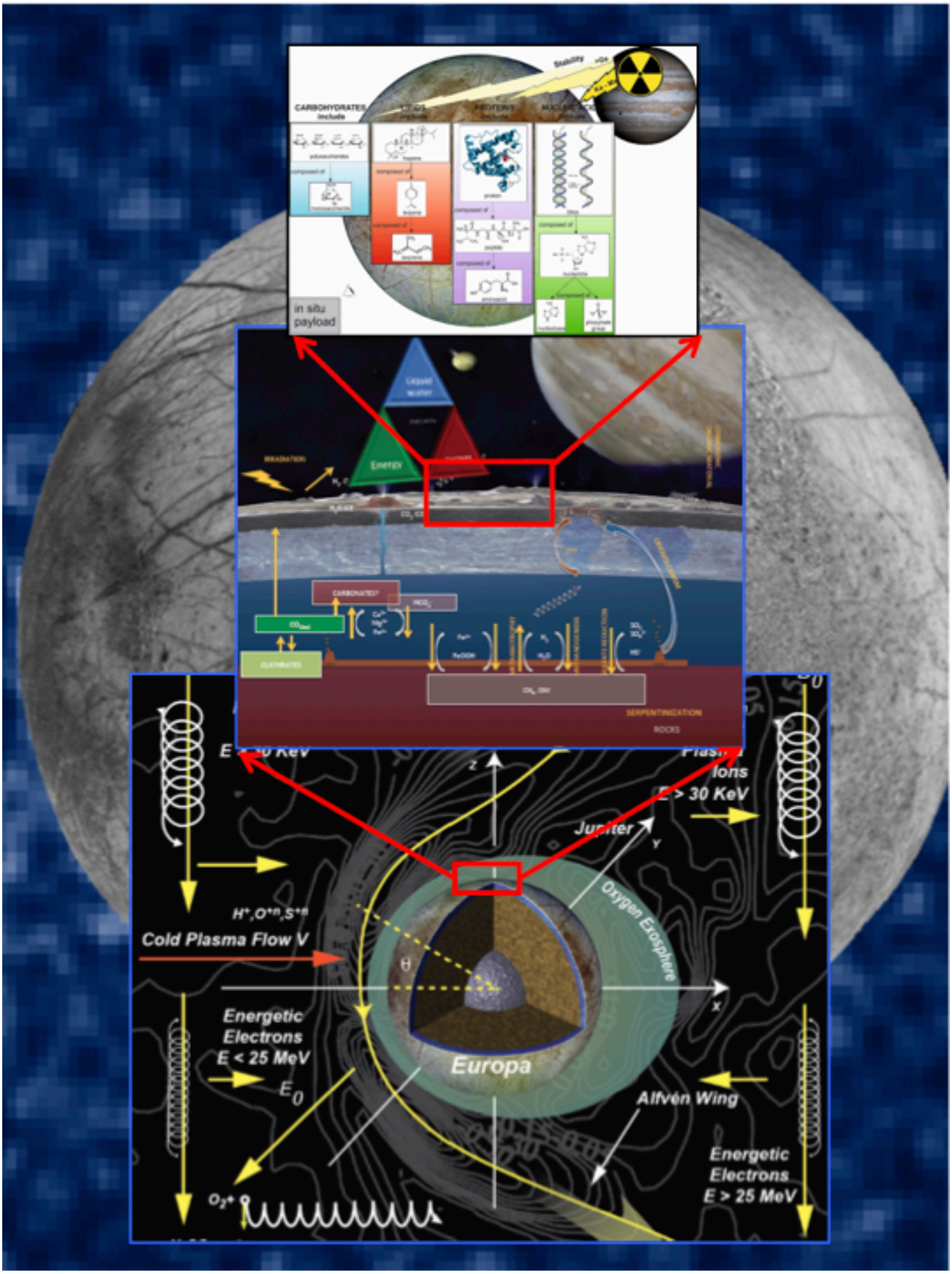
Joint Europa Mission (JEM)

A MULTISCALE, MULTI-PLATFORM MISSION
TO CHARACTERIZE EUROPA'S HABITABILITY AND SEARCH FOR EXTANT LIFE



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Cover figure legend: *This logical chart of our Science Plan shows the three successive scales investigated by JEM, from bottom upwards: (1) the global Europa, a complex system responding to the two main types of Jovian forcing, tidal forcing and magnetospheric forcing; (2) the scale of Europa's potential biosphere (median figure), at which we will more particularly characterize the ocean and ice sheet and (3) finally the local scale at which we will perform life detection experiments.*

The JEM science plan successively articulates five priority science objectives, culminating with the search for biosignatures of life at the surface, sub-surface and eventually in the exosphere, to reach its Overarching Goal.

Abstract: Europa, together with Enceladus, is the best possible destination to search for and possibly find life in the outer solar system. Strong indications that Europa may indeed be inhabited come from recent key discoveries: the Galileo discovery of a sub-surface ocean in contact with a silicate floor that could be a source of the key chemical species for biomolecules, the many indications that the icy crust is active and may be partly permeable to the transfer of materials, including elementary forms of life, and the identification of candidate thermal and chemical energy sources necessary to drive a metabolic activity. To understand how the Europa system works and whether it may have developed a biosphere under the effect of its proper evolution and of forcing by the other components of the Jupiter System we need to design and fly to this Ocean World a multi-scale, multi-platform, interdisciplinary mission that will perform combined orbiter and lander science investigations. Here we summarize the science and technology strategy of this proposed Joint Europa Mission (JEM), based on the NASA lander concept and on a novel ESA-designed platform which will carry and deliver the lander to its destination, relay its data back to Earth and will finally reach a low-altitude near-polar Europan orbit to perform orbital science operations for about three months. While the orbiter will perform an in-depth investigation of Europa's geophysics, ocean and habitability, investigations by the Europa lander will be focused on the search for bio-signatures in solid and liquid samples. The impacts of planetary fields, of plasma, neutrals and dust environment, and of Europa's internal structure on its habitability will be characterized from the orbital survey and during the final descent phase.

