stars with VR measurements; galactic coordinates projection with pixel size of 0.2 deg^2.Medium: VR distribution; Medium: VR precision; the dotted line is the end-of-mission requirement. © *from Katz et al. [5].*

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LISA PATHFINDER, testing key technologies for the future gravitational wave observatory

On 3 December 2015, the LISA PATHFINDER satellite was launched from Kourou en route to the first Sun-Earth Lagrangian point. Its mission: to test technologies able to directly detect the gravitational waves predicted by Albert Einstein.

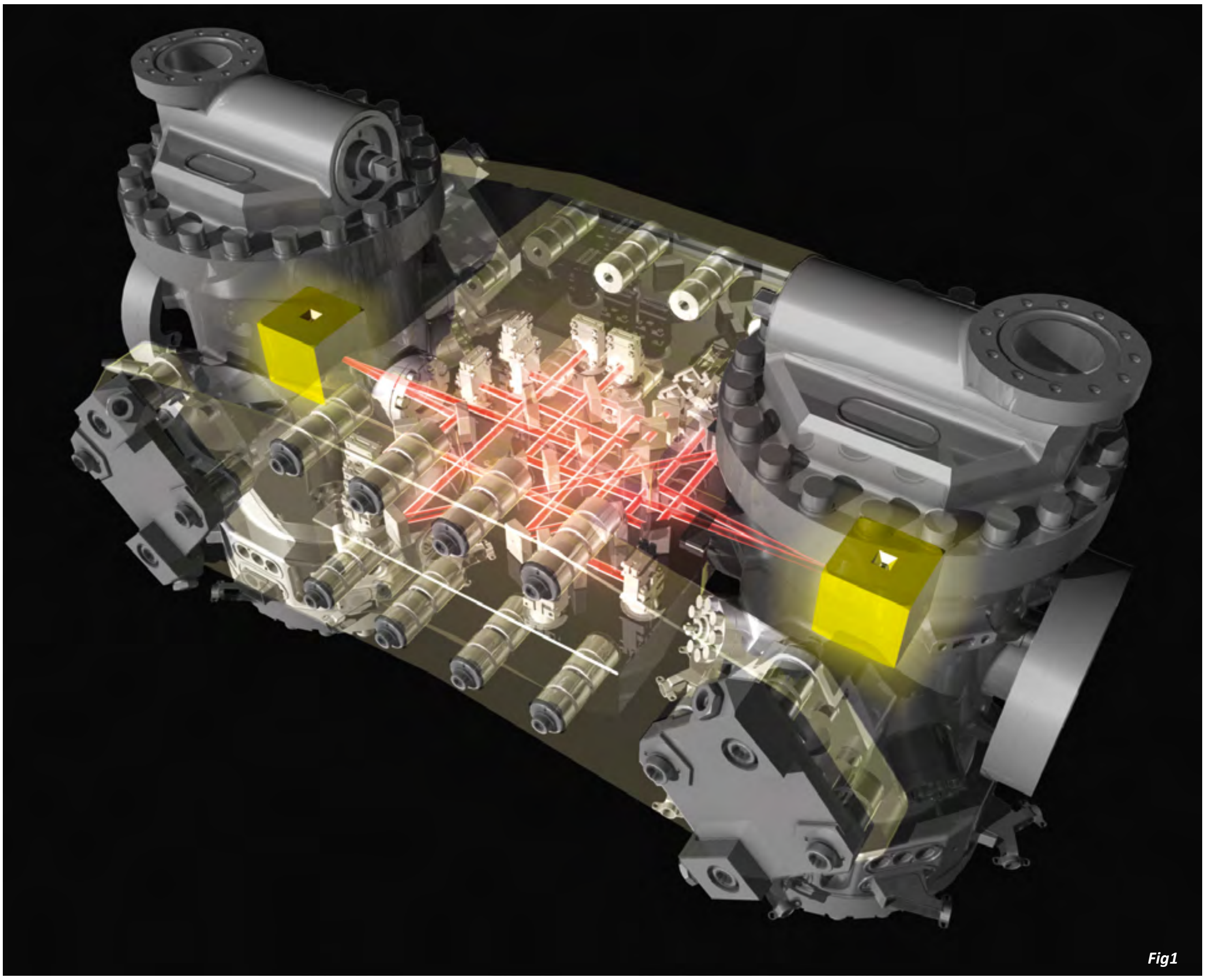
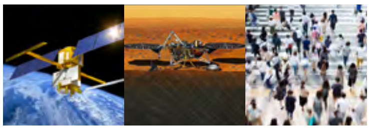


