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The Thomas Pesquet PROXIMA mission: An overview of accomplishments and science results

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ABSTRACT

The Proxima Mission of ESA Astronaut Thomas Pesquet began with the launch of the 49 Soyuz (49 S) from the Baikonur Cosmodrome on 17 November 2016 (GMT322) at 20:20 GMT. Following a nominal 34-orbit rendezvous, the 49 S docked with the Rassvet module on the International Space Station on 19 November 2016 (GMT324). Along with ESA crewmember Pesquet were Russian crewmember Oleg Novitsky and US crewmember Peggy Whitson. The Proxima mission concluded on 02 June 2017 (GMT153) after Pesquet spent 196 days in low earth orbit. This paper gives an overview of the Proxima mission and the forty ESA objectives conducted during this time ranging from human physiology to material science, from robotics demonstrations to educational outreach activities. On-board and ground activities are described, crew-time usage is assessed, and scientific results are compiled. Five years after the completion of Proxima, we review the results of this research.

1. Introduction

The mission of a European Space Agency (ESA) astronaut represents a crucial step in achieving ESA's scientific research objectives, its technology demonstrations, and education outreach efforts (see Fig. 2Figure 2 and 3).

Unfortunately, characterizing the success of a particular mission isn't easy. The timeframe for data analyses can be long and, accordingly, publications and dissertations take even more time to emerge. Furthermore, the data collection for a given experiment will not often be completed during the mission of a single astronaut. Rather, he/she/they may conduct part of an experiment that requires many more sessions (or years) of additional scientific runs, or a dozen more human research subjects. Therefore, it may sometimes be a decade before the complete set of samples or subjects is achieved, data analysed, and results published.

Unfortunately, this time-lag hampers ESA in characterizing, understanding, and promoting the value of its human spaceflight program. Absence of such valuation may jeopardize agency decisions, investment prioritization, and the procurement of programmatic funding.

Abbreviations: Activity energy expenditure, AEE; Automatic Identification System, AIS; Autonomic nervous system, ANS); Baseline data collection, BDC); Cycle Ergometer with Vibration Isolation and Stabilization System, CEVIS); Le site du centre national d'études spatiales, CNES); Central nervous system, CNS; Commercial off the shelf, COTS; Crew-time Tracking Log, CTTL; Canadian Space Agency, CSA; Danish Aerospace Company, DAC; Daily Operations Report, DOR); Deutsches Zentrum für Luft-und Raumfahrt, DLR); Dose Distribution Inside the International Space Station - 3D, DOSIS-3D; ESA Active Dosimeter, EAD; Early Detection of Osteoporosis in Space-2, EDOS-2; European Modular Cultivation System, EMCS; Electromagnetic Levitator, EML; European Physiology Module, EPM; Education Payload Operations, EPO; European Space Agency, ESA; Experimental Science Requirements, ESR; Extra vehicular activity, EVA; Flight day, FD; Grey matter, GM; Human and Robotic Exploration Requirements and Utilization, HRE-RU; International Space Station, ISS; Internal Mobile Unit, iMU; Japan Aerospace Exploration Agency, JAXA; Low Earth Orbit, LEO; Muscle Atrophy Research and Exercise System, MARES); Microbial aerosol tethering on innovative surfaces in the international space station, MatISS; Mission Operations Implementation Concept, MOIC; Microgravity User Support Centre, MUSC; Multi-Purpose Computer & Communications, MPCC; Magnetic Resonance Imaging, MRI; Microgravity Science Glovebox, MSG; Material Science Laboratory, MSL; The National Aeronautics and Space Administration, NASA; Nitric Oxide, NO; Nitric Oxide synthase enzyme, NOS; Operations Nomenclature, OpNom; Passive Dosimeter Package, PDP; Principal Investigator, PI; Requirements Planning Team, RP-Team; Sample Coupling Electronics, SCE; Science Technology Education and Math, STEM; Tissue Equivalent Proportional Counter, TEPC; User Support Operations Centre, USOC; United States Operational Segment, USOS; Utilization Accomplishment Report, UAR; Weekly Science Summary, WSS; White Matter, WM.

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Furthermore, lack of tangible results can confound the communication role of the astronaut who, as a highly visible representative of the program, is expected to articulate the full impact of their own mission, answer existential questions about human spaceflight, and address specific concerns about agency expenditures.

As an additional complication, the programmatic valuation of ESA's Low Earth Orbit (LEO) program (consisting of SciSpacE, ESA Technology Demonstrations, Commercial, and National Contribution payloads) is fundamentally difficult to quantify. The research facilities aboard the International Space Station (ISS) are subject to unique physical and science constraints that are not present in other laboratories [1]. Therefore, metrics used to assess the contributions of National Laboratories [2,3] may not necessarily be appropriate to apply when assessing ISS programmatic impact. Constraints of science and technology research aboard the ISS include severe restrictions on the mass and volume of equipment and consumables, high inertial forces during take-off and landing, and exposure to high doses of ionizing radiation that can degrade both hardware and software [4]. In addition to these challenging conditions, include the complicating factor of microgravity that may significantly alter the intended functioning of equipment [5]. Due to the operating constraints of the ISS laboratory, the experiments themselves are also restricted in terms of power and heating and venting requirements, as well as the material safety and material toxicity that may be used. Significantly, the principal investigators are unable to execute the experimental procedures themselves, and must rely instead on automation, ground commanding, and crew intervention. The work of the astronauts therefore comprises a critical part of the science. Unlike scientists and technicians in a terrestrial laboratory, however, astronauts must divide their research efforts with other crucial service and system activities to ensure their own survival and maintain their habitat. As noted by social scientist Paola Castaño [6], "… *in most big science projects or National Laboratories, the individuals in charge of data collection are not the same ones in charge of fixing the toilet in their facilities on a regular basis, handling the trash, nor flying the vehicles that take them to the location.*"

Here, we take a step towards identifying the impact and value of the ESA Human Spaceflight efforts by examining an ESA crewmember's contribution to science, technology, and education objectives.

This paper gives an overview of the Proxima Mission of Thomas Pesquet (17 November 2016–02 June 2017), summarizing the ESA objectives conducted during this time: research in human physiology, fundamental physics, material science research, robotics demonstrations, and educational outreach activities, as well as payload facility upkeep. The ESA objectives from this mission are detailed, and a breakdown is given of the crew-time used to achieve these objectives. We give an overview of the Proxima mission ESA research outcomes to date. In many cases, the results are only now under review and publication. This is especially germane in the case of human physiology payloads since these research projects take some time to acquire the requisite number of study participants. In other cases, payloads are still under execution on-board the ISS. Therefore, this paper should be viewed as an interim review – and not a final accounting of programmatic or mission value. Nonetheless, it is a glimpse into research results for the ESA Human Spaceflight Program.

2. Method

For this study, we reconstructed the operations conducted for both ESA payloads and payload facilities (referred to collectively as *Utilization*) during the Pesquet mission through several sources. These included ESA's official crew-time tracking logs (CTTL) which account for all ESA's Utilization activities aboard the ISS (weekly synchronized and validated with NASA's records), ESA's inputs to the multilateral weekly science summary (WSS), and ESA's contributions to the USOS end-of-increment document, the Utilization Accomplishment Report (UAR). These documents are maintained by ESA's Human and Robotic Exploration Research and Utilization (HRE-RU) Requirements Planning Team (RP-Team). We examined ESA's Experiment Science Requirements (ESR) and Mission Operations Implementation Concept (MOIC) documents which outline the constraints and requirements and operations procedures for each payload. We also used the Daily Operations Report (DOR) records maintained by the Columbus Control Centre (COL-CC) and the European User Support Operations Centres (USOCs) to identify and understand the relevant on-board operations. Significantly, in addition to these sources, the records and first-hand account of ESA Astronaut Thomas Pesquet were used to validate the reconstruction and give relevant operational details about the Proxima mission.

To identify the quality of the data obtained during the Proxima mission, we sought to examine the content of the reports submitted by the Principal Investigator (PI) 30-days following the completion of on-board operations. We used all post-flight accomplishment reports available in ESA archives for this period (Aquamembrane II, Space Headaches, SOLACES-SOLSPEC, and SODI-DCMIX#3). To supplement these data, we corresponded with the Principal Investigators identified in the Experimental Science Requirements (ESR) documents for the Proxima mission payloads (though we did not make requests for the outcome of routine maintenance of ESA on-board facilities), requesting that they respond to eight open-ended interview questions (see Table 1). The response rate for our request was 87%. Unless otherwise noted, the results reported in this paper are guided from these responses (given in February/March 2022), combined with a literature review of the relevant publications.

3. The Proxima Mission

Every first space mission is a rollercoaster ride and the adventure of a lifetime: so much effort and so many sacrifices culminate in this trip to space, and Proxima was no exception. After seven years of intense training all over the world, and almost as much time prepping for the teams on the ground, the Proxima mission of ESA astronaut Thomas Pesquet was ready to begin. It started with the launch of the 49 Soyuz (49 S) from the Baikonur Cosmodrome on 17 November 2016 (GMT322) at 20:20 GMT. Following a flawless night launch and a nominal 34-orbit rendezvous, the 49 S docked with the Rassvet module on the International Space Station on 19 November 2016 (GMT 324). Along with ESA Crewmember Pesquet were two veteran space flyers: Russian cosmonaut Oleg Novitsky and NASA astronaut Peggy Whitson. The Proxima mission concluded on 02 June 2017 (GMT153) after Pesquet spent 196 days in low earth orbit, working and living on the ISS, and making enough memories for a lifetime.

Vehicles that flew during the Proxima mission are as follows:

Table 1
Open-ended interview questions submitted to PIs of ESA Proxima science and technology and education payloads.

Interview Questions submitted to PIs regarding their Proxima mission research
1. Could you please share a list of publications (and possibly some copies of your papers) that resulted from this research?
2. Did this research give you the results you were aiming for (were your objectives met)?
3. Were there any surprising results from this research (anecdotes and data are appreciated)?
4. What were some of your key findings from this investigation (if possible, please summarize the findings in terms of space applications and terrestrial applications)?
5. In your opinion, how does this research contribute to the state of the art?
6. Have you conducted any follow-up research based on the results from this work? If so, could you please share this with us?
7. Based on the results you've collected to date, can you anticipate any follow-up research that might be needed?
8. Is there any message you'd like us to share with the astronauts who conducted work for this research?

- The Russian 65 Progress cargo vehicle (65P) launched on 01 December 2016. It was lost on ascent.
- The Russian 64 Progress cargo vehicle (64P) undocked from the Pirs docking compartment on 31 January 2017
- HTV-6 cargo vehicle launched on 09 December. After 45 days berthed, Kimbrough and Pesquet used the SSRMS to release HTV-6 on 27 January 2017.
- SpaceX-10 cargo vehicle successfully launched on 19 February 2017
- On 10 April 2017 the 48S and its crew, Commander Shane Kimbrough, Andrey Borisenko, and Sergey Ryzhikov returned to Earth after 174 days in space
- OA-7 cargo vehicle successfully launched on 18 April 2017
- The 50S Soyuz MS-04 successfully launched on Thursday, April 20th with Fyodor Yurchikhin and Jack Fischer

On 13 January 2017, Thomas Pesquet conducted his first Extra Vehicular Activity (EVA) with Expedition 50 Commander Shane Kimbrough. During a spacewalk that lasted nearly 6 h, the two astronauts successfully installed three new adapter plates and hooked up electrical connections for three of the six new lithium-ion batteries on the ISS.