1. **Introduction.**

Finding traces of extant life beyond Earth in the Solar System would be a huge accomplishment showing us that the dominant paradigm of the origin of life (de Duve 1995) is correct: rather than being the result of a "one-off", freak process, life (biology) would be shown to be a simple continuum process taking advantage of every favorable condition (the so-called "habitability") to make progress towards ever increasing chemical complexity. To really understand life, we must relate its discovery to the habitability of its host planet (or satellite) and, moving backward in time, relate this habitability to the processes that have favored its emergence and preservation in its host planetary system.

Astrobiologists agree today that the conditions for habitability are directly related to the definition of life we can formulate on the basis of the only model of life we know, namely terrestrial life. From this standpoint, habitable environments must meet three basic requirements symbolically represented by the "Triangle of Habitability" (cf. Westall and Brack, 2018; Westall et al., 2018): 1). The presence of liquid water, which is the best solvent known for inorganic and many small organic substances. The H_2O molecule has unique properties that are specifically useful for life, e.g. latent heat due to the chemical bonds, potential for high salt content due to its density, broad range of temperature and pressure stability, etc. 2) The availability of life-essential chemical elements, such as H, N, C, O, S, P, as well as transition metals that help provide structure to the biomolecules and provide nutrients to the organisms. Transition metals are made available through the dissolution of the minerals. 3) Energy sources available for life to maintain metabolism. In the absence of light, energy accessible for life is usually provided by chemical disequilibria sourced either by radiation, reactions activated by temperature, or by redox reactions. An additional key dimension to planetary habitability is time. We do not know how quickly life appeared on Earth. The process must have been sufficiently fast at the beginning to impede backward reaction, but the emergence of forms of increasing complexity likely needed longer time scales, thus implying the maintenance of habitability conditions over very long times.

Based on these considerations, Lammer et al. (2009) explored the variety of known configurations of planets and satellites to derive four classes of 'habitable worlds", or Habitats, as being the ones that meet partly the habitability conditions. Classes I and II relate to our terrestrial planets, and to the presence of liquid water at their surface. Classes III and IV correspond to objects where liquid water can be found, not at the surface, but in sub-surface oceans, which are found among the icy satellites of Jupiter and Saturn: they are the "Ocean worlds". Among them, Europa stands out as one of the most promising destinations, and certainly the most promising one in the Jupiter System. To understand why, let us first examine how the coupling of Europa to the Jupiter system may have maintained it "inside the triangle of habitability".

1.1 Europa as a "Complex System" responding to Jupiter system forcing.

What we know of the Galilean moons today is essentially the legacy of the exploration of the Jupiter System by the Galileo mission. First, we recognize three likely "ocean worlds": Europa, Ganymede and Callisto, whose sub-surface oceans, if confirmed, meet the first and most important condition for habitability. If we then turn to their internal structure, the two innermost moons, Io and Europa, are essentially "rocky moons". Thus, Europa's possible ocean must be in direct contact with the thick silicate mantle, which occupies most of its volume. A third important characteristic is that Io, Europa and Ganymede are trapped in a 4:2:1 mean motion resonance, the so-called "Laplace resonance", which provides them with a continuous source of internal heating due to the dissipation of tidal motions. Finally, both Io and Europa are recognized as "active moons". While this is straightforward for volcanic Io, the permanent resurfacing processes of Europa's terrains also places it in this category. The recent repeated, though still tentative, observations by the Hubble Space Telescope (Roth et al. 2014) of plumes rising hundreds of kilometers above Europa's surface reinforces the relevance of this classification.
Examined altogether, these four macroscopic properties point to Europa as the unique Galilean moon likely bearing a subsurface ocean in direct contact with the silicate mantle (the very definition of a Class III habitat), subject to tidal heating, and displaying signs of activity at its surface. Liquid water, a permanent energy source, and access to heavy elements at the sea-floor: it is for all these reasons that we propose that Europa be the target of the first mission to land on an Ocean moon to search for life. Let's now focus on a "systemic" understanding of how this "Ocean world" is coupled to the Jupiter System, and on how the dynamics of the coupled Europa/Jupiter-System may play an important role in the long-term preservation of habitability conditions at Europa.
One can describe Europa as a system of concentric and coupled layers, from core to exosphere and plasma envelope, responding globally to Jupiter system forcing. This forcing is essentially of two types: gravitational (tidal) forcing, and magnetospheric forcing.

1.1.1. Tidal forcing.
Figure 1 illustrates the Laplace resonance linking the mean motion of Io, Europa and Ganymede and shows the temporal spectrum of the gravitational perturbations exerted on Europa (from Lainey et al., 2006). Because of this orbital resonance, the three innermost Galilean moons continuously exchange their orbital energy and angular momentum.