Fig1



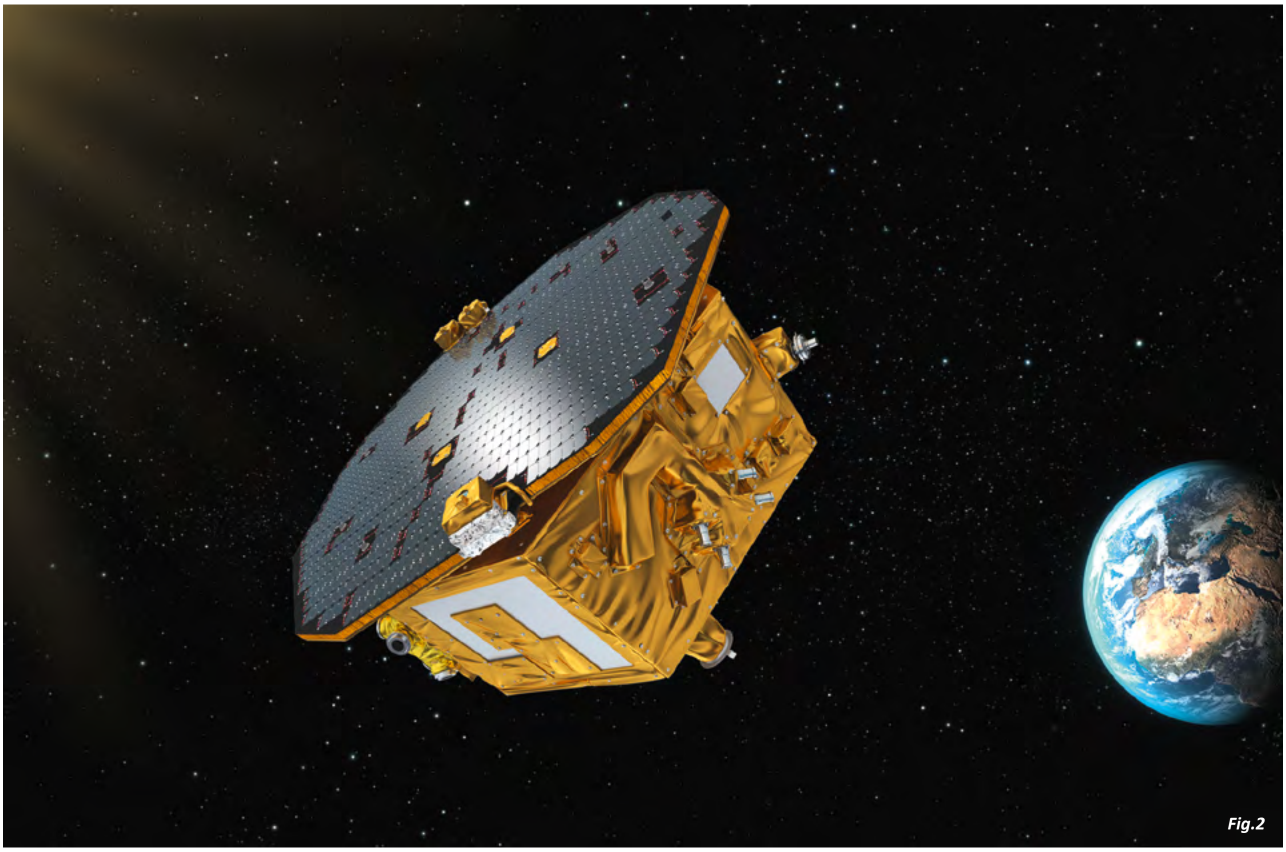


Fig.2

The European Space Agency (ESA) is pursuing an ambitious physics mission about the gravitational Universe (L3 mission) that aims to directly observe gravitational waves—the tiny ripples in the fabric of space-time predicted by Einstein's theory of general relativity—using 3 satellites forming a giant optical interferometer. The presence of these waves will be signaled by minute relative movements between 2 test masses in free fall at the end of each of the interferometer's arms.