On 23 March 2017, Pesquet performed his second career EVA with Kimbrough. They prepared the Pressurized Mating Adapter 3 (PMA3) to accommodate future commercial crew vehicle docking, and installed a new computer equipped with advanced software for the adapter. They also lubricated the latching end effector on the Canadarm 2 robotic arm, inspected a radiator valve suspected of a small ammonia leak, and replaced cameras on the Japanese exposed platform. The EVA lasted for 6 h and 34 min.

Four other EVAs were performed during Proxima, for which Pesquet was responsible for setting up the suits, the tools, and the airlock, and executing all procedures needed for the suited crewmembers to egress and ingress the ISS safely and on schedule. He also piloted the robotic arm to assist the crewmembers outside during one of these EVAs.

Beyond these high-level activities, the mission was dedicated to scientific research, with the necessary maintenance and logistics to enable human presence in this hostile environment and to keep the ISS in good condition. A record number of Utilization hours was accounted for during the mission.

A complete list of the ESA objectives conducted during Proxima is given in the subsequent section.

4. Proxima Mission Payload and Facility overview

Forty ESA Utilization objectives were associated with the Proxima mission. Many of these were performed directly by Thomas Pesquet. These included human subject research payloads as well as various investigations in biology and biotechnology, earth and space sciences, educational activities, physical and materials sciences, technology development, and facility maintenance activities. A complete list of payload and payload facilities with objectives conducted during the Proxima mission are given in Table 2, along with brief descriptions of each.

This overview makes clear the broad range of research and facility objectives during an ESA astronaut mission.

5. Resource Utilization

ESA is limited in the amount of crew-time the Agency can spend in any given period. The United States Operational Segment (USOS) is a partnership between NASA, JAXA, CSA and ESA, formalized by a series of cooperative agreements [7]. Under the terms of this partnership, ESA has access to a fixed 8.3% of USOS resources. This translates to approximately 1.35 h of crew-time per crewmember per week. Investing this crew-time into science and other related activities (such as technology demonstrations and education activities) requires careful budgeting, planning, and accounting.

Table 2
Payloads and facilities in the Proxima mission. Note that each is referred to by its Operations Nomenclature (OpNom).

Payload/Facility OpNom	Description
Biology (1)	
Extremophiles	Analyse the adaptation and evolution in archaea and extremophile bacteria on ISS & compare with spacecraft clean rooms and visiting vehicles
Environmental Science and Radiation Physics (3)	
DOSIS-3D	Determine absorbed dose and the dose equivalent using a variety of active and passive radiation detector devices distributed in ISS
Solar SOLSPEC	Study solar variability at short and long term and achieve absolute measurements
Solar SOLACES	Measure solar spectral irradiance of the full disk from 17 to 220 nm at 0.5–2 nm spectral resolution & solar spectrum irradiance from 180 nm to 3000 nm
Education (3)	
EPO Astro-Pi 2.0	Student-written software/code run by ISS Astro Pi computers
EPO Pesquet EPO Task List	Education and outreach programs run by ESA and CNES in support of the Proxima mission
Human Subject Research (10)	
Brain-DTI	Find/study biomarkers of neuroplasticity in vestibular signal processing
Cartilage	Determine effect of microgravity on cartilage morphology, cartilage biology; study correlations between cartilage morphology and muscle atrophy
EDOS-2	study post re-entry bone losses, and define mechanisms of long-term recovery of spaceflight induced bone losses
Energy	Measure changes in energy balance due to long-term space flight; determine astronaut energy requirements
GRIP	study of adaptation of grip-force/load-force coordination to conditions of microgravity environment
GRASP	Study if/how gravity acts as a reference frame for the control of reach-to-grasp
Immuno-2	Study changes to the immune system due to stress response in space
Muscle Biopsy	Study molecular cell markers to evaluate the efficiency of countermeasures to prevent muscle atrophy in spaceflight
Sarcolab-3	Examine declines in muscular strength, function and neuromotor control during spaceflight
Space Headaches	Assess incidence and characterize headache episodes in astronauts
Fluid Physics (2)	
Geoflow II	Study/characterization of thermal convection flow patterns between spherical shells (both rotating and non-rotating) under a central force field
SODI-DCMIX #3	Measurement of diffusion coefficients of selected ternary mixtures
Material Sciences (4)	
EML Batch 1.2c	Investigation of metastable phase formation of magnetic alloys; determination of surface tension and interfacial tension of CuCo alloys; thermophysical property data measurement of industrial alloys in the liquid phase as a function of temperature; influence of melt convection on phase selection in technically important peritectic alloys; measurements of the thermophysical properties of supercooled Ti–Zr–Ni liquids
EML Batch 2.1	Meta-stable States and Phases and in the field of Measurement of high-accurate Thermophysical Properties of Liquid Metallic Alloys at high temperatures
MSL Batch 2b SETA	Investigation of eutectic growth in ternary Al–Cu–Ag alloys in a high temperature furnace
PK-4 (R) Science Campaign	Study of individual particles in solid and liquid phases on the most fundamental level using complex plasmas
Technology Demonstrations (12)	

(*continued on next page*)

Table 2 (*continued*)

Payload/Facility OpNom	Description
Aquamembrane	Forward osmosis technology using a biomimetic membrane based on Aquaporins, water channel proteins with excellent water permeability and solute rejection
CNES Aquapad	Quantify and identify *E. coli* and Enteroccocus in a sample of water in the ISS using a patented Paper Analytical Device technology
CNES Echo	Demonstrate functionality of ultrasound imaging data and remote guidance capability with motorized probes operated remotely from ground
CNES Everywear	Ambulatory data collection system making use of wearable sensors connected to a station iPad, wirelessly synchronized with ground
CNES Fluidics	Investigate/validate numerical and analytical predictions of the behaviour of fluids under microgravity
CNES Matiss 1.0	Evaluate the suitability of antimicrobial surfaces to reduce surface microbial contamination in manned spacecraft
DLR Magvector	Measure the magnetic field on the Ram and Wake side of an electrical conductor
DLR Wisenet	Distributed sensors that enable monitoring of physical or environmental conditions such as temperature, pressure, humidity, acceleration, etc
ESA Active Dosimeter (EAD)	Active (powered) dosimeter system meant to establish the option for advanced operational utilization aboard the ISS and other human spaceflight
Haptics-2/Interact	Real-time control of ground-based robots with haptics force-feedback by ISS-based crew
Skinsuit	Evaluate the efficacy of a countermeasures suit in reducing/preventing low back pain and preventing spine elongation
Vessel ID System	System transmitting information about vessel identity, position, heading, nature of cargo, destination etc. on dedicated frequencies in the maritime VHF band
Facilities (5)	
Biolab Rack	ESA experiment facility supporting biological experiments on microorganisms, cells, tissue cultures, small plants and small invertebrates
EMCS Rack	European Modular Cultivation System (EMCS) is an ESA experiment facility dedicated to studying plant biology in microgravity
EPM Rack	European Physiology Modules (EPM) is an international standard payload rack equipped with science modules to investigate the effects of long-duration spaceflight on the human body
Mini-ECCO	A conditioned container for passive temperature-controlled transportation of experiments for the ISS
MobiPV	A modular network enabled application for an operator/technician to use as an interactive electronic technical manual browser. To be deployed on a commercially available mobile device or laptop

To achieve its objectives, therefore, the agency relies not only on this nominal “prime” allocation, but also on joint agreements between international partners and, importantly, on the willingness of the crew to perform additional activities, designated as “reserve” crew time. Reserve activities can be performed when other partners (usually NASA) lack sufficient on-board tasks to populate the schedule on a given day, creating an opportunity for otherwise unallocated ESA activities to be inserted. Alternately, reserve activities can be conducted by the crew during their scheduled personal time on a voluntary basis. The period during the Proxima mission was exceptional in the number of activities performed, the crew-time far exceeding ESA’s allocation. The 85h30 m of ESA prime crew-time was supplemented by 56h15 m of crew-time from ROSCOSMOS and 29h50 m of crew-time from NASA. Impressively, Thomas Pesquet spent a total of 33h40 m on reserve activities. Reserve activities conducted by Pesquet included more than half of the activities needed to complete the ESA Active Dosimeter experiment, and nearly all activities (05h40 m) to complete the sequences of the Haptics-2 robotics test. Additionally, Pesquet conducted 12h55 m of education activities for ESA in his spare time. As a result of these efforts, 207h00 m of crew-time was spent towards ESA Utilization objectives during the 196 days of the Proxima mission. This is an unusually impressive 121h30 m worth of additional crew-time Utilization. The total as-flown crew-time was therefore 2.42 times the activities conducted under ESA prime crew time during this period (see Fig. 1) (see Fig. 2).

The research category that took the most amount of Proxima crew-time (at 108h55 m representing 53% of all as-flown crew time during this period) were the Human Research experiments. From most-to-least crew-time these were:

1 Sarcolab-3 (66h30 m)
2 Energy (17h25 m).
3 EDOS-2/IMMUNO-2 (11h05 m)
4 GRASP (06h50 m)
5 GRIP (04h35 m).
6 Space Headaches (01h45 m)

It makes sense that Human Subject Research payloads are so costly in terms of crew-time since the burden of data collection rests exclusively on the crewmember. Other payloads may be streamlined through technology automation or ground operations to minimize the amount of crew intervention required. However, human research payloads require that the crew play the role of both subject and scientist, and this can become time consuming. This is particularly true when the hardware setup or measurements are particularly complex, and when an additional crew are needed to support measurements - as in the case of the MARES rack setup and associated measurements for Sarcolab-3.

Technology Demonstrations comprised 19% of all crew-time activities, and Material Science and Education both at 10%. Environmental Science and Facility maintenance were each 4% of the crew-time, Fluid Physics at 4% and Biology at ~0.05%. We should note here that, in some ways, the category of Technology Demonstration may be slightly misleading – since this category encompasses all ESA Tech Demo payloads as well as those payloads conducted as National Agency contributions. While some National Agency payloads may have scientific impact and might therefore reasonably be categorized as science, they have not passed through ESA’s SciSpacE Announcement of Opportunity (AO) screening, which selects payloads based on a process of peer review for scientific merit, and an ESA-internal operations review for technical feasibility.

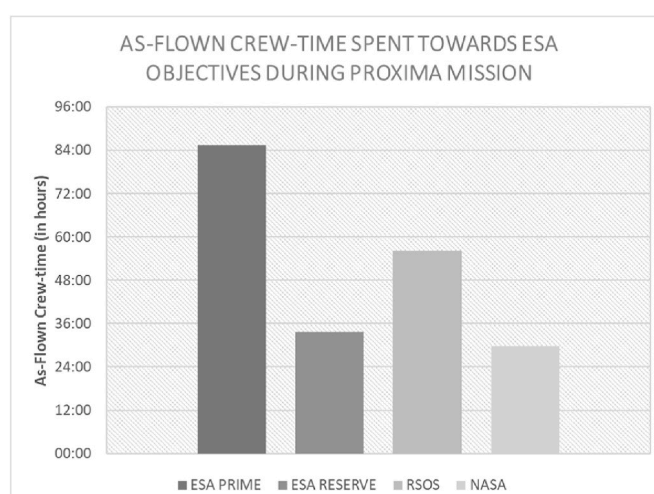

Fig. 1. Total amount of crew-time (in hours) spent on ESA Utilization objectives during the Proxima mission. During this mission, ESA Nominal Prime allocation, and international partner crew-time (arranged through barter agreements) and Reserve crew-time comprised a total of 207 h of ESA activities to be conducted.