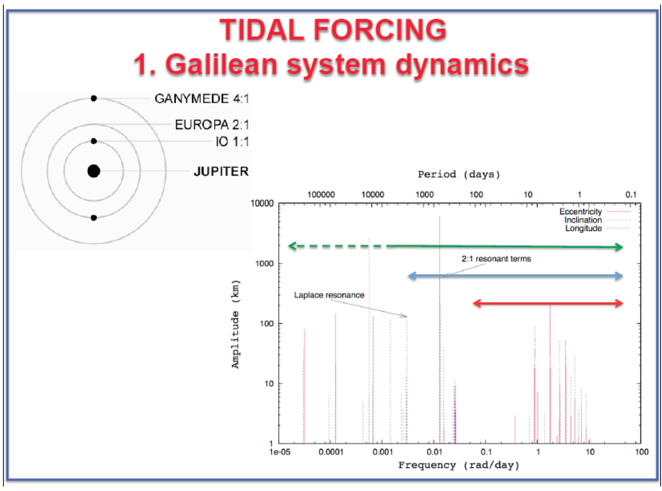

Figure 1: Tidal coupling of Europa to the Jupiter System is controlled by the dynamics of the Galilean satellite system and its Laplace resonance (left). The figure shows the very broad spectrum of gravitational perturbations exerted on Europa's motion in its reference frame. The short periods, to the right, correspond to the orbital motions of the different satellites and their beats, which induce the most important tidal stresses. The long periods to the left correspond to all long-period oscillations of the system and include the pendular motions in the Laplace resonance. The ranges of periods accessible respectively to JEM alone (red line), to the succession of missions to Jupiter (blue) and to the combinations of long series of astrometric measurements from the ground and from space (green) are also indicated (derived from Layné et al., 2006)

Tides are a major actor for heating the interior of the moons, with a heat flow up to 70 times the radiogenic heating at Io (Hussmann et al. 2010). They affect both Jupiter and its moons. Because the moons are synchronous, orbital eccentricity is the most evident way to allow for tidal forcing inside them. It is the Laplace resonance that maintains the eccentricities of Io and Europa to substantial values while the orbits are secularly evolving under tides.
In addition to the eccentricity of their orbits, the existence of an obliquity and of large physical librations may allow for tidal friction inside the moons too. A clear measurement of the obliquities

and physical librations will allow a more accurate estimation of heating inside these bodies (Wisdom 2004).
On long time scales, the evolution of the Galilean system links the moons internal evolution with their orbital one. In the case of Europa, this coupling provides a permanent source of heating to the ice shell and mantle. While we recognize this, the temporal variation of total tidal heating and the vertical distribution of this heat between mantle and ice shell are very poorly constrained by observations. Figure 2 shows a simulation result from Tobie et al. (2003) predicting that most of the tidal heating goes into the ice shell, but this is still a fully open debate which can be solved only by adequate observations, such as the ones we plan to perform with JEM.

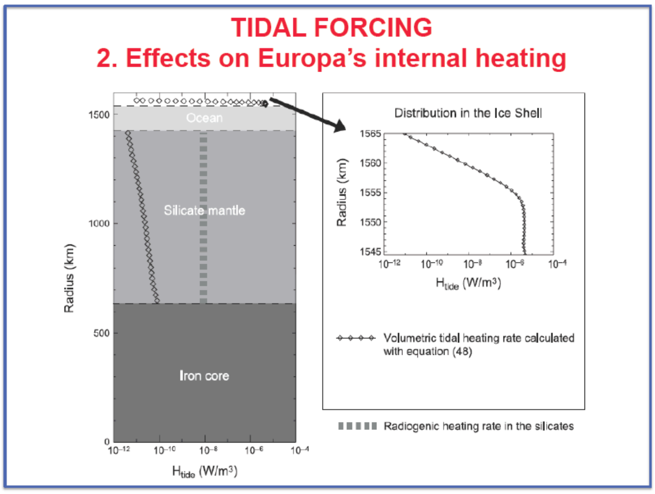

Figure 2: Tidal coupling between Io, Europa, Ganymede and Jupiter is responsible for a continuous transfer of angular momentum and energy between Jupiter and the three moons, resulting in continuous heating of their interiors, ice shells, and oceans. The model of Tobie et al. (2003) shown here predicts that most of this heating goes to the ice shell in the case of Europa. Observations from an orbiter will be critical to solve this open question.

1.1.2. Magnetospheric forcing.

At the Jovicentric radial distance of Europa, the dynamics of the magnetosphere is dominated by three phenomena. (a) Jupiter's field lines host the strongest radiation belts in the Solar System, whose harshest region extends slightly beyond Europa's orbit; (b) Jupiter's magnetic field lines corotate with the planet; (c) the dominant source of plasma is Io's volcanic activity, which results in the injection of about one ton/s of fresh iogenic ions into the corotating magnetic flux tubes. The centrifugal force acting on these tubes drives an outward diffusion of this Iogenic plasma, which dominates all other plasma sources throughout the inner and middle magnetosphere. Europa is imbedded inside the Jovian radiation belts, and it opposes its obstacle to the corotating magnetic flux tubes and plasma. Europa actually opposes two different obstacles to this magnetospheric flow, resulting in the complex distribution of plasmas, energetic particles, magnetic fields and electric currents described in Figure 3.

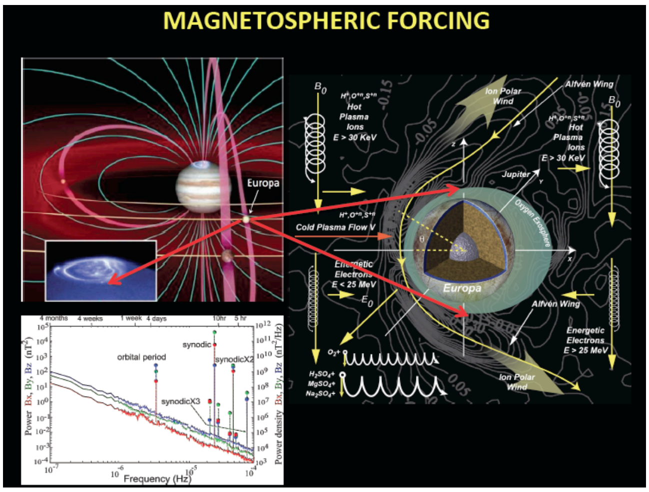

Figure 3: A simplified representation of Europa's interaction with the Jovian magnetosphere, which involves two obstacles: Europa's surface, and its subsurface ocean. This interaction generates effects from the planetary scale (a giant electrical current system coupling Europa's ionosphere to the Jovian ionosphere) to the very local Europan scales (the space weathering of Europa's icy surface by magnetospheric thermal and radiation belt particles). The broad-band spectrum of magnetic fluctuations associated with this interaction, seen in the Europan frame, allows an accurate magnetic sounding of Europa's ocean (diagram in white insert, courtesy K. Khurana).