LISA PATHFINDER is a scaled-down model of an interferometer arm packed into a single satellite that tests key technologies required to place the 2 test masses in perfect free-fall conditions and measure their relative movement with unprecedented precision. LISA PATHFINDER also draws on the very latest developments to minimise other forces acting on the masses housed inside the LTP instrument (LISA Technology Package) and to measure their movement. With its inertial sensors, laser metrology, drag-free control and ultra-precise micro-propulsion systems, it is a truly ground-breaking mission.

CNES and its partners in the French consortium coordinated by the APC (Astro-Particles and Cosmology) laboratory are involved in this ESA-led mission for which they are supplying a subsystem of the LTP instrument's optical bench. They are also involved in operational science data analysis.

SCIENTIFIC HIGHLIGHTS

Results of the mission, entitled Beyond the required LISA free-fall performance: new LISA PATHFINDER results down to 20 μHz, have been published at the beginning of February 2018 in PRL (Physical Review Letters).

Since the publication of the first results, the noise results have been significantly improved due to the continued decrease in pressure around test masses, through a better correction of non-inertial effects and a better calibration of the electrostatic forces actuation. In addition, the availability of numerous long noise measurement runs has allowed the measurement of noise with statistics down to 20 μHz.

These results recently demonstrate the ability to use an LPF-like geodesic reference system with the required precision to do gravitational-wave science from space at frequencies as low as 20 μHz.

MISSION STATUS

Following a 6-month extension beyond the nominal mission, the LISA PATHFINDER mission ended on 18 July 2017. However, data processing is still under way. Noise results have been recently published (see the above paragraph) while other experimental observations are still under evaluation.

The excellent results achieved are now paving the way to the LISA mission that was selected as the third ESA Large mission, dedicated to the gravitational Universe. The LISA phase A started in April – May 2018, the approuval is expected between 2022 and 2034 to be compatible with launch no later than 2034.

Fig. 1: Artist impression of the LISA Technology Package *©ESA*

Fig. 2: An artist's rendering of LISA PATHFINDER on its way to Earth-Sun L1 *©ESA/C. Carreau*

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New LISA PATHFINDER results: beyond the required LISA free fall performance

The final results of the LISA PATHFINDER mission, the technology demonstrator for the LISA mission, have been published recently [1]. The majority of the limiting noise are understood: optical interferometer precision at high frequencies, Brownian at mid-frequency and actuation, and non-inertial force at low frequencies. The characterisation and correction of glitches enable long measurement. The differential acceleration obtained is (1.74±0.05)× 10^{-15} m. s^{-2}. $Hz^{-1/2}$.

The LISA PATHFINDER mission (LPF) is a technology demonstrator for future space based gravitational waves observatories such as LISA, the large mission L3 of the ESA Cosmic Vision programme that is starting an industrial Phase A. LPF consists of 2 free falling test-masses separated by 37 cm in a single spacecraft (S/C). Each test-mass (TM) is in a housing with electrodes surrounding each of the 6 faces of the TM. The test-masses are Au-Pt cubes of 2 kg and 4 cm separated from electrodes by a gap of 4 mm. The electrodes are used to measure the position of the TMs and also to act on the TMs. The distances between the 2 TMs and between the S/C and one TM are measured with an extreme precision using several interferometers. The S/C is controlled to follow one of the TM (TM1) using a complex system of control loops and cold gas micro-propulsion. The second TM (TM2) is controlled, at low frequencies, on the sensitive axis (the axis joining the 2 test-masses) to stay at a constant distance with respect to TM2. See Fig. 1.

The main measurement is the differential acceleration between the 2 TMs. This measurement is obtained by subtracting the commanded force on TM2 and the weak coupling between the TMs and S/C from the interferometer measurement. The performances are measured between 0.1 and 100 mHz. Since we want to see if the technology is sensitive enough for being used for gravitational wave observatory, the aim is to achieve the lowest possible differential acceleration.

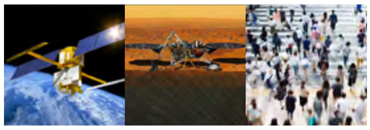
The LPF mission has been launched on the 3 December 2015 from Kourou. In mid-January, it arrived on its final orbit around Lagrange point L1. The nominal operations started on the 1 March and ended the 26 June. The extended operations started in December 2016 and ended in June 2017. The operations consist in a series of experiments either to measure the noise level over the frequency band of interest or to act on the instrument in order to measure the parameters of the system. These experiments last from days to weeks. During the operations the parameters were tuned to optimise the performances.