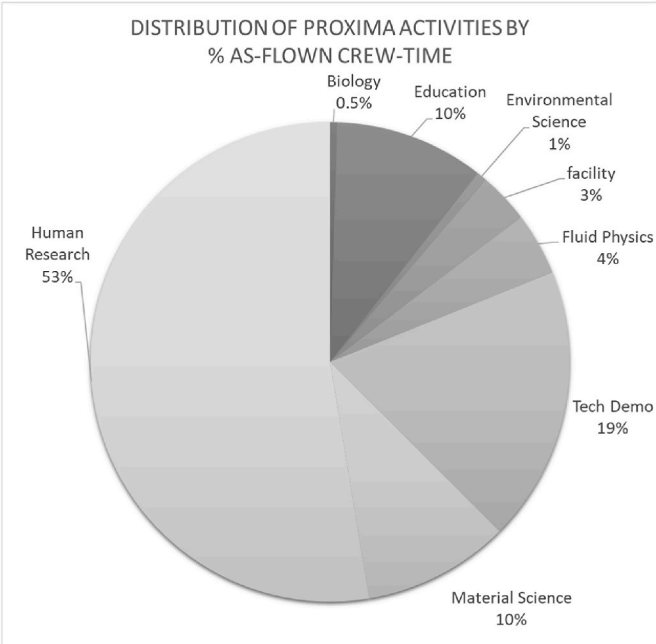

Fig. 2. Distribution of crew-time used during the Proxima mission - according to payload type.

Perhaps the most important takeaway from this discussion of crew-time is that it provides a lens through which to view the scientific results of the mission. Each minute of crew-time is precious, a fleeting opportunity for researchers to access a truly unique laboratory environment, to probe scientific and technological realms that are infeasible any other way. We rely on teams of operators to facilitate this exchange, and on the crew themselves to put the final pieces together. It is remarkable that the relatively small amount of crew-time spent aboard the ISS has often resulted in disproportionately impressive outcomes. We examine some of these outcomes in the following sections.

6. Proxima results

Herein, we review the activities and results of the Utilization payloads of the Proxima mission. In this reporting, we do not adhere to the research category convention as defined by ESA's SciSpacE and technology demonstration programs (e.g. as listed in Table 2). Instead, there subjects seem to be related, we group payloads together. For example, we group science and technology demonstrations together if their objectives are related. (Please note that we do not herein include summaries of the outcomes of routine maintenance to facilities).

6.1. Human subject research

There were ten ESA Human Subject Research Studies during Proxima, most of which Thomas Pesquet participated in, either as a subject or operator, or by providing logistical support to other subjects. Most investigations required activities on-board the ISS, but some experiments required no in-flight sessions (pre- and post-flight baseline data collection, BDC, sessions only). These included Energy, which measured an Astronaut's Energy requirements for long-term space flight, a crucial factor needed for sending the correct amount of the right types of food with space crews, and Sarcolab-3, a study that investigated the adaptation and deterioration of the soleus, or calf muscle, where it joins the Achilles tendon, which links it to the heel and carries loads from the entire body. In a study complementary to Sarcolab-3, the ESA Muscle Biopsy study took samples from two different leg muscles in astronauts before and after spaceflight – studying structural and molecular/biochemical changes to the tissue. Other ESA Human Research payloads investigated the impacts of the space environment on brain structure and function (Brain DTI and GRIP and GRASP), on headaches (Space Headaches), on bone and cartilage health (EDOS-2 and Cartilage, respectively), and the immune system (Immuno-2). We review these in the following paragraphs.

6.1.1 Brain-DTI

The BRAIN-DTI project is the first prospective study to look at brain structural and functional changes after spaceflight and to include a follow-up measurement a half-year after the astronauts' return from the ISS [8]. With no previous knowledge on such changes, this research using pre- and post-flight Magnetic Resonance Imaging (MRI) of the brain is providing the very first insights into brain changes resulting from a space mission. Researchers mapped out various volumetric changes in the brain [9,10] indicating that the brain moves upward within the skull and the cerebral spinal fluid (CSF) around the brain is redistributed and its flow likely hampered. Analyses further clarified that the grey matter (GM) volume changes do not represent a change in the net amount of GM, but rather represent a shape change – changes that are partially detectable a half-year after the space mission. One implication of these findings is a possible association between the CSF and GM shape changes with the spaceflight-associated neuro-ocular syndrome (SANS). SANS is characterized by ocular structural changes and impairment of visual acuity, which can have strong operational consequences. Significantly, in these structural studies of the brain, researchers did not find decreases in GM or white matter (WM) mass, meaning that there is no evidence of atrophy in the brain [11]. On the other hand, they did see GM and WM mass increases, meaning that the net amount of tissue increased in three major motor areas of the brain: the primary motor cortex, the basal ganglia, and the cerebellum – areas that are all responsible for movement. Functional MRI scans also showed altered brain function and functional connectivity in motor and vestibular brain regions after spaceflight - indicating that motor strategies and vestibular information are required to adapt in a weightless environment. The current findings from BRAIN-DTI give strong evidence for adaptive changes in the brain, known as neuroplasticity, specifically in the motor system. To date, we've identified six academic publications for this payload. Research is ongoing and we anticipate new discoveries and publications in upcoming years.

6.1.2. Cartilage

Studying cartilage health can be a challenge due to its very slow response rate. It can take month if not years for changes at the tissue level to become visible, meaning that long-term ground-based studies are infeasible. Researchers are therefore limited in their ability to answer fundamental questions about cartilage adaptation and degeneration resulting from immobility-driven joint conditions on Earth. Research using ISS crewmembers represents the only model of sufficient length of mechanical unloading in healthy individuals to investigate the effects of unloading and immobilization on cartilage health. For this study, the research team performed magnetic resonance imaging (MRI) on crewmember joints, and analysed biomarkers in biological samples [12]. This study is already giving significant insight into the general understanding of the role of immobilization for cartilage health, and helping scientists and doctors understand and treat immobility-driven joint conditions on Earth. The investigation is also helping scientists to assess the risk of cartilage degeneration during long and midterm space missions. Experiment results suggest that space missions of only four to six months duration alter cartilage metabolism and initiate cartilage degeneration [13,14,15,16,17,18]. In future space missions it will be important to monitor cartilage health, to understand how cartilage adapts in this environment, and to identify ways to monitor this tissue. This research serves as a basis for identifying preventive and acute countermeasure regimens and is expected to also provide the foundation for assessing the risk for joint injury during long term exploration missions (for example, when crews re-enter gravity environments after space travel to the moon or Mars). To date, the research team has published four papers in academic journals, a book chapter, and given more than fifteen presentations at conferences. An extensive amount of data is still being analysed, with more publications expected.

6.1.3. EDOS-2

Astronauts exhibit bone loss similar to osteoporosis in space (~1% loss per month). The EDOS-2 (Early Detection of Osteoporosis in Space-2) experiment addressed whether there is a post re-entry bone loss similar to that seen after bed rest (i.e., bone loss increasing in the first phase after return to earth) and establishes when the bone lost will recover - since studies have shown that recovery time for bone integrity is much longer than the flight time. Understanding the physiology of immobilization-related bone losses is paramount to the development of efficient countermeasures. For the weight-bearing tibia bone, researchers were expecting significant bone loss associated with increased bone resorption activity and only partial recovery one year after landing – however it was surprising for them to discover that some fragility features (cortical porosity and trabecular bone loss) did not recover at all. The "big" surprise came from the smaller weight-bearing radius. These did not show any changes at landing, confirming what researchers had previously seen in the MIR space station. However, there were some changes sometime afterwards - a progressive deterioration becoming significant one year after landing. Such deterioration is concomitant to an overall decrease in bone remodelling activities (both resorption and formation activities). Researchers still do not understand why there is this deterioration at such a long time after flight and are currently studying some hypotheses in preclinical models [19,20,21]. These results were statistically significant globally – but there were interindividual differences between subjects. Researchers are currently trying to clarify if there are some bone structural traits that predict the severity of space-induced bone loss. They also plan to examine the individual level of physical activity before, during and after space missions to see whether the differences can be accounted for between pre-flight and inflight - and inflight and post flight subject data.

6.1.4. Energy

The Energy investigation measured an Astronaut's Energy Requirements for Long-Term Space Flight, a crucial factor needed for sending the correct amount of the right types of food with space crews. Eleven astronauts were examined during exercise and rest cycles three months before launch, three months after arriving aboard the ISS and adapting to the space environment, and after return to Earth. Physicians measured metabolic rates, urine content, and bone density to determine energy needs. During six-month missions on the ISS, a large inter-individual variability in body composition changes was observed. Astronauts maintaining pre-flight total and activity energy expenditures, partly due to unexpected non-exercise activity, maintained fat-free mass but lost fat mass. Conversely - those who decreased energy expenditures lost fat-free mass but gained fat mass (fat mass balance reflects unmatched energy intake adaptation to expenditure during flight). On average, astronauts who maintained energy expenditure during flight were also fitter on the ground. The study concluded that both inflight total physical activity and ground fitness predicted spaceflight-induced total energy expenditure and body composition changes and thus energy requirements [22].

This experiment holds timely application for future human space travel since Space agencies' human exploration roadmaps are particularly concerned about energy balance control [23]. Although exercise is a cornerstone of countermeasure programs employed to prevent microgravity-induced body composition and fitness changes, the energetic cost of physical activity in space has never been studied. There are also terrestrial applications for this research including technological developments to assess body composition and energy intake at the individual level, and also to understand the impact of exercise in the context of sedentary behaviours.

6.1.5. GRASP

During Proxima, on 22 May 2017, Thomas Pesquet performed the commissioning of both the GRASP and GRIP hardware.

The purpose of the GRASP research is to understand if and how gravity acts as a reference frame for the control of reach-to-grasp, and thereby better understand how the Central Nervous System (CNS) integrates information from different sensory modalities, encoded in different reference frames (See Fig. 3). To correctly position the hand with respect to the spatial location and orientation of an object to be reached/grasped, the CNS must compare visual information about the target and proprioceptive information from the hand. Previous studies have shown that, when aligning a hand to a remembered target orientation, the brain encodes both target and response in visual space when the target is sensed by one hand and the response is performed by the other, even though both are sensed only through proprioception [24]. Terrestrial research has also indicated that gravity plays a central role in spatial perception, with otolithic signals reciprocally aligning the reference frames in which the available sensory information can be encoded [25]. The response of the CNS integration of these sensory modalities in the absence of gravity, therefore, is likely to yield significant insight into these mechanisms. GRASP is an active investigation and requires additional subjects to statistically validate the scientific observations and conclusions to date. However, researchers report that the experiment is providing key data that can be used to test and challenge their hypotheses – and that the data so far are of high quality.