The first obstacle is the Europan surface, which interacts with all particles in the flow. While the thermal plasma flow is deviated around this obstacle, energetic particles bombard the surface, producing space weathering, particle absorption and desorption, induced chemical reactions and desorption of surface molecules. Measuring its chemical composition bears a high astrobiological

interest, since biomolecules present in Europa's surface layer may have made their way to the Europan charged particle environment as ionospheric and pick-up ions.
The second obstacle is the conducting ocean, which opposes the penetration of magnetic field lines. In the sub-Alfvenic regime, this interaction induces a large potential drop, on the order of 200 kV, between the Jupiter-looking side of Europa and the opposite side. This potential drop in turn drives a current system which flows through the tenuous ionosphere of Europa and partly through Jupiter's ionosphere.

1.2 Europa as a potential habitat

Let us re-examine now the relationship of Europa to the "triangle of habitability" in the light of the coupling mechanisms we just described.

a) Tidal interaction with Jupiter and the other Galilean satellites produces heat dissipation inside the solid components of Europa, mantle and ice sheet, with a still unclear distribution between these two sinks. This energy complements radiogenic heating and may play an important controlling role in the maintenance of a liquid ocean, the activity of the rocky mantle and in the thickness of the ice shell. Geophysical models fed by Galileo data show that the total aqueous reservoirs of the Europa interior are likely 2-3 times greater than the total water volume of Earth's oceans today. The huge amount of energy available is also manifested as geological features that deform the icy crust around the Europan globe. Some of them apparently are linked to aqueous reservoirs or the ocean. The geological interpretation of these features indicates the possible presence of giant shallow lakes in the subsurface, recent plume activity and diapirism, showing that ice shell can mix vigorously,

b) Europa's subsurface ocean is likely in direct contact with a silicate seafloor, likely having a similar composition to the early terrestrial oceanic crust. It is still an open question whether the rocky mantle is geologically active. This totally unknown but possible interactive activity may release essential elements for life. We know from terrestrial analogs that catalytic reactions associated with hydrothermalism at the seafloor alter rocks, making them porous, by favoring oxidation of minerals; they also produce oxidized and reduced fluids, as well as organic compounds and hydrogen. Mg-sulfates that are observed on the icy surface could be abundant in the ocean, forming from the oxidation of sulfides. Carbon species such as carbonates, methane or other hydrocarbons can form from carbon dioxide or primordial organics depending on the hydrogen fugacity or decomposition temperature.

c) Apart from those produced during hydrothermal alteration of the rocks, other chemical gradients are produced on the surface. The moon orbits well inside the Jovian radiation belts, whose particles have direct access to its surface, where they induce a host of radiolytic processes on the surface material, including the synthesis of oxidizers, again a source of free energy. Europa thus has the potential of displaying a redox couple between its sea floor and its surface, which can be a source of chemical energy if the oxidized species can be transported through the ice shell by endogenous processes, such as subduction as proposed by Kattenhorn and Prockter (2014).

Now, provided that the ice shell is "partly permeable" to the transfer of chemical species between the liquid ocean and the icy surface, two key cycling processes may co-exist there:

- a net transport of radiolytically produced oxidizing species from surface to the ocean;
- and conversely, the possibility of transfer of biomolecules and even of specific forms of life from the deep ocean to the surface, and more importantly to the subsurface where they could have a chance to survive the radiation conditions there.

Under these assumptions, the sub-system of Europa extending from the ocean silicate floor to the ice shell surface constitutes a candidate "Europan biosphere".

1.3 The potential dark biosphere of Europa.

How could life possibly emerge in this environment? Of all possible scenarios for the origin of life in Europa, abiogenesis at hydrothermal vents, with their highly reactive surfaces and protective porous niches, is proposed by many as the favored analogue (e.g. Baross and Hofmann 1985; Russell and Hall, 1997), as well as hydrothermal sedimentary environments (Westall et al., 2018). Light may not be essential for the emergence of life.
If there is continued hydrothermal activity on the seafloor of Europa, the most likely forms of life to have lived possibly in the past and at present would be chemotrophs. These are surface specific life forms whose biomass development and distribution is controlled by access to hydrothermal fluids

and chemical gradients. For possible traces of life on Europa to be detected today, either extant or extinct, it will be necessary for the traces to be transported up to the base of the ice shell and through it towards the surface. Under this restricting assumption, how can we design a “winning strategy” for our quest for life there?