FIRST RESULTS

The first results have been published in [2] using only the first 45 days of data. The performances obtained were excellent with a differential acceleration 5.5×10^{-15} m.s^{-2}.$Hz^{-1/2}$ (blue curve on Fig. 2).

Interferometer readout performances

At high frequency (> 30 mHz) the measured differential acceleration is not due to TMs motion but is dominated by the performance of the interferometer readout system. The error on measurements of this optical system is about 30×10^{-15} m.$Hz^{-1/2}$ which is 100 times better than the requirement and the on-ground measurements.



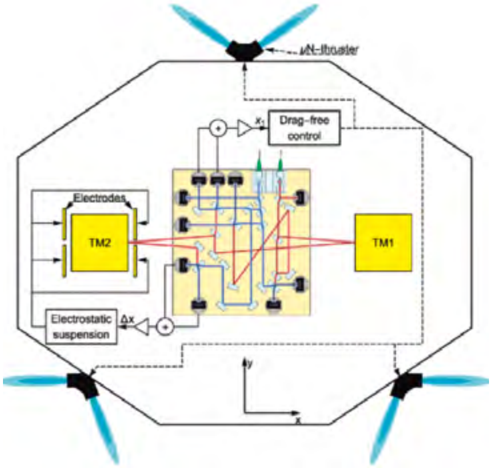


Fig.1

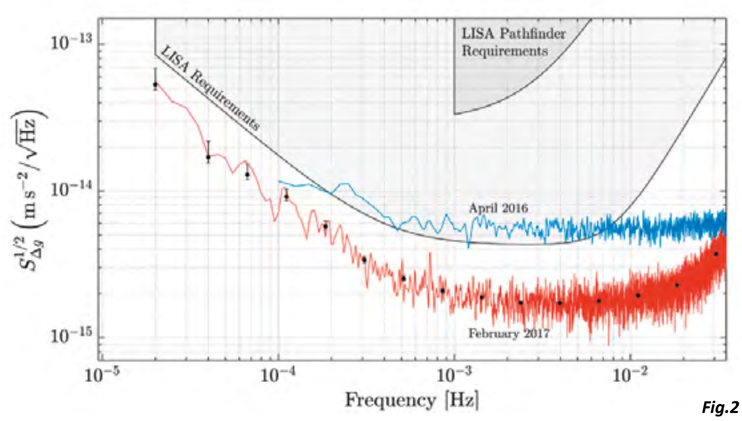


Fig.2

Fig. 1: Simplified representation of LISA PATHFINDER spacecraft showing the Test Masses, the electrodes around them, the optical bench interferometer and the Cold Gas thrusters *© from [2].*

Fig. 2: ASD of differential acceleration of LISA PATHFINDER test masses as a function of the frequency. The red line corresponds to a ~13 day long run taken at a temperature of 11°C in February. The blue corresponds to a run in April 2016 at a temperature of 23°C. See [1] for further information *© from [1].*

Brownian noise

In the mid-frequency band (1 to 30 mHz), the differential acceleration measured is dominated by the Brownian noise, due to the residual molecules in the housing that hits the TMs. The vacuum can surrounding the housing is open to space via a venting duct and the quality of the vacuum consequently improves with time, decreasing the impact of the Brownian noise. A decrease of this noise has also been observed by lowering the temperature.

FINAL RESULTS

During the operation extension, changes have been made both on the hardware and on the data processing in order to optimise the performances. The final result is the red curve on Fig. 2.

Decrease of the Brownian noise

The Brownian noise reduces due to the decrease of pressure in the housing along time and with a reduction of 10° C of the whole temperature of the instrument. The final differential acceleration is $(1.74 \pm 0.05)\times10^{-15}$ m.s^{-2}.Hz$^{-1/2}$, twice the LISA requirements.

Glitches

We observed sporadic quasi-impulse force events or “glitches”. The average rate of glitches is (0.78 ± 2) per day. The physical origin is not yet understood. They are observationally indistinguishable from a quasi-impulsive force acting on one of the 2 TMs, transferring a differential momentum over time spans ranging from seconds to, in rarer cases, hours. Observed glitch amplitudes are as large as pm.s^{-2}, with a typical impulse Δv of the order of 10 pm.s^{-1}.