Researchers are working to apply the fundamental knowledge gained in the GRASP experiments to practical situations in tasks requiring high precision, such as when remotely piloting a spacecraft or when performing minimally invasive surgery using an endoscopic camera and a teleoperated robot. If these data prove reliable, researchers plan to embark on a new series of modelling and experiments to take these effects into account. From there, experiments will be conducted to see how the knowledge gained can be applied on Earth to address problems of sensorimotor deficiencies due to injury, neural disorders, or normal aging, and to demonstrate how countermeasures and better technological designs (*e.g.*, augmented reality) can counteract the disorienting effects of removing gravity as a reference for eye-hand coordination.

6.1.6. GRIP

In the GRIP experiment, researchers study the effects on the abilities of human subjects to regulate grip force when manipulating objects

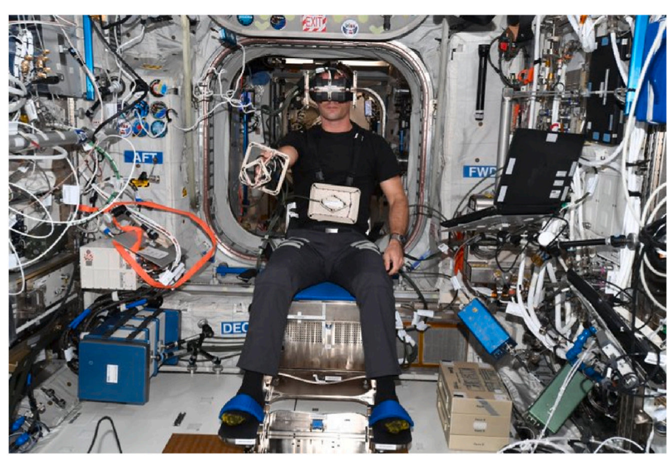

Fig. 3. During the Proxima mission, Thomas Pesquet commissioned the GRASP Hardware. Later, in his 2021 Alpha mission, Thomas became a subject in this important experiment (Credit: photo originally appeared on Thomas Pesquet's Twitter account at https://twitter.com/Thom_astro/status/1393216723218751495).

[26]. Despite decades of research in the field, many aspects of this role are still poorly understood – a knowledge gap that has profound implications for diseases that affect motor control such as cerebral palsy [27]. A better understanding of the biomechanics and motor control of dexterous manipulation is necessary to develop efficient rehabilitation methods for patients suffering from sensorimotor disabilities and to develop future haptic devices. A scientific team within the GRIP team lab has studied hand dexterity in children with cerebral palsy and is working on new bimanual intensive therapies to help improve hand function in these children [28].

By studying the grip regulation action of healthy subjects in microgravity conditions, researchers gain insight into terrestrial diseases that affect motor control. For instance, how does the brain define "up" and "down" in the absence of gravitational load when programming and controlling arm movements? Does such sensorimotor reference frame evolve during long-term exposure to microgravity? Why are aiming movements toward remembered target locations less accurate in microgravity? [29,30]. By finding answers to these questions, researchers can better understand the consequences of some sensorimotor disabilities such as vestibular loss. Furthermore, future space missions will be able to anticipate sensorimotor challenges in altered gravito-inertial environments, and develop appropriate countermeasures (*e.g.*, new tools or new training programs) to ameliorate their effects.

As GRIP is an ongoing investigation (see Fig. 4), and since knowledge of the results can influence the behaviours of subjects (and potential subjects), researchers are refraining from publishing too many details from GRIP [31] and were circumspect in their response to our request for information. Nevertheless, they report that their objectives are being met so far, both in terms of data quality and scientific output. The trends that are emerging from the data seem to corroborate some of their initial hypotheses, invalidate others and bring new, unexpected results. The preliminary findings extend current knowledge about the important role of gravity in proprioception. GRIP is also extending researcher's understanding of how the brain handles gravitational forces during object manipulation for sensorimotor coordination and weight/mass perception. Current results have confirmed a very rapid adaptation of the grip/load force coordination in microgravity, although subtle differences relative to ground were noted.

6.1.7. Immuno-2

Space flight creates stressors on humans that, in turn, modulate the immune system. The mechanism by which this occurs is still unknown,

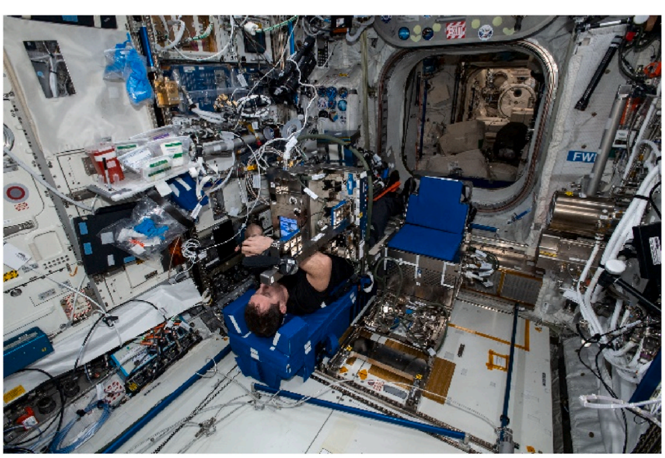

Fig. 4. On 22 May 2017 Thomas Pesquet completed the GRIP hardware commissioning. This picture comes from Pesquet's execution of GRIP during his Alpha mission in 2021 (Credit: photo originally appeared on esa. int at https://www.esa.int/ESA_Multimedia/Images/2021/05/Thomas_Pesquet_with_GRIP_experiment).

as are the long-term consequences for cosmonauts and astronauts. Most current research stems from short-term spaceflights as well as pre- and post-flight analyses. In Immuno-2, the immune function of 12 cosmonauts participating in a long-duration (>140 days) spaceflight mission was monitored pre-, post-, and on two time-points in-flight [32]. Researchers found that, while the classical markers for stress such as cortisol in saliva where not significantly altered, blood concentrations of the endocannabinoid system (ECS) were highly increased in-flight – indicating a biological stress response. Furthermore, subjects showed a significant rise in white blood cell counts: neutrophils, monocytes and B cells increased by 50% whereas NK cells (a type of immune cell that has granules with enzymes that can kill tumour cells or cells infected with a virus) dropped by nearly 60% shortly after landing. Analysis of blood smears showed that lymphocyte percentages, though unchanged pre- and post-flight were elevated in-flight [33]. Functional tests on the ground revealed stable cellular glutathione levels, unaltered baseline and stimulated reactive oxygen species release in neutrophils (a type of white blood cell that serves as the immune system's first line of defence), but an increased shedding of L-selectin (a major regulator of leukocyte adhesion, migration, and signalling) post-flight. Furthermore, a significant reduction in low regulatory T cells was observed post-flight but returned to normal levels after one month. In tandem, high in-flight levels of regulatory cytokines dropped rapidly after return to Earth. From these findings, researchers concluded that long-duration spaceflight triggered a sustained stress dependent release of endocannabinoids. This, combined with an aberrant immune activation mimicked features of people at risk for inflammation related diseases. These effects partially persisted 30 days after return to Earth. Researchers would like to expand both in-flight testing and post-flight observation periods to tackle the underlying mechanism for and consequences of these immune changes [34]. Such information could be used to develop corresponding mitigation strategies based on a personalized approach for future interplanetary space explorations.

6.1.8. Muscle Biopsy

Skeletal muscle functions are based on cellular signalling mechanisms, which undergo considerable changes due to muscle activity or inactivity on Earth. Nitric Oxide (NO) generated by NO-synthase enzyme (NOS) are unique signalling molecules mediating basic physiological muscle functions including micro-perfusion capacity, soreness, and muscle force generation capacity in a specified muscle [35,36]. Homer proteins located at the nerve-muscle interface act as postsynaptic signal proteins involved in contraction coupled intracellular calcium pathways and were also studied as indicator of postsynaptic molecular changes in muscle [37].

In the Muscle Biopsy experiment, Researchers collected muscle tissue samples from the hip vastus lateralis (VL) and the calf soleus muscle (SOL) from astronauts flying to the International Space Station before and after their mission. They did a full analysis of the tissue on both the morphological (structural) as well as on the molecular/biochemical level. Researchers are continuing to analyse and publish data, and caution that a complete analysis and reporting of results is needed. We are accordingly circumspect in what we report here. Initial observations note a change in connective tissue between cross-sectioned muscle fibres in post-flight muscle samples. Researchers also are evaluating the cross-sectional area of single myofibers in sample, and initial results suggest a variable subject-specific inflight exercise outcome (on myofiber size). Researchers have noted an increase in NOS immunosignal intensities following a long duration mission, and attribute this to inflight exercise effects [38].

6.1.9. Sarcolab-3

The study was designed to examine declines in muscular strength, function and neuromotor control during long-duration spaceflight. The knowledge gaps addressed by this study relate to the risks to human space travellers associated with in-flight changes in muscle function.

Specifically, the study sought to characterize adaptive in-flight changes in lower limb muscle strength and neuromotor control performance using the Muscle Atrophy Research and Exercise System (MARES). During Proxima, Thomas Pesquet performed three separate complex in-flight measurement protocols for Sarcolab-3 (see Fig. 5). Although the Sarcolab-3 experiment is ongoing with ground-only measurements, the in-flight portion of the experiment is complete. Key findings from the research are that reductions in thigh muscle strength and power are evident very early after exposure to microgravity, whereas reductions in calf muscle strength and power develop more slowly [39]. With very mixed time courses across different crew members, muscle function seemed more pronounced in the calf than in the thigh, with the calf muscle wasting amounting to approximately 15% after 4 days of recovery [40]. No overt effects were observed on reflexes and central nervous activation capacity. Although the small sample size does not allow proper statistical verification of its hypothesis, the science team is of the opinion that outcome-variation across crew members may be explained by exercise participation and/or responsiveness to exercise.

6.1.10. Space headaches

Headache can be a common complaint during space flights. Headache negatively affects mental and physical capacities on Earth and can consequently be expected to have negative effects on astronauts'/cosmonauts' performance during a space mission. Researchers investigated the occurrence, timing, and characteristics of headache and possible associated symptoms during long-term spaceflights in a total of 66 (healthy) astronauts, who did not have a history of regular headaches. Prospective data were collected in 24 astronauts and retrospective data from 42 astronauts were used to confirm the findings. Researchers found that episodes of headache were provoked both in the first week (in almost all astronauts) and during stay (in the majority of astronauts) throughout the spaceflight but with different symptomatology and incidence [41]. Whereas a migraine phenotype with associated nausea, vomiting, facial oedema, and nasal congestion was more prevalent in the first week, a tension-type headache phenotype predominated in the later phases of microgravity. These results improved not only the researcher's understanding of space headaches – but also their understanding of the pathophysiology of on-earth headaches, such as migraine, tension-type headache, and headache due to increased intracranial pressure. Headache intensity and the necessity for any form of treatment were similar over the course of the space flight. Occurrence of headache episodes declined, and duration of headache episodes were found to shorten with a longer stay in microgravity. These results imply that, as with space motion sickness in the first days of stay in microgravity, on average the human body is able to counteract the headache impact of microgravity during longer stays. Researchers have completed their analysis and have submitted a manuscript to the journal Lancet Neurology [42].