An efficient strategy to search for life at Europa must encompass three main types of contexts: the biological, the chemical, and the geological/geophysical contexts. Traces of extant or extinct life could be found potentially at the surface and near-surface environment of the ice, incorporated through reworking (impact gardening, mass wasting and internal dynamics) of material brought up from aqueous reservoirs, or in plumes of oceanic water spewed up into the exosphere: those are the places to look for. But it should also be noted that Europan bio-signatures, if they exist, will be strongly influenced by the extreme environmental conditions reigning on the surface of the ice and in the exosphere – high radiation, production of corrosive oxidizing species and radicals, tenuous atmosphere and low water activity. This would lead to rapid death of living cells and rapid degradation of the organic components of life. The remnant organic molecules are likely to be refractory, particularly if they have been exposed to the surface for long periods of time. Therefore, the search for signs of life needs access to fresh endogenic materials, which should be coming from the habitable environment in the case of extant life, and must be performed with a specific instrumentation and in the appropriate layers: a) subsurface sampling, essential in our strategy, must search for better protected samples that could be analysed in different physical states (solid/liquid). Analysis of samples in the aqueous phase will be obtained by melting near-surface ice samples, while chemical disequilibria will be simultaneously characterized during the search for bio-signatures; b) it should be noted that capturing compounds in a plume, if and when it occurs, is another indirect way of access to material emerging from the sub-surface.

2. JEM science objectives.

The JEM science plan and overarching goals will take maximum advantage of the achievements of previous missions to the Jupiter System (Juno, JUICE, Europa Clipper) to optimize its complementarity with them while focusing on the search for life at Europa. JEM will fly for the first time a Europa orbiter and a lander to Europa’s surface to perform unique astrobiology and geophysics/geochemistry science. Its **Overarching Goal** can be formulated as follows:

“Understand Europa as a complex system responding to Jupiter system forcing, characterize the habitability of its potential biosphere, and search for life in the surface, sub-surface and exosphere.”

This Overarching Goal can be developed into three main science objectives:

a) Understand Europa at the global scale as a complex system of coupled layers responding to Jupiter System forcing;

b) Define the potential habitable zone of Europa (ocean and ice shell), with a focus on the critical exchange processes of its icy surface with the sub-surface and the aqueous reservoirs below it, and with the exosphere above it;

c) Search for the signatures of a potential biosphere on the local scale. This is the culmination and converging point of our science plan: the search for and detect bio-signatures.

We describe now how we address a set of complementary science themes which will contribute to addressing these three science objectives.

2.1. The Europan magnetic field and plasma environment

The interaction of Europa with the Jovian magnetospheric field and flow results in a complex distribution of plasmas, energetic particles, magnetic fields and electric currents. The resulting charged particle population is a complex mixture of ions of different origins: to the primary population of iogenic ions, dominant in the Jovian plasmasheet, the Europan interaction adds ions of Europa origin coming from their exosphere, or even directly from its surface or subsurface through potential plumes. Measuring its chemical composition bears a high astrobiological potential, since biomolecules present in Europa’s surface layer may have made their way to the Europan charged particle environment as ionospheric and pick-up ions. The challenge on JEM composition measurements is to find endogenic materials amidst the background of magnetospheric species constantly raining down on the surface, i.e. resolving the minor and trace abundances of other species against the dominant iogenic sulphur and oxygen background.

With JEM, a 3-D picture of the complex magnetic field configuration produced by the Europan magnetospheric interaction and of the associated current systems can also be obtained for the first time. One can distinguish four contributions to this overall configuration: (1) the background undisturbed Jovian magnetic field, which is produced by the internal dynamo of Jupiter and by the additional large-scale Jovian current systems; (2) a hypothetical and never yet detected intrinsic Europan magnetic field, generated by a hypothetical core dynamo mechanism: only upper limits for it have been been derived (e.g. Schilling et al., 2004). Continuous low-altitude measurements by JEM will decrease its detection threshold by at least an order or magnitude; (3) the magnetic fields produced in the Europan environment itself by the Europan magnetospheric interactions with Europa's atmosphere, which results in various current systems: the Alfven-wing magnetic perturbations and current systems, and the closure of these current systems through the Europan ionosphere; (4) the electric currents induced into Europa's conducting ocean and their associated magnetic field, whose expected (and observed) amplitude is on the order of 50-100 nT.

To achieve the ultimate goal of an accurate magnetic sounding of Europa's ocean using its natural magnetic signal, one must separate the four contributions to the global distribution of magnetic fields and electric currents and then substract contributions (2) and (3) – the local external current sources to be able to separate the Jovian source (1) and the oceanic response to its variations (4). This goal, i.e., the description and separation of these four contributions, will be achieved with models of various levels of complexity. For the large and comprehensive data obtained by JEM, we will develop a comprehensive model that will allow us to separate the four contributions and simultaneously constrain the system parameters, such as ocean thickness, conductivity, and atmospheric densities with a novel approach based on a dynamical, general inversion technique in the spirit of "data assimilation" techniques currently in use in meteorology.

As shown in the inset of Figure 3, Jovian magnetic fluctuations offer a much broader spectrum of fluctuations for magnetic sounding than just the peaks associated to the revolution periods of Jupiter and Europa and their main harmonics. Taking advantage of its long residence in low altitude near-polar orbit, JEM will make it possible to use a very broad band of that spectrum. For an ocean depth on the order of 50 kilometers or more, using sounding periods of weeks rather than days, as made possible by an orbiter, allows a much more accurate determination of the ocean depth. The investigation of a broad frequency range permitted by JEM's orbiter's multi-weeks survey and the two-point measurements achieved by JEM's lander/orbiter design will guarantee the assessment of both salinity and thickness.