Low frequency noises

The availability of numerous long noise measurement runs allows to study the low frequency performance. Below 1 mHz, the differential acceleration is observed to follow a 1/f behaviour. After correcting for noninertial effects and optimising the electrostatic force actuation on the second TM, a differential acceleration of $(6 \pm 1)\times10^{-14}$ m.s^{-2}.Hz$^{-1/2}$ has been obtained at 20 µHz.

DISCUSSION

Demonstration for LISA

This performance provides an experimental benchmark demonstrating the ability to achieve the low-frequency science potential of the LISA mission. With similar acceleration noise performance as LPF, LISA will be able to achieve more than the scientific programme described in [3]. For example, it allows the observation of heavy Super-Massive Black Hole Binaries for several periods of 10 days.

Platform stability

One of the important outcomes of LPF is the possibility to estimate the stability of the platform relative to its corresponding geodesic. Using a State Space Model to extract, from the observed S/C movement, the stability on all degrees of freedom, the following values are estimated: At 1 mHz, the stabilities in acceleration are shown to be of the order of 3×10^{-15} m.s^{-2}.H$^{z-1/2}$ for X_{SC} and 5×10^{-15} m.s^{-2}.Hz$^{-1/2}$ for Y_{SC} and Z_{SC} (see Fig. 1). For the angular degrees of freedom, the values are of the order 3×10^{-12} rad.s^{-2}.Hz$^{-1/2}$, for ΘSC and 2×10^{-13} rad.s^{-2}.Hz$^{-1/2}$, for H_{SC} and Φ_{SC}. The corresponding accelerations for LISA stabilities are being estimated.

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MICROSCOPE, a microsatellite challenging the universality of free fall

Launched in 2016, the CNES microsatellite MICROSCOPE (MICRO-Satellite à traînée Compensée pour l'Observation du Principe d'Equivalence) tests the universality of free fall for the first time in space using an experiment 100 times more precise than anything on Earth.