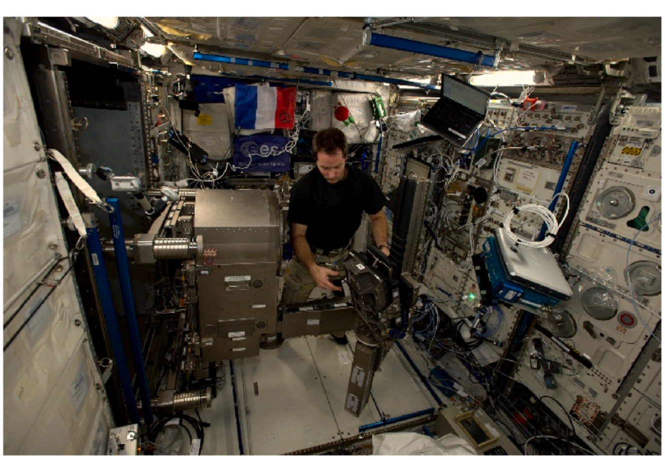

Fig. 5. On 29 November 2016 Thomas Pesquet set up the MARES rack for the Sarcolab-3 measurements (credit: photo originally appeared on esa. int at https://www.esa.int/ESA_Multimedia/Images/2016/11/Mares_machine).

6.2. Bacteriological studies

Since its construction, the International Space Station (ISS) has been inhabited by humans and also, by extension, microorganisms. There were four studies in the Proxima mission to assist in the identification, detection, and filtering of on-board contaminants, as well as the study of materials that could slow bacterial growth. The Extremophiles experiment sampled the bacteria in the extreme microbe biotope of the ISS (an environment characterized by a higher radiation impact than on Earth, low nutrient levels and unique but almost stable conditions). Here, researchers were surprised to find that ISS microbes are not more harmful than the microbes in an equivalent ground-based laboratory (as previously believed). The CNES Aquapad payload demonstrated the ability to quantify and identify bacteria harmful to human health (E. coli and Enterococcus) in ISS water samples using a simple and transportable method that can be used not only in future spaceflight, but also in water safety in developing countries or following natural disasters. The Aquamembrane II investigation tested a forward osmosis technology for filtering water, and the CNES MatISS payload tested the ability of various surfaces and coatings to resist bacterial growth. In one key finding, the team identified a particular hydrophobic surface resistant to bacterial growth that can be industrialized and therefore may be used in the construction of spacecrafts, future space stations. It may also be used in closed environments in terrestrial habitats (elevators, planes, submarines, etc.) we discuss these payloads in the following paragraphs.

6.2.1. Aquamembrane II

The Aquamembrane experiment tested a forward osmosis technology using a biomimetic membrane based on Aquaporins, water channel proteins with excellent water permeability and solute rejection. The goal of this experiment was to validate that the technology could treat ISS wastewater by confirming the feasibility of membrane filtration.

The first part of the Aquamembrane experiment was successfully performed by Andreas Mogensen during his short duration mission in September 2015. Thomas Pesquet continued testing this technology during Proxima to see if it was a viable solution for future space flight water treatment. As a result of this work, researchers could confirm that membrane filtration in space is possible. The experiment achieved both water flux (with no significant reduction in water flux compared to ground tests) and a reduction of water contaminants. This forms the foundation for future work and encouraged the team to continue to develop a prototype system for water re-use in space based on membrane filtration. This research and the follow-up projects extend the possibilities for processing water in space and thus provide another tool to make long-term exploration possible. The application for water recovery in space also inspired the researchers to further explore water reuse in extreme environments on earth (e.g., cave exploration). Based on these projects, researchers are also planning to build and test a breadboard of a water recycling system which can reuse water from urine and condensate in human spaceflight vehicles, e.g., for ISS and Lunar Gateway. As a result of this research, the team presented at two conferences [43,44].

6.2.2. CNES aquapad

The aim of the French National Centre for Space Studies CNES (Le site du Centre national d'études spatiales) Aquapad technology demonstration was to quantify and identify E. coli and Enterococcus in a 1 mL sample of water in the ISS. The Aquapad device was based on PAD (Paper Analytical Device), a patented technology that allows the bacterial growth inside a cellulosic support containing culture medium powder. Thomas Pesquet conducted four instances of water sampling and analysis: in November and December 2016, and January and March 2017. The Aquapad device showed itself able to provide a multiplex detection and quantification of two major faecal contaminants from the same water sample: Enterococcus and E. coli bacteria. The research team believes that detecting these contaminants is important for crew-health – and provides a complementary or replacement method to the Coliform detection bag currently in use on-board the ISS since the presence of Enterococcus or E. coli bacteria in the drinking water can only mean faecal contamination and would consequently signal the potential presence of pathogenic enteric bacteria or enteric viruses in water. Another advantage of the method is the potential recyclability of the filtered water going through the device. The analysed water sample could easily be recovered and recycled in the ISS which is a key feature for long duration manned space missions (e.g., to the Moon or Mars). Results from this payload were presented at the 70th International Astronautical Congress (IAC) [45]. The Aquapad technology is currently being evaluated in the Antarctica base Concordia. It also has potential application in water safety in developing countries or following natural disasters.

6.2.3. CNES MatISS 1.0

Bacteria present a significant challenge in space since they tend to accumulate in the constantly recycled atmosphere of the International Space Station (ISS). Biocontamination in manned spacecrafts and in future habitats could have substantial impacts on crew health and biodegradation of equipment. The main objective of the French National Centre for Space Studies CNES MATISS payload was to find better materials with which to construct a space station or spacecraft – particularly for longer missions farther from Earth. Researchers also monitored how bacteria form biofilms that protect them from cleaning agents and help them adhere to surfaces. During the Proxima mission, FE-5 Thomas Pesquet installed the MATISS 1.0 holders (on 21 November 2016) and subsequently retrieved the MATISS surface holders (on 01 June 2017) and packed these for return on the 49 Soyuz. The results from this research went far beyond the researchers' expectations [46]. In one key finding, the team identified a particular hydrophobic surface that can be industrialized and therefore may be used in the construction of spacecrafts and space stations – as well as in closed environments in terrestrial habitats (elevators, planes, submarines, etc.) Three types of surface hydrophobic coatings (coating on which water drops do not adhere) and an untreated surface mounted on glass were exposed to microgravity for 6 months to investigate the surface deposition of the inevitable bio-contamination emitted by the astronauts. Upon return of the samples, optical microscopy and image analysis showed a broad spectrum of particles (from large textile fibres and skin flakes to single micrometre microbial cells) on all the surfaces. On average, large particles were found to accumulate twice much on the most hydrophobic coatings, whereas fine particles tended to accumulate on the less hydrophobic tested coatings. This allows the inference that higher hydrophobicity surfaces prevented small particle contamination carried by water droplets – providing an important basis for further research. As of the writing of this report, the next generation of the MATISS experiment is still ongoing.

6.2.4. Extremophiles

The ISS represents a special and unusual microbial biotope. The facility is not influenced by any other surrounding biological environment, but only by the influx and efflux of crew members, supplies to support the crew, and technical items. Even more, the ISS can be considered an extreme biotope for microbes: the environment is characterized by a higher radiation impact than on Earth, low nutrient levels and unique but almost stable conditions (such as microgravity). In this Extremophiles investigation, sampling sessions at selected locations inside ISS were performed to analyse the presence and distribution of archaea and extremophile bacteria.

There were three Extremophiles sessions in total: two with dry sampling, and one with wet sampling. This study showed that the ISS microbial communities are highly similar to those present in ground-based confined indoor environments and are subject to fluctuations, although a core microbiome persists over time and locations [47]. The genomic and physiological features selected by ISS conditions did not appear to be directly relevant to human health, although adaptations towards biofilm formation and surface interactions were observed.

The researcher's results did not raise direct concern with respect to crew health but indicated a potential threat towards material integrity in moist areas. Other groups had previously believed that there was a higher threat from these ISS microbial communities towards human health, but the results from this research could largely defeat this hypothesis (findings that were later confirmed in research conducted by a US group). This was a major finding of this study: that ISS microbes are not more harmful than the microbes in an equivalent ground-based laboratory. This result was a surprising one as researchers expected a stronger "pressure" from the extreme environment to the microorganisms. They were also surprised to be able to detect archaea widely in many samples. Research results were reported in four academic publications.

6.3. Fluid physics

Microgravity provides a unique environment in which to study fluid dynamics. Accordingly, three fluid physics payloads were run during the Proxima mission: CNES Fluidics, Geoflow-II and SODI-DCMIX#3.

The CNES Fluidics experiment helped to improve the modelling of sloshing in satellite tanks – important since sloshing can introduce instability in satellites, affecting the accuracy of their pointing (e.g., for Earth observation). This experiment was also used to understand wave turbulences – namely the interaction of non-linear surface waves, and to observe capillary effects that would normally be invisible due to the dominant effects of gravity. As a result of this research, scientists identified a strong capillary wave turbulent behaviour unexplained by existing theories. Geoflow II observed flows in spherical geometries that were subjected to a central force field – using a medium that had a pronounced temperature dependent viscosity. This provided insights into mantle convection where temperature dependent viscosity plays a fundamental role. Viscosity contrast generated stagnant lids are an essential feature of mantle convection and are at the basis of the still not fully understood formation of plate tectonics. The DCMIX experiment successfully measured the diffusion coefficients of selected ternary mixtures taking advantage of the reduced gravity environment available aboard the ISS. We discuss these payloads in more detail in the paragraphs below.

6.3.1. CNES fluidics

Since its arrival on-board the ISS on 22 February 2017 during Thomas Pesquet's PROXIMA mission, the French National Centre for Space Studies (CNES) Fluidics experiment has been operated on a regular basis as part of ESA's ISS research complement. One major intention of this experiment was to improve the modelling of sloshing in satellite tanks – an objective with a clear and practical application. Sloshing can introduce instability in satellites, affecting the accuracy of their trajectory and their pointing (e.g., for Earth observation), and their fuel use. This purpose was met – and researcher's numerical simulations were found to be in good agreement with empirical measurements [48,49] The second purpose of this experiment was to examine and understand wave turbulences – namely the interaction of non-linear surface waves, and to observe capillary effects that would normally be invisible due to gravity. This purpose was also achieved by this research [50]. Moreover, researchers have identified a strong capillary wave turbulent behaviour currently unexplained by existing theories. These results have made it possible to continue the realization of new profiles of experiments and new tanks to validate/refine models of fluid behaviour, by obtaining rare flight data.

To date, four academic papers, four conference presentations, and three academic theses have emerged from this research.

6.3.2. Geoflow-II

GeoFlow aimed at observing flows in spherical geometries that were subjected to a central force field. Such a condition, obviously impossible to reach on ground, was achieved by simulating buoyancy driven convection through a central dielectrophoretic field in reduced gravity conditions. The sample used in the Geoflow II was unique as it studied such a flow in spherical geometries with a medium that had a pronounced temperature dependent viscosity. This topic is of high interest in mantle convection studies where temperature dependent viscosity is believed to play a fundamental role. The extremely high temperature difference across the mantle generates a variation of viscosity up to a factor 105 that deeply influences the properties of the flow in the entire domain. It particularly affects the properties of the upper boundary layer that, being very viscous, takes the form of a so-called stagnant lid, where convection is heavily depressed, and conduction becomes an important heat transport mechanism [51] Viscosity contrast generated stagnant lids are an essential feature of mantle convection and are at the basis of the still not fully explained formation of plate tectonics. The purpose of GeoFlow II was to observe the basic properties of the flow in the small viscosity contrast regime, by achieving the maximal viscosity variation allowed with the hardware limitation of the GeoFlow insert of the Fluid Science Laboratory.