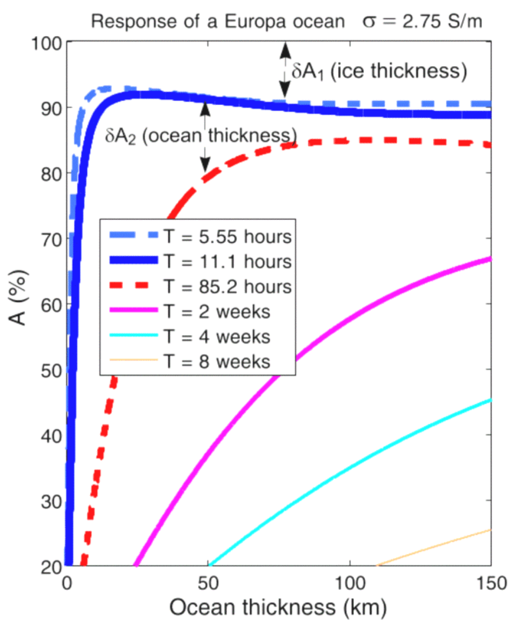

Figure 4: Response (surface induced field at pole/inducing field) of a Europa ocean with conductivity similar to that of the Earth's at six different periods. An ice thickness of 30 km was assumed for results shown in both of these figures. Figure adapted from Khurana et al. (2009)

Summary of magnetic field and plasma measurement requirements on JEM:
a) Determine the global structure of magnetic fields, electric currents and plasma and energetic populations in the Europan environment;
b) Separate the four contributions to Europan magnetic fields and current systems, and in doing so produce a quantitative estimate of the amount of momentum and energy exchanged between Jupiter and Europa in their electrodynamic interaction;
c) after subtraction of the effects of local electric current sources, use the natural fluctuations of the Jovian background magnetic field of Jupiter flowing by Europa to perform a broad-band magnetic sounding of the Europan sub-surface ocean and uniquely determine its depth;
d) Determine the composition/flux of plume material to characterize properties of any subsurface water.

2.2. The global structure of the solid body and potential biosphere of Europa, and their response to Jupiter System tidal forcing

Although on Earth seismology is the prime tool to illuminate the interior structure, for other planets and icy satellites, alternative geophysical investigations have been proven to be valuable and insightful. To achieve our measurement objectives, altimetry, gravimetry, the characterization of rotation and magnetic measurements have to be combined, using the geophysical investigations available on the orbiter and on the lander geophysical station, to provide estimates of:
(1) the harmonic expansion of the static gravity field and of the topography up to degree 30-40, (2) the amplitude (precision < 10-2) and phase (precision < 1°) of the gravity variations (k2 Love number) and topographic deformation (h2 Love number) of the Europan tides, from which an accurate estimator of the ice shell will be derived as illustrated by figure 5 below, (3) the libration and rotation properties of Europa, from radio science (gravity field), altimeter data and surface lander positioning, (4) the instantaneous orbital characteristics of Europa and its long-term evolution, using the PRIDE astrometry technique similarly to JUICE.

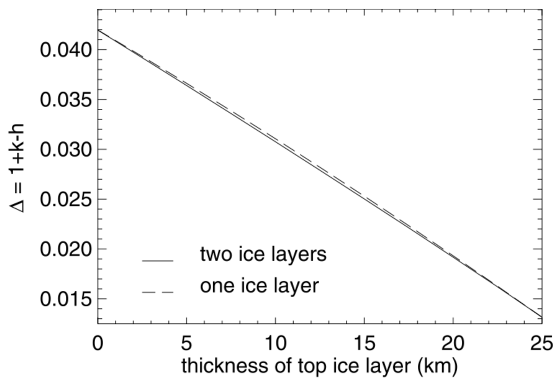

Figure 5: Example of the complementarity of gravity (k) and altimetry (h) measurements, here used to distinguish the mechanical properties of the ice shell (from Wahr et al., JGR, 2006).

By combining those very complementary individual measurements, a rich set of integrated information on Europas's internal structure, dynamics and energy budget will be produced, including: (1) detailed radial profiles of the key geophysical quantities; (2) an assessment of the assumed hydrostatic equilibrium; (3) a global description of the undulations of the critical interfaces: ice shell/ocean, ocean/rock mantle, rock mantle/core (if the latter is precisely defined); (4) an accurate description of tidal deformation and heating (amplitude and spatial distribution), possibly including constraints on the distribution of total tidal heating between the different layers.
Figure 6 illustrates this complementarity of techniques (rotation monitoring, electromagnetic sounding, gravimetry, seismic or acoustic sounding…) and shows how their combination will provide a comprehensive description of key characteristics of the different layers of Europa's interior including:

- A detailed characterization of Europa's potential interface:
    - the thickness and some rheological properties of the ice shell;
    - the depth, thickness and composition of the ocean;
- a high-resolution model of the interior (mantle) and a 3-D description of the undulations of its interfaces;

- and some information, at an unprecedented level of accuracy, about the state of the core and the possible existence of a dynamo.
- It is in the context of this advanced geophysical description of Europa at the global scale that a detailed investigation of transfer processes at its surface will be undertaken.