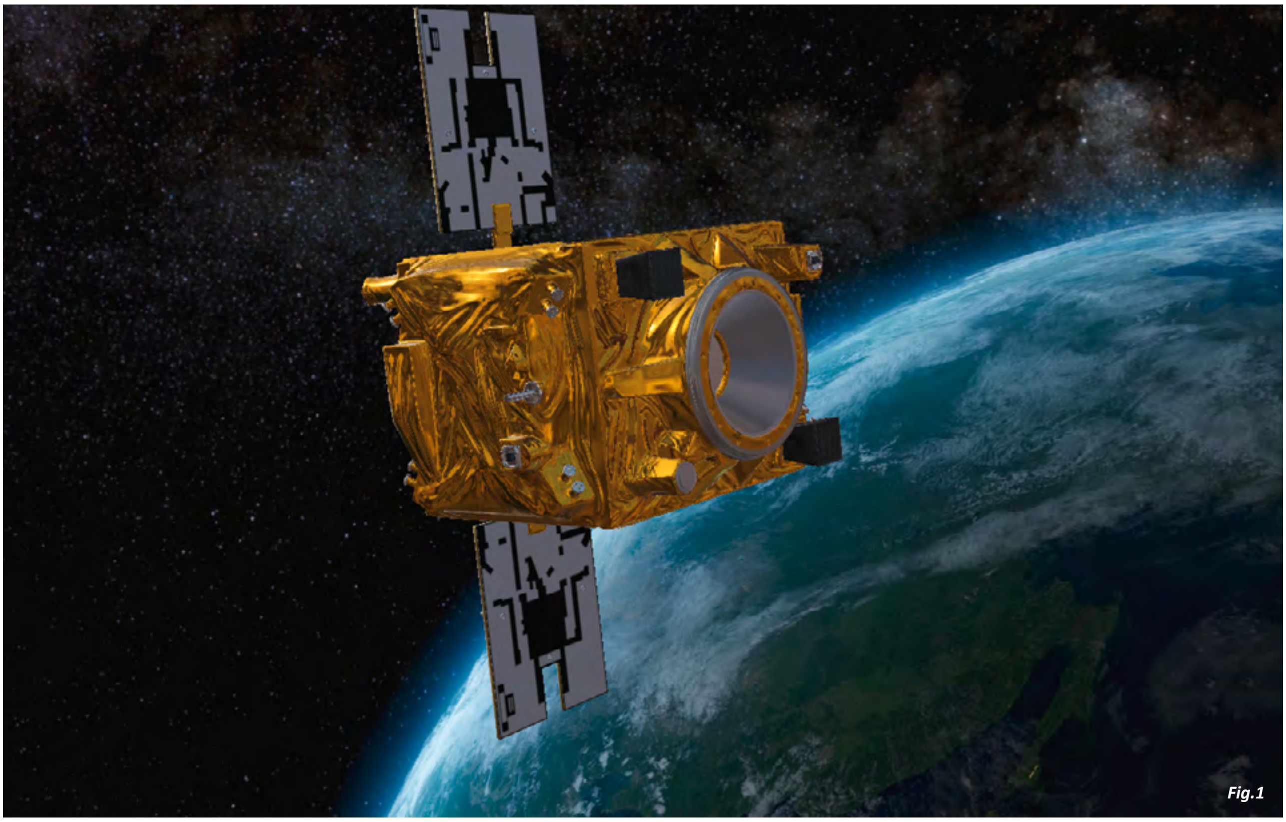

Fig.1

Back in the 17th century, Galileo conceived an experiment, without actually performing it, in which he dropped 2 objects of different composition and mass together from the top of the Tower of Pisa. In his theory, as the 2 objects hit the ground at exactly the same time, he deduced that in a vacuum all bodies fall at the same speed. This is what we call the universality of free fall or equality of gravitational and inertial mass, which Albert Einstein later stated as the Equivalence Principle and made it the basis of his theory of general relativity.

Although it has been verified with a degree of precision of the order of 10^{-13}, this principle is nonetheless being pushed to its limits by new theories seeking to reconcile gravitation with fundamental nuclear and electromagnetic interactions,

which predict that it could be violated at very weak levels. The MICROSCOPE satellite will probe these limits further and test the principle with a precision on the order of 10^{-15}. In space, it is possible to study the relative motion of 2 bodies in an almost perfect and permanent free fall in an orbiting satellite, shielded from perturbations encountered on Earth (notably seismic perturbations), over the course of several months.

The experiment is flown on a 300-kg microsatellite—heavier than a usual 100-150 kg microsatellite—built around CNES' Myriade bus and equipped with cold-gas microthrusters capable of compensating for the tiniest trajectory perturbations that might otherwise skew its results. CNES is providing 90% of funding for this mission, for which it is also prime contractor in charge of satellite bus development, satellite integration and testing up to launch, and construction and operation of the mission control centre.

The development of the MICROSCOPE mission was a cooperation between CNES-ESA-ONERA-DLR-INSU-GEOAZUR-ZARM.

SCIENTIFIC PAYLOAD

The payload is set up at the centre of the satellite with the T-SAGE (Twin Space Accelerometers for Gravitation Experiment) instrument made of 2 independent SAGE differential accelerometers, each possessing a mechanical module and an electronic control unit, plus a joint electronic unit for the interface with the satellite. They are exactly the same, except for the use of different materials for the test masses. In one instrument (SUREF) the 2 test masses have the same composition, and are made from a platinum/rhodium alloy. In the other instrument (SUEP), the test masses have different compositions:platinum/rhodium for the inner test mass and titanium/aluminum/vanadium for the outer test mass.

To achieve the test of the Equivalence Principle, the 2 concentric cylindrical test masses are minutely controlled to maintain them motionless with respect to the satellite inside independent differential electrostatic accelerometers. If the Equivalence Principle is verified, the 2 masses will be subjected to the same control acceleration. If different accelerations have to be applied, the principle will be violated: this event would shake the foundations of physics.

The Principal Investigator is Pierre Touboul (ONERA) and Gilles Métris (OCA – GéoAzur) is Co-PI of the mission.

SCIENTIFIC HIGHLIGHTS

The first scientific results of the MICROSCOPE mission have been published in the Physical Review Letters (PRL) in December 2017. The results, based on about 10 % of the scientific data collected, show no violation of the weak Equivalence Principle and improve the accuracy by an order of magnitude, reaching 2.10^{-14}. This result is given with conservative upper limits for some errors.