The GeoFlow experiment on the ISS was designed to study convective flows in a spherical gap under microgravity conditions. The main challenge, however, was the visualization of the fluid flow especially under the safety requirements of the Columbus module. The Wollaston shearing interferometry unit of the Fluid Science Laboratory was therefore used as measurement device for temperature fluctuations. The resulting interferograms in terms of fringe patterns serviced as the basis for advanced post-processing. They were used to identify convective patterns, to track these structures, and to reconstruct the inaccessible three-dimensional temperature field [52]. A comparison between experimentally gained results and numerically calculated interferograms was also conducted – showing that convective patterns are automatically recognized and tracked accurately in experimental images by means of the generalized structure tensor. Furthermore, generic numerical simulations were used to deduce the internal temperature distribution by comparison with interferograms from the experiment. The results were enlightening for the researchers and have resulted in at least twelve academic publications following the Proxima mission.

6.3.3. SODI-DCMIX#3

The main purpose of DCMIX is the measurement of diffusion coefficients of selected ternary mixtures taking advantage of the reduced gravity environment available aboard the ISS. A combination of different and complementary techniques were used in this experiment to characterize flight candidate samples among water-based and hydrocarbon mixtures. These were used to test thermodiffusion theories and develop physical and mathematical models for the estimation of (thermo)diffusion coefficients. The DCMIX3-system (water + ethanol + triethylene glycol) is a strongly interacting hydrogen-bonding mixture that shows sign changes of the non-isothermal transport coefficients (i.e., the direction of thermodiffusion is reversed at certain compositions and/or temperatures). The team was able to achieve all its objectives for this research [53]. One key finding of the DCMIX3 campaign was the existence of sign changes of the Soret and thermodiffusion coefficients both for the binary mixtures along the boundaries and for the ternary mixtures within the Gibbs triangle [54,55]. The team was further able to prove the existence of a specific composition where all three Soret coefficients vanish simultaneously. At this very composition the mixture will not develop any concentration shift in the presence of a temperature gradient.

There were some surprising results from the research. In particular, understanding the unusual behaviour of the error bar for the Soret experiments which allow to explain the seeming discrepancy between ground and microgravity measurements. It also helped to match the results of different techniques in ground laboratories. The DCMIX project has tremendously enhanced the scientific understanding about ternary mixtures. Almost all literature that exists today about the Soret effect and thermodiffusion in ternary liquid mixtures [56] has been published in connection with the DCMIX project, which resulted in a total number of 188 academic publications and 21 PhD and other theses. Of these, 21 articles and 12 theses were published since the Proxima mission.

6. 4 Radiation physics

There were two ESA radiation payloads in the suite of ESA Proxima experiments. The first was Dosis-3D, an ongoing experiment to map the radiation environment in the ISS, and ESA Active Dosimeter, a technology demonstration that showed the feasibility of active crew personal dosimetry.

6.4.1. DOSIS-3D

International Space Station crewmembers are continually exposed to varying levels of radiation which can be harmful to their health. The main objective of the DOSIS 3D experiment is determining the absorbed dose and the dose equivalent using a variety of active and passive radiation detector devices distributed throughout the ISS [57]. This experiment is state of the art for two reasons: first, that the detectors are, in themselves, state of the art. Second, that researchers are comparing the data measured with new developments in the field of radiation detectors as developed for ISS applications. The experiment is still ongoing – and DOSIS 3D is extended up to the end of the lifetime of the ISS. In addition to performing an installation and de-installation of passive dosimeter packages (PDPs) during his mission, Pesquet also worked on the Google Street View application for the ISS. Using this application DLR together with ThinkSpace was able to generate something researchers called the “DOSIS 3D Data Viewer” [58]: a Google Street View application married with radiation data aboard the ISS allowing the viewer to acquire a graphical representation of the evolution of on-board radiation doses over time.

6.4.2. ESA Active Dosimeter

For the ESA Active Dosimeter (EAD) project an active (powered) dosimeter system was developed and manufactured especially for this ISS demonstration. This was to measure the European astronaut’s radiation exposure, to support risk assessment and to enable dose management by providing a differentiated data set. The hardware consisted of several small portable “Personal Active Dosimeters” (MU = Mobile Unit′s) and a “Personal Storage Device (PSD) for MU storage, data read out and telemetry. The PSD furthermore contained a “Tissue Equivalent Proportional Counter” (TEPC) and an “internal MU” (iMU) to enable complex environmental measurements and cross calibrations. The final goal of this payload was the verification of the system capabilities for medical monitoring at the highest standards. This technology demonstration showed that active crew personal dosimetry was feasible – even within tight budgetary limits. In addition, stationary plus mobile environmental surveillance of ionizing radiation could also be realized and provided a great deal of flexibility. The ESA Active Dosimetry System development provided a basis for another suite of active, and independent, small sized dosimeters anticipated to follow soon on the Artemis 1 Mission. Moreover, the European Active Dosimetry Systems development led to an ESA patent [59].

6.5. Robotics

The Proxima mission not only contributed to scientific knowledge, but also gave practical information about Telerobotics through the Haptics-2 investigation. Telerobotics have terrestrial use in delicate, remote, and/or dangerous work. Future manned missions to the moon and Mars will likely rely on remotely controlled robots to conduct necessary surface activities, thereby gaining mission efficiency and minimizing risk to crew.

6.5.1. Haptics-2

In the Haptics-2 robotics protocol, the human operator (Thomas Pesquet) operated a force-feedback joystick, fulfilling a small set of technical tasks remotely with a single degree-of-freedom robotic joint on ground (see Fig. 6). These tasks included a balancing and contact task with a remote slave, and a remote Space-to-Ground personal handshake. This was the first time that Haptic remote operation from an astronaut in microgravity had ever been performed. This therefore pushed the state of the art – both in terms of the sense of haptics and teleoperation from space to ground. Haptics-2 showed the feasibility that astronauts in micro-gravity environments connected to robots via lossy satellite links can perform manipulation tasks with haptic feedback. This haptic feedback allows for more manipulation options than remote operation without it. This is also relevant for all remote robotics operations on earth like inspection robotics, rescue robotics, bomb disposal robotics underwater or remote surgery where there are similar lossy connections be it via satellite 5G or less [60]. Haptics-2 laid the groundwork for future space-based robotics, allowing researchers to push the envelope further than ever before. Understanding gleaned from Haptics-2 was critical for follow-on experiments like Kontur 2 and ANALOG-1. ANALOG-1 included a new 7-degree of freedom device to control a robot to pick up geological samples from the ISS. Here the insights, experiences and result from Haptics-2 served as a critical foundation. Currently, the researchers are working with DLR and Samantha Cristoforetti and Jessica Watkins on a complex follow-up experiment during Increment 67 called “Surface Avatar”. ESA’s robotics capabilities are anticipated to have many practical applications in human spaceflight, as well as in lunar and space exploration.

6.6. Environmental science

There were four environmental science payloads conducted during this mission including two important long-running ESA environmental monitoring payloads that reached their conclusion during Proxima: SOLAR (observations of long-term solar radiation) and Vessel-ID (space based maritime vessel tracking). The other two payloads were technology demonstrations: Magvector measured the earth’s magnetic field and WiSe-Net established a way to measure environmental conditions aboard the ISS. We discuss these payloads in the following paragraphs.

6.6.1. DLR magvector

The German Aerospace Centre (Deutsches Zentrum für Luft-und Raumfahrt, DLR) Magvector experiment qualitatively investigated the interaction between a moving magnetic field (of Earth origin) and a very good electrical conductor. Using highly sensitive magnetic sensors, Magvector detected the change of the field strengths to simultaneously measure the magnetic field on the Ram and Wake side of the electrical conductor. In total, nine Magvector science runs were conducted. On 23 March 2017, the final run was complete and FE-5 Thomas Pesquet closed out the experiment. Researchers reported that their technical goals for this payload were achieved, but that the data uncovered a lot of new questions. Moreover, data evaluation was also more complex than originally anticipated. To process and understand the results, it became necessary to include more scientists. Science institutions like Max Planck Gesellschaft are currently evaluating parts of the resulting data and building models on open questions. Data evaluation from payload is still ongoing. As of the date of this report, two poster sessions on MAGVECTOR have been presented, but no academic publications.

Fig. 6. Thomas Pesquet performing the Haptics-2 protocols on 21 February 2017 (Credit: photo originally appeared on https://www.flickr.com/photos/thom_astro/32490413962).

6.6.2. DLR WiSe-Net

The German Aerospace Centre, DLR, conducted the Wireless Sensor Network (WiSe-Net) experiment on-board the ISS as a technology demonstration to develop reliable miniature sensors to take precise measurements of the ISS – an important technology for monitoring the environmental conditions inside the station. WiSe-Net consisted of a network of four sensors the size of MP3 players. These ‘motes’ collected data round-the-clock, giving precise information of the environmental conditions in the Columbus Laboratory including temperature, humidity, air pressure and light intensity. They then used wireless connections to transmit the readings to a base station. The system provided statistics on the quality of the wireless network and the results exceeded the researchers’ expectations. The team had expected data loss – but no data loss occurred. The team also reported to ESA that it would be possible to obtain energy from the environment in Columbus, removing the need for batteries in future iterations of such technology. As of the writing of this paper, we have no academic publications/presentations of these data.

6.6.3. SOLAR

SOLAR was a solar observatory aboard the ISS, located on the zenith external platform of the Columbus module. It was launched with Columbus on 7 February 2008. The mission was planned for 18 months – but after the initial success of the payload, the mission was extended – for a total of nearly nine years. The SOLAR payload accommodated two solar science Instruments (SolACES and SOLSPEC) onto one Columbus External Payload Adapter (CEPA) [61]. To support sun observation, the SOLAR Instruments needed to maintain directionality towards the sun - a function that was achieved by the means of a unique dedicated pointing device (the Course Pointing Device, CPD). The SOLACES payload examined solar rotation, measuring the EUV/UV solar spectral irradiance between 15 nm and 220 nm [62]. In the first 18 months of the payload, measurements were taken while the Sun was in quiet condition with just a few active regions (sunspots and facula). Their effect was generally manifested by a quasi-periodical modulation of the spectral irradiance as the Sun rotates in 27 days, having an amplitude depending on the mean solar activity level. These effects are important for solar physics, atmosphere, and climate physics as inputs to the corresponding models – as well as for space meteorology. After almost 9 years of duty, on 13-February 2017, during the Proxima mission, the SOLAR mission reached its end, and Thomas Pesquet helped to decommission the payload. Some of the key findings of this investigation were: Absolute EUV spectral data was used in applied solar-terrestrial physics, (e.g., in ionosphere-thermosphere modelling, correction of GPS data, quantification of surface changes due to interaction with energetic solar EUV photons that cause degradation and effectivity changes in optical and other space instruments, predicting changes in satellite orbit, and evaluation of materials for long-term operation in space.) There were some surprising results from this research. In the EUV spectral range, the solar activity minimum between the 23rd and 24th solar cycle was extended by one year compared to the previous solar minimums [62]. The absolute EUV solar minimum did not coincide with the classical minimum. The solar cycle 24 showed two maxima with significantly lower EUV spectral irradiance, resulting in lower thermospheric and ionospheric densities and temperatures. As a result of the findings from this research the science team was able to propose follow-on science – particularly a climate satellite mission with space-evaluated spectrometers, photometers, radiometers and bolometers based on the SolACES method. In addition to determining the annual changes in the total and spectrally resolved local Earth energy imbalance (which affect global warming or cooling) the measurements should also aim to determine a global and local Pro Climate Ratio to provide tools for better climate prediction and its dramatic consequences for life on Earth.