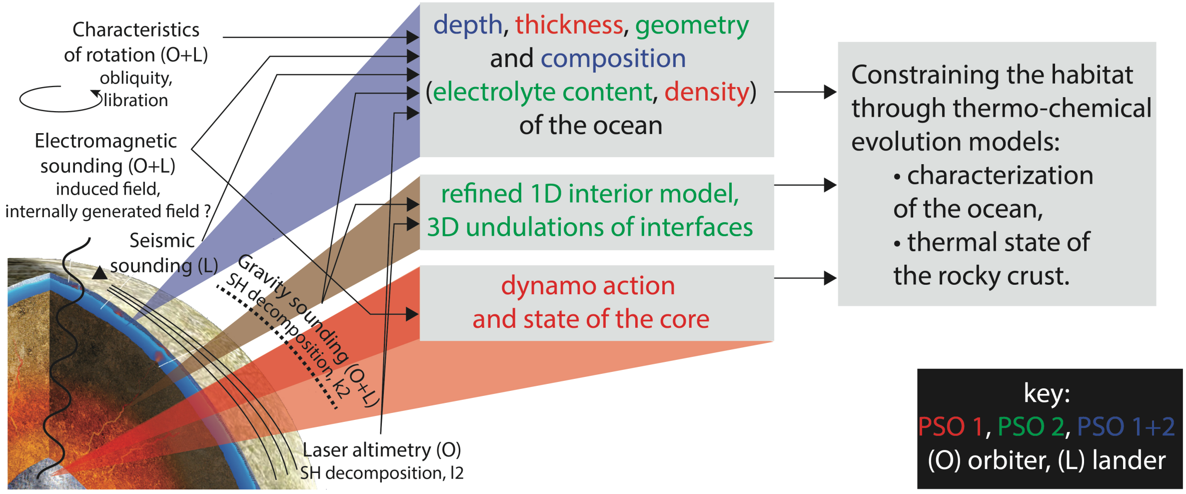

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Figure 6: Synergetic orbiter / lander investigation of Europa's response to Jupiter's magnetic and gravitational forcing

2.3. exchange and transformation processes at the interface between the ice-shell surface/subsurface and the exosphere/ionosphere including potential plume characterization

Europa's surface is composed of an icy porous regolith (50 to 100 µm grains). It is permanently bombarded by Jovian magnetospheric energetic ions (essentially keV to MeV Sn+ and On+ coming from Io's torus) and electrons (equivalent of 100 to 1000 times the dose rate at the Moon) and by photons (Cooper et al. 2001). The radiolysis and photolysis induced by this bombardment alters the optical layer of the surface on time scale between 10 and 10^9 years. The typical yield of S+ and O+ at keV to MeV energy is around 1000, so that the ice resurfacing rate induced by sputtering should be of ~0.1 microns / year (or 100 m/Gyr), significantly lower than the resurfacing rate due to meteoroid. As a consequence, the regolith can be a substantial trap for radiation altered material.
Incident magnetospheric particles and photons decompose Europa's icy surface into H_2, O_2 and H_2O_2. Preferential loss of the volatile H_2 leaves an oxidized surface, a gravitationally bound O_2 atmosphere and peroxide trapped in ice (Shematovich et al. 2005). This processing also determines the state of trace species such as S, C, Na, K and Mg. Sources and sinks of trace species in Europa's icy surface are: implantation from Io plasma torus, upwelling or venting from interior sources, and meteorite impacts.
Being a result of Europa's interaction with Jovian radiation, Europa's exosphere (illustrated in Figure 7) is expected to display a gas composition closely related to its surface composition. This relation can therefore be used as a guiding principle to understand from JEM exosphere measurements how the surface composition is processed by radiolysis/photolysis, enriched by exogenic sources and is eroded by sputtering.
JEM low-altitude orbits and mission duration are particularly adapted to characterize the potential plumes from Europa recently observed by HST with vertical extent of about 160 km. JEM will perform in situ measurements of the dust, plasma, and neutral plume composition. Volatiles, organic and inorganic compounds from the interior source could be measured and therefore associated to the sources in the aqueous/ice crust layers. Depending on the plume energy and density materials, compounds (which could give different information about habitability, e.g. salinity of the ocean) will be measured from the orbiter altitude.
Evidences of water plumes erupting from the surface up to 200 km around the southern hemisphere have been reported recently by Hubble Space Telescope images (Roth et al. 2014, NASA report 26/09/2016) and by re-analysis of Galileo magnetic field data (Jia and Kivelson, 2018). Ejecting materials would be coming from the interior of Europa, potentially from liquid layers, so they could include important information about the habitable environments or even evidences of life. This astonishing discovery offers a unique opportunity to access the interior materials.

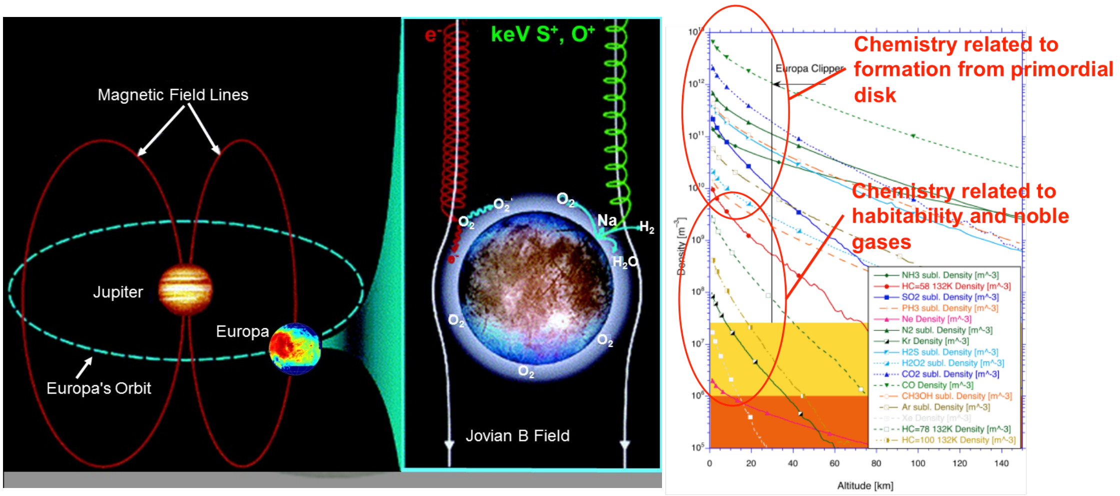

Figure 7: Cartoon representing Europa in Jupiter's magnetosphere and showing how the Jovian plasma moving with Jupiter magnetospheric line induces a trailing/leading asymmetry and bombards Europa's surface, sputtering the icy surface and forming Europa's exosphere composed essentially of O2 and of trace species (left); Calculated exospheric density profiles for species expected to be present based on the formation model (right). "SP" stands for sputtering, and "subl." Stands for released together with sublimation water. HC are hydrocarbon molecules with the indicated mass.