MISSION STATUS

As the mission duration is limited by the gas quantity, the scientific mission was achieved in February 2018. Then technological experiments will be conducted until September 2018. Then the satellite will be passivated to avoid any risk of explosion. To be compliant with the law on space operations, MICROSCOPE is equipped with an innovative deorbit system, called IDEAS. This equipment is made of 2 deployable wings of 4,5 metres. At the end of the mission, the wings of IDEAS will be inflated and rigidified to increase the drag surface of the satellite. Thanks to this system, the reentry in the atmosphere will last 25 years instead of 73 years.

In parallel, scientists still have a lot of work to achieve the data processing. The processing of the whole data set will allow improving the statistical errors. Remaining non yet processed data will allow to improve the accuracy of experiment. Specific investigations will be pursued to better understand the systematic errors and possibly correct them.

Hopefully, the final scientific results should be published in 2019.

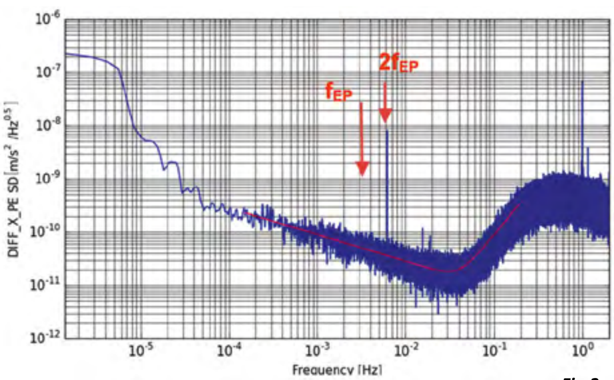

Fig.2

Fig. 1: The MICROSCOPE satellite © *CNES / Virtual-IT 2017*

Fig. 2: Square root of the measured PSD of the differential acceleration along X during the scientific session 218 with SUEP © *OCA / ONERA CMS MICROSCOPE*

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The MICROSCOPE mission: first results of a space test of the Equivalence Principle

The MICROSCOPE satellite was launched in April 2016 in a heliosynchronous orbit at 710 km altitude. This space mission is dedicated to test the Weak Equivalence Principle (WEP) with an accuracy of 10^{-15}. At the foundation of General Relativity (GR), it constitutes the major test target for any new theory of gravity. The science payload is based on 2 differential accelerometers that compare the acceleration of 2 pairs of free falling test-masses. In December 2017, the first result of the mission was published in Physical Review Letters [1]: no evidence of a WEP violation with 10^{-14} level of accuracy.

SCIENCE OBJECTIVE OVERVIEW

According to the WEP, all bodies should fall at the same rate in a gravitational field. The MICROSCOPE mission aims to test its validity by measuring the force required to maintain 2 test masses (of titanium and platinum alloys) exactly in the same orbit. A pair of test-masses of the same composition (platinum alloy) is also used to establish the zero of the experiment.

Einstein interpreted this universality of free fall as equivalence between gravity and inertia, and used this principle as the starting point for the theory of General Relativity [2]. GR has an extraordinary capability of prediction in astrophysics, recently well illustrated by the direct detection of the gravitational waves induced by 2 coalescing black holes [3].

However, how should we conceive a unified physics theory that make consistent GR and quantum field theory? In Cosmology, how can we reconcile dark energy and dark matter with the model of the expansion of the universe? Super string or quantum gravity theories could be good candidates to answer these questions. The challenge of these theories is that the WEP has to be violated at a certain level.

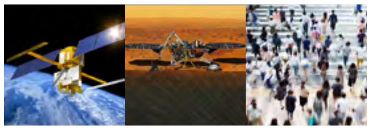
MISSION PRINCIPLE

The WEP is often expressed in terms of the Eötvös parameter for 2 materials A and B:
$\delta(A, B) = 2(aA - aB)/(aA + aB)$
aA and aB being the free fall accelerations of the 2 bodies A and B.

In the past decades, the laboratory tests performed on ground laboratories or by means of Lunar Laser Ranging have reached accuracy upper limits on δ of about 10^{-13} [4, 5]. The limitation of these experiments are mainly due to the environment (seismic noise, local gravity field fluctuations, atmospheric turbulences, etc.).

The MICROSCOPE satellite takes advantage of a very quiet environment provided by space. Moreover, the non-gravitational forces or the disturbing torques acting on the satellite are counteracted by on board cold gas thrusters. In order to accurately compare the accelerations of 2 test masses of different compositions "freely falling" in the same orbit around the Earth, the forces required to keep the 2 test masses in relative equilibrium are measured during long periods of time [6, 7].