As of the writing of this paper, we record 77 total publications resulting from the SOLACES/SOLSPEC payload, 21 of which emerged following the Proxima mission.

6.6.4. Vessel-ID

Automatic Identification System (AIS) is a system transmitting information about vessel identity, position, heading, nature of cargo, destination etc. on dedicated frequencies in the maritime VHF band. AIS was originally designed to work at ranges of maximum 40–50 nautical miles to support collision avoidance and port traffic management. When Vessel-ID was initiated in 2006, it wasn't clear whether space-based AIS would be viable. A clear picture of global spectrum use at the designated AIS-frequencies wasn't well documented, and there was a high likelihood of terrestrial interference particularly in areas of high ship volume.

The aim of the Vessel-ID System experiment was to collect AIS data from Low Earth Orbit and to perform measurements of the VHF signal environment in the maritime VHF frequency band [63]. On-board work and EVA installation of the VESSEL ID System (Space-based AIS on COLUMBUS) began on 21-May 2010 with Increment 23–24 and the payload was decommissioned on 25 October 2019 during Increment 61–62.

Vessel ID was not only a demonstration of technology, but a capability demonstration and development platform as well, facilitating ship tracking, ship traffic studies, studies of signals and equipment development. These data enabled the team to support satellite AIS designs - including assumptions about the effects of interference and large numbers of ships within the sensor horizon and improving global vessel traffic maps [64]. Moreover, the experimentation in the Vessel ID project and cross-comparison with as the Novel SAT-AIS receiver development helped document ionospheric effects, in particular Faraday rotation. This helped in the development of SAT-AIS systems for ESA, Norway, and other missions [65]. This research also inspired investigation into AIS data quality parameters. Data and analysis of Vessel ID supported work in the International Telecommunication Union (ITU) and International Maritime Organization (IMO) to allocate two additional AIS frequencies, as well as an additional message type suitable for space-based AIS reception. These resulted in significant improvements in measuring high traffic density areas such as the Baltic, the North Sea, and the Mediterranean, as well as the Gulf of Mexico, Straits of Malacca, and the South China Sea. Data and Analysis from Vessel ID has also supported development of a tool to geo-locate AIS-transceivers using Doppler and time difference of arrival.

There are multiple anecdotes about the specific real-world practical use of the Vessel-ID data including assistance in rescue and recovery efforts following the Great East Japan Earthquake on 11 March 2011 and the subsequent damage to the reactors at the Fukushima Nuclear Power Plant, assistance in crime fighting in West African territorial waters, and successful search and rescue operations support on 25 January 2012 when the fishing vessel Hallgrimur sank in the Norwegian Sea.

6.7. Material science

ESA's material science research has shown prolific outcomes deserving of a more extensive review than this paper can allow. For example, the Electromagnetic Levitator (EML) is a long-running payload hosting the study of many experiments and hundreds of samples. Similarly, the results from the Material Science Laboratory (MSL) have provided outstanding scientific and industrial value as they allow the study of microstructure features of materials during the solidification process – such as in casting, welding, soldering and additive manufacturing. The initial cast structure plays a deterministic role in chemical and structural distribution in the material. Material properties are highly dependent on these distributions as well as the microstructure features of the material.

As with EML and MSL, PK-4 is its own unique laboratory. PK-4 facilitates state of the art research in the field of complex plasmas. Finally, in the field of material science, the DCMIX project looked at diffusion coefficients in binary and ternary mixtures.

Due to the ongoing, comprehensive, high-throughput nature of these payloads, these Material Science experiments are perhaps the most prolific in terms of producing new physical insight, publications, and facilitating further academic research. However, they also present the most difficulty in mapping outcomes to the mission of a particular astronaut. We look at these in the following paragraphs.

6.7.1. EML

The electromagnetic levitator (EML) is a facility that allows the container-less processing of materials in space. Suspended in an electromagnetic field generated by a solenoidal coil, metal alloy samples can undergo melting and solidification under ultra-high vacuum and/or high gas purity conditions. The EML supports research in the field of meta-stable states and phases and in the field of measurement of high-accurate thermophysical properties of liquid metallic alloys at high temperatures. During the Proxima mission, astronaut Thomas Pesquet conducted installation of the Sample Coupling Electronics (SCE) into the EML Experiment Module, thereby substantially enhancing the capabilities of the EML facility. The SCE was new device for the inductive measurement of electrical resistivity and density of liquid metals and semiconductors. This enabled the measurement of electrical conductivity and sample radius (from which sample density and thermal expansion can be derived). The SCE has been in frequent use for various samples and investigations since its installation. During the Proxima mission, EML Batch 1.2c science was also completed and the EML Batch 2.1 Science campaign was initiated [66]. Among these experiments were the THERMOLAB sample Ti6Al4V. This is the most common titanium alloy: light, strong and corrosion resistant. It is used for a variety of applications that include aerospace components, biomedical implants and surgical tools, sports gear (like bicycle frames), but also for architecture (e.g., Guggenheim Museum Bilbao) and jewellery (watch casings). The thermophysical property data obtained from the experiments serve as input data for computer models that are used to predict and optimize manufacturing processes (casting) for such components. Another sample conducted during this time was ICOPROSOL sample Ti39·5Zr39·5Ni21. This is a model alloy that is of scientific relevance as it is a quasi-crystal forming liquid. The data gained from these experiments were also used to validate a new model for crystal nucleation. Although we cannot directly attribute specific EML research results with the Proxima mission (and therefore do not include these in the Proxima mission statistics), we note that EML research completed during the lifetime of the instrument has resulted in 236 Journal publications, 71 conference papers, 24 book chapters, and 8 PhD and other theses.

6.7.2. MSL

Solidification takes place in industrial applications – including casting, welding, soldering, and additive manufacturing. The initial cast structure plays a deterministic role in chemical and morphological distribution in the material. Material properties are highly dependent on these distributions as well as the microstructure features. If microstructure evolution dynamics under various experimental conditions are known, material properties can be optimized, superior materials - and hence engineering components that will function at extreme conditions - can be designed. Such modelling and optimization relies on the empirical investigation of microstructure evolution during solidification. On Earth, this solidification is affected by convection. Therefore, microgravity (space based) solidification studies are needed to reveal the fundamentals of these process in three-dimensional (3D) samples, and to examine the direct effect of experimental parameters on microstructure selection. Data are used to validate existing models and to provide experimental references. This was the motivation of the SETA experiments performed in microgravity conditions aboard the ISS [67,68]. During the Proxima mission, the crew conducted multiple exchanges of MSL Batch 2b SETA cartridges. Shortly after the completion of Proxima, the remainder of all SETA Cartridge Assembly (SCA) samples on-board were fully processed in MSL. All data were analysed alongside analogous experiments performed under terrestrial conditions. Such a comparison made it possible to optimize sample dimensions and growth profiles. This effort is anticipated to result in designing materials with specified microstructures to produce industrial components with desired and optimized material properties. There are at least four academic articles and one presentation associated with MSL Batch 2 SETA following the Proxima Mission [67–71].

Researchers are still conducting ground analysis on the samples retrieved during the Proxima mission and we expect that results will be forthcoming.

6.7.3. PK-4

Complex plasmas consist of micrometre-sized particles embedded in ionized gas. These systems, evolving from the 1994 discovery of crystalline structures in laboratory plasmas [68], make up a new form of soft matter. Under some conditions, complex plasmas can also be regarded as classical model systems of fluids and solids and offer insights into the dynamics of these systems on the individual particle level with the microparticles in complex plasmas acting as proxy atoms. Complex plasmas thus provide a new experimental approach for fundamental studies of strong coupling phenomena. In nature as well as in man-made plasmas dust can appear naturally, forming so called “dusty plasmas”. The study of complex plasmas is a very broad field of interdisciplinary research. The PK-4 project is a joint European-Russian collaboration – and PK-4 is a successor of the PK-3 “Nefedov” and PK-3 Plus space experiments [72]. Scientists from Europe, Russia and other nations worldwide benefit from this project – participating in experiments, analysing the resulting data, and contributing to theoretical and numerical modelling. PK-4 [73] was launched to the ISS in November 2014, with hardware commissioning in June 2015. The first science campaign of PK-4 was then performed in October 2015. During the Proxima mission, a science campaign for PK-4 was conducted. As part of a joint agreement, these runs were conducted by the Russian crew who performed three science runs on 14 February 2017.

PK-4 a project in fundamental physics, so the aim in not necessarily to produce direct terrestrial or space applications – however, some of the key PK-4 findings are: charging or de-charging properties of microparticles in plasma [74], accurate measurement of the ion drag force or the agglomeration of positively and negatively charged microparticles, a better understanding of processes from fluid and solid state physics like crystallization and melting of 3-dimensional complex plasmas, the discovery of string formation in electrorheological plasmas, investigation of wave and shock wave propagation in liquid systems, and of lane formation and phase separation in binary mixtures consisting of two different particle sizes [75,76].

One of the highlights of the research with PK-4 concerns the investigation of the phase transition from an isotropic fluid to a so-called string fluid. This phenomenon is similar to what is observed in electrorheological fluids – however, it was not expected in DC complex plasmas. Researchers report eighteen academic publications and conference proceedings subsequent to the Proxima mission.

6.8. Human spaceflight enablers

Technology demonstrators on the ISS are often designed to address specific operational issues in current missions. There were three such payloads during the Proxima mission: CNES Echo, CNES Everywear, and Skinsuit. We discuss these in the following paragraphs.

6.8.1. CNES Echo

The CNES Echo Unit is a high-performance medical imaging ultrasound device that uses ultrahigh frequency acoustic energy waves to visualize anatomical structures in the human body. Specialized signal processing and analysis software provides advanced interpretation of acoustic echoes leading to estimates of tissue motion, fluid flow rates, tissue deformation, cardiac synchronization, and volumetric quantities. The Echo project aimed to demonstrate ergonomic functionality, acquisition of high-quality ultrasound imaging data and remote guidance capability with motorized probes operated by an expert from ground, thus saving training and on orbit crew time and optimizing science results. The goal of the Echo commissioning objective was to demonstrate a new tele-operated ultrasound technology using ISS Multi-Purpose Computer & Communications (MPCC) during the Proxima Mission. The long-term objective was to integrate the Echo hardware into related on-board activities, such as the Canadian Space Agency’s Vascular Echo experiment. Although there are no identified publications associated with this payload, we hereby confirm that this technology is used as intended aboard the ISS.

6.8.2. CNES Everywear

The CNES assistant was an ambulatory data collection system making use of wearable sensors connected to a station iPad, and then wirelessly synchronized with ground. This was intended to demonstrate extensive physiology data collection for both science and medical follow-up purpose by improving usability for the astronauts.

All Everywear functions were embedded inside a dedicated custom iPad application, the Everywear application, and experiment hardware consisted of the following: a station iPad (provided by NASA), a biometric smartshirt, a biometric patch, a self-applied tonometer sensor. The main goals of this first uses were to provide medical support for nutritional assessment, medical logging, and exercise monitoring (via the biometric smartshirt). During Proxima, Pesquet commissioned this payload, and the data was downlinked an analysed by ground teams (due to privacy concerns, these results are not published). Moreover, he used Everywear for nutritional assessment almost daily during both his Proxima and Alpha missions. The Everywear tool was subsequently adopted by ESA for all ESA crewmembers. Everywear is now an operational tool, supporting MedOPS and more than a dozen science objectives [77,78].

6.8.3. SkinSuit

The SkinSuit countermeasure technology was designed to increase the axial load gradually from the shoulders to the feet, thereby reproducing the regime normally imparted by gravity. This may be compared to the Russian Pingvin Suit [79], which imposes two stages of vertical loading via rubber chords and a leather belt. The bi-directional elastic fibres of the SkinSuit create a loading regime of hundreds of stages, producing a simulation of gravity. During his Proxima mission, Thomas Pesquet performed a total of six days of SkinSuit activities – in clusters of two consecutive days at a time: on 2-3 Feb, 29-30 April, 13-14 May. In ground based analog testing, researchers found some evidence that the technology was effective in reducing spinal elongation [80], however the axial load provided by the SkinSuit on-board the ISS was not measured. Instead, operational aspects of the suit were assessed – specifically hygiene and microbiology, comfort, thermoregulation, donning/doffing, impingement, and range of motion. There were three academic articles and one thesis [81] associated with the execution of this payload.

6.9. Educational payloads

In addition to the fundamental science and technology research, many educational activities were conducted by Thomas Pesquet during the Proxima mission as part of the Educational Payload Operations (EPO). The EPO demonstration activities are considered an essential aspect of educational ground activities as they encourage and strengthen the teaching of science curriculum, thereby stimulating student curiosity and motivation to continue studying science, technology, education, and math (STEM). The Proxima mission educational payloads were initially used by 2000 classrooms - growing to 10,000 in the time since. To date, the ESA EPO office records more than 100,000 participants of the EPO activities. The EPO Mission X and AstroPi have developed in ESA Education School Projects which are run on an annual basis during the school year. Each project continues to grow and develop with the support and help of the ESA ESERO network across the ESA Member States.

6.9.1. EPO Astro-Pi 2.0

The primary goal of this education payload is engaging European students, raising their skill levels, and stimulating their interest in pursuing science, technology, engineering, and math (STEM) subjects. Two Astro Pi computers were originally launched with Tim Peake for a standalone activity [82]. At the conclusion of Peake's Principia mission, ESA was offered ownership of the payload and initiated an expanded European Astro Pi Challenge with the Proxima mission. The basic elements from this Astro-Pi 2.0 formed the basis of the Astro-Pi challenge as it is today – an ever growing, expanding, and improving educational opportunity [83]. During the Proxima mission in 2016/17 there were approximately 1800 participants with 64 teams achieving flight status, in 2020/21 (Alpha mission) this number expanded to over 14,000 participants, with 232 teams achieving flight status (plus another 6000 teams achieving flight status with the activity Mission Zero). 350 teams participated in phase one of the AstroPi payload – developing experiment ideas. Of these, 249 were selected and received Astro Pi classroom kits. The second phase involved the writing of programs. There were 195 entries with 45 winners, and 19 highly commended teams selected to fly on ISS. Each year Astro Pi reaches approximately 15K students with Mission Zero and upward of 4K with Mission Space Lab.

6.9.2. EPO pesquet

The EPO experiments conducted by Thomas as part of EPO Pesquet enjoyed high participation in the targeted student communities and was noted to be one of the highest participation years to date. The Proxima mission Exo-ISS demonstrations (CrISStal, CERES, CatalISS) were followed by almost 2000 classes in France and in Europe and, in many instances, students duplicated the Exo-ISS activities on ground. There is a Facebook group of participating teachers with approximately 10,000 members. Similarly, the related education Mission eXplore logged more than 100,000 worldwide participants. The writing contest conducted as part of EPO Pesquet garnered approximately 250 submissions, with three winners selected (1 photo, 1 writing, 1 drawing). Several of the materials and activities developed by CNES as part of the Proxima mission are still available for educational use today.

6.10. Results by the numbers

A standard metric for quantifying the impact of a given program, project, or effort, is the number of academic articles, presentations, and theses that have resulted. To provide perspective on the outcomes we're reported on the Proxima mission, therefore, we summarize the numbers of publications we believe to be associated. We herein define publications as articles in peer-reviewed journals, conference presentations, and theses at the bachelor, masters, and PhD levels. These are listed in Table 3. In addition to the number of academic publications, we also provide a count of the number of distinct websites (e.g., news stories, videos, etc) resulting from each payload. This can sometimes be a good indicator for payload impact for education payloads whose intended audience is not the same as for science payloads.

Table 3
Results Publication count resulting from Proxima Utilization activities.

Payload	Publication count	News/online count
Aquamembrane	2	
Brain-DTI	5	
Cartilage	14	
CNES Aquapad	1	
CNES Echo	N/A	
CNES Everywear	3	
CNES Fluidics	8	
CNES Matiss 1.0	6	
DLR Magvector	2	
DLR Wisenet	N/A	
DOSIS-3D	4	
EDOS-2	7	
EML	176 EML articles/presentations/theses since 2017	
Energy	1	
EPO Astro-Pi 2.0	2	19
EPO Pesquet	N/A	42
EPO Task List		
ESA Active Dosimeter	N/A	
Extremophiles	2	
Geoflow II	12	
GRASP	2	
GRIP	4	
Haptics-2/Interact	N/A	
Immuno-2	5	
MSL Batch 2b SETA	5	
Muscle Biopsy	11	
PK-4 (R) Science Campaign	10	1
Sarcolab-3	8	
Skinsuit	4	
SODI-DCMIX #3	32 SODI-DCMIX articles/presentations/theses since 2017	
Solar SOLSPEC	21 since 2017	
Solar SOLACES		
Space Headaches	2	
Vessel ID System	3	8

While these metrics can give some insight into the academic reach and impact of the research, we acknowledge that there are some caveats with this method. The first regards completeness since we cannot guarantee that this list encompasses all existing documentation. Moreover, we expect publications on this research to continue following the release of this paper. Therefore, we consider this value to be a lower limit. The second caveat regards strength of association. Simply because an academic article was published following the Proxima mission does not mean that the published research was a direct result of the Proxima mission activities (nor the Proxima mission activities in isolation). This is particularly difficult to compute for a payload where the preceding years of operations were precursors to the Proxima activities, and where such work has resulted in a proliferation of subsequent publications – not all of them associated with the mission. We've done our best to filter and select for publications that directly resulted from Proxima. For this reason (for example) we do not include the EML publication count in the total tally. A similar issue exists for payloads with a similar profile as EML – such as PK-4 and SODI-DCMIX and SOLAR, and the number of publications in those categories should be viewed through this lens.

With the caveats in mind (and removing the EML papers from the total count), we look at the resultant metrics (see Fig. 7). In the period following the Proxima mission, there were more than 70 internet articles/media, and at least 158 academic publications (articles, conference presentations, and theses) associated with the Proxima mission payloads. Of these, human research payloads resulted in the largest number of publications (53), followed by Fluid physics (44), Technology Demonstrations (29), Environmental Science/Radiation Physics (25), Material Science (15), Biology (2), and Education (2). These can be viewed in Fig. 7. EML payloads form their own special category with 175 publications since 2017 – although not all of these can be directly associated

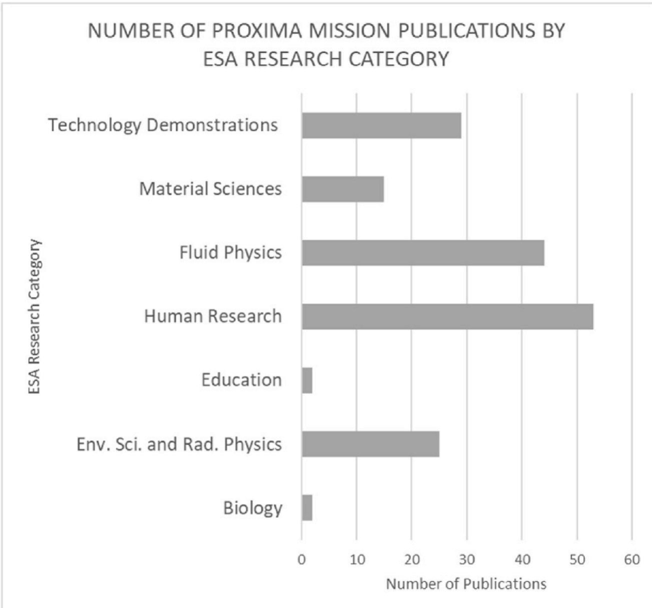

Fig. 7. Number of academic publications (articles, presentations, and theses).

with the Proxima mission. These metrics, caveated though they are, provide a glimpse into the impact of this mission.

7. Lessons Learned

To date, there is little consistency in how research results from the research conducted during ESA human spaceflight mission results are tracked and recorded. While there are requirements for 30-day and 1-year accomplishment reports associated with all ESA SciSpacE activities, we can see from this paper that such a timeframe is insufficient to capture the scope and depth of LEO based research. The program would strongly benefit from routine collection, analysis, and reporting of research results. Furthermore, this work highlights the need for an analytical rubric for assessing strategic return-on-investment within the European Space agency's Human Spaceflight program. The data presented in this report would no doubt have greater value when used as consistently collected metrics within such a framework.

8. Conclusions

Research aboard on the ISS is conducted under extreme conditions and challenging constraints. Nevertheless, in the years since its inception, science and technology demonstrations in LEO has become routine - establishing a robust baseline for future space-based research programs.

This paper reviewed the research conducted during Thomas Pesquet's Proxima mission. Open ended questionnaires were submitted to the relevant PIs, and their answers were synthesized along with a review of their academic literature to create this paper. The diversity of experiments, technology demonstration, and educational outreach activities conducted during this time has led to a growing body of scientific publications.

The objective of this review of accomplishments was to derive an understanding of tangible results and operational impact of ESA ISS research. This is intended to contribute to the characterization and valuation of ESA's human spaceflight program and thereby to assist in future investment decisions.

The presence of a long-duration high-capability laboratory in microgravity facilitates experiments that would otherwise be infeasible. This review should make clear that, even within a limited window of an ESA astronaut mission, even some of the simplest physical experiments on ISS are leading to impressive results – many with relevant terrestrial applications.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas Pesquet is an Astronaut for the European Space Agency. Elizabeth Heider is an employee of Space Applications Services N.V., working for the European Space Agency in a service contract. Dr. Heider also owns a Dutch Consulting business, Cap-Geo ZZP.

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