T-SAGE (Twin Space Accelerometers for Gravitation Experiment) is the scientific payload, provided by ONERA, and is integrated within the CNES' microsatellite MICROSCOPE. It is composed of 2 parallel similar differential accelerometer instruments (called Sensor Unit, SU), each one with 2 concentric hollow cylindrical test-masses, see Fig.1. Both SU are identical except for the outer test-mass. In one instrument (SUREF) the 2 test-masses have the same composition: Platinum/Rhodium alloy (90/10). In the other instrument (SUEP) the test-masses have different compositions: Platinum/Rhodium (90/10) for the



inner test-mass and Titanium/Aluminium/Vanadium (90/6/4) (TA6V) for the outer test-mass. The payload is integrated inside a magnetic shield and a thermal cocoon at the centre of the microsatellite.

Experiencing almost the same Earth gravity field, the 2 concentric test-masses are constrained by electrostatic forces to follow the same orbit. Hence, a WEP violation ($\delta(A, B)\, g \neq 0$) would result in a difference $-\delta(A, B)\, g$ in the electrostatic feedback forces, where g is the Earth's gravity field at 710 km altitude ($7.9 m/s^2$). The researched signal is modulated at a well-defined frequency, denoted f_{EP}, by the apparent modulation of g seen in the direction of the measurement (cylinder axis) when the satellite orbits in inertial pointing or rotates about the normal axis to the orbit plane (see Fig. 2).

Testing the WEP with an accuracy of 10^{-15} necessitates measuring a differential constraining force per unit of mass (henceforth called acceleration) between test mass pairs with an 1σ accuracy of $7.9\times10^{-15} m\ s^{-2}$ at f_{EP}. A small disturbance arising from the off-centring between the 2 test masses with respect to the gravity gradient, is well detected at $2\ f_{EP}$, and can be used for calibration. As the Earth's gravity field is well modelled and the satellite attitude and position are precisely measured, it is possible to estimate the components in the orbital plane Δx and Δz of the off-centring simultaneously to the Eötvös parameter.

THE FIRST RESULTS

Since the end of the commissioning phase, in November 2016, more than 2000 orbits (12×10^6sec) have been collected for the EP test. The first result presented in PRL was performed on only 120 orbits with the SUEP and on 62 orbits with the SUREF. It brings no evidence of violation to 10^{-14} level, one order improvement with respect to previous experiments. The Eötvös parameter δ and the Δx and Δz components of the off-centrings are estimated in the frequency domain with a least-square fit [8, 9]. The SUEP systematic error has been evaluated to be less than 9×10^{-15} and is being better estimated with specific test on board to characterise the temperature sensitivity.

The Eötvös parameter for the SUEP instrument is obtained with 120 orbits (713 518 s):
$\delta(Ti, Pt) = [-1 \pm 9(stat) \pm 9(syst)] \times 10^{-15}$ at 1σ uncertainty on the least-square fit for the statistical error. The test performed with the SUREF instrument over 62 useful orbits (368 650 s) yields: $\delta(Pt, Pt) = [+4 \pm 4(stat)] \times 10^{-15}$ at 1σ. This estimation is fully compatible with a null result (which is expected for this instrument), suggesting no evidence of systematic errors at the order of magnitude of 4×10^{-15}.

CONCLUSION

The WEP test has been currently improved by one order of magnitude with MICROSCOPE. This first results already puts new constrains on some theories ([10], [11]).

Thousands of orbits of scientific measurements should be available by the end of the mission in autumn 2018. The integration over longer periods of the differential accelerometer signal leads already to an important reduction of the stochastic error. Forthcoming sessions dedicated to complete the detailed exploration of systematic errors will allow us to improve the accuracy of the experiment.

ACKNOWLEDGEMENTS

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Fig. 1: Picture of the flight model mechanics that is composed of 2 cylindrical sensor units, each one containing 2 test-masses for the differential acceleration measurement. *© ONERA.*

Fig. 2: Artist view of the satellite in orbit with a schema of the payload and its 4 test-masses. The arrows show the trajectory of the satellite around the Earth and the rotation about the Y axis (normal to the orbital plane): the combination of both motions defines the measurement frequency. *© CNES, Virtual-IT 2017 and ONERA.*

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