Summary of exosphere measurement requirements on JEM.

a) Determine the nature of Europa's exosphere by identifying the composition of major and trace species and determining their spatial distribution, including the relation with magnetosphere and surface;
b) Ascertain the roles of the magnetosphere and dust as drivers of the exosphere formation;
c) Ascertain the role of the surface/subsurface as driver of the exosphere formation.

2.4. Exchange processes between the ice-shell surface/subsurface and the potential habitable zone

Observations from previous missions to the Jupiter system show that the interior layers might be connected with the surface through several geological features. Exchange processes between the ice-shell surface/subsurface and deep aqueous layers constrain the signatures of the non-accessible habitable zone that are available for JEM observations. Basically, they are recorded in the geological features and materials of the surface/subsurface.

In order to recognize which features are young and have endogenous origin, JEM will benefit from: a) Europa Clipper and JUICE mission results of remote imaging, spectroscopy and radar scanning at regional resolution of the Europa; b) JEM global geophysical measurements described earlier (e.g. topography) that will provide new input for enhancing the geological interpretation of such exchanging features; c) JEM novel information at local scale.

Summary of measurements requirements on JEM for understanding the exchanges between the ice-shell surface/subsurface and the potential habitable zone.

- Detect any geological feature which involves exchange processes between surface/interior at the landing site and determine whether any activity exists today
- Determine the proximity to liquid water reservoirs in the landing site area
- Characterize the bio-signature preservation potential of accessible surface materials at the landing site
- Characterize the physical properties at the landing site
- Characterize the habitability key compounds of the near surface
- Characterize the wet context of exchanging materials

2.5. Bio-signatures at the surface / subsurface

Our JEM strategy to search for life takes advantage of the multi-platform architecture and of the opportunity to study different layers, to sample materials from the near-surface and to analyze them in different phases. Space exploration considers distinct categories of bio-signatures since each one needs different analytical instrumentation and has different limitations of detection:

a) Generic biomolecules. They are biological monomers and polymers (like polysaccharides, lipids, proteins or some form of information-transmitting molecule similar to DNA) that may reveal a complex prebiotic chemistry or even active biochemistry.

b) Organic indicators of past or present life. As mentioned above, high radiation conditions on the Europan surface may degrade any material if it is exposed for any length of time. It is expected that biomolecules will break up and react, producing degraded organic compounds that can also be symptomatic of the presence of complex chemistry. It is critical to validate the biological origin of those degraded signatures.

c) Inorganic indicators of past and present life, such as biogenic stable isotope patterns in minerals and organic compounds, biogenic minerals, or coupling of certain atmospheric gases which would be a product of metabolism, which eventually could persist when the measurements are performed.

d) Morphological and textural indicators of life. This means any object or pattern indicating bio-organic molecular structures, cellular and extracellular morphologies, or biogenic fabric on rocks.

Discerning the origin of bio-signatures is mandatory, specifically for the simpler organics since they may as well come from meteorites landing on the surface of Europa. Some materials from the exosphere could also precipitate onto the surface after their expulsion from plume activity. It should be mentioned that organics may form by the interaction of surface materials with the radiation environment if CO_2 is originally present in the ice matrix (Hand et al., 2007). Detection of formamide (CH_3NO) is particularly crucial since it is a key compound for the formation of nucleic acids. However, an exogenous origin of some organics (e.g. PAH) cannot be ruled out.

JEM plan for the search for bio-signatures will focus on local scale studies on a landing site where fresh and young material will be expected, coming from the near surface or even from the plumes, if they are detected. In near-surface investigations, direct sampling and contact analysis instruments are absolutely necessary since the concentration of bio-signatures is assumed to be very low. Sampling materials at depths below 5-10 cm from the leading hemisphere is required for access to unaltered molecules. Our JEM strategy for detection of chemical bio-signatures (categories 1, 2 and 3) contemplates that some measurements may require the sample to be in the solid or liquid phase for analysis. The necessary state of the sample is conditioned by the bio-signature typology and the technique used for its recognition. Simple molecules of categories 2 and 3 can be detected and identified directly by vibrational spectroscopy if they are present in the solid matrix of ice. For isotopic ratios and some more complex organics (e.g. aminoacids, lipids), definite identification can be performed by mass spectrometry measurements after sample volatilization, which is a step of the GC/MS procedure. In order to unambiguously identify macromolecules of category 1 (e.g. polysaccharides, proteins or DNA/RNA) a biochemical analytical technique is necessary, such as antibody microarrays immunoassays. This technique can identify macromolecules because they bind to their particular 3D structures in a liquid medium, which is needed to transport the antibodies and to allow binding to the specific antigens/target molecules. In JEM, the liquid medium is obtained by melting the ice sample of the near surface. Antibodies can also recognize and identify small but still complex molecules as aromatic aminoacids (Phe, Tyr, Trp) and PAHs such as benzo-a-pyrene.

In addition to near-surface science, JEM also foresees the possibility of detecting bio-signatures of extant life in the exosphere and potentially in plumes, whose several occurrences have recently been reported. These traces could include organic and inorganic bio-signatures expelled from the habitable zone, even cells, cellular material, or biomolecules. Closer to the “vent” exit points, deposits containing rock fragments hosting either extant (or recently dead) life forms or the fossilized remains of life might be found. This way, traces could be incorporated into the surface and near-surface environment of the ice through reworking (impact gardening, mass wasting and internal dynamics) of material brought up from liquid reservoirs.

Summary of JEM measurement objectives for the search of bio-signatures.

- Identify generic biomolecules
- Detect and characterize any organic indicator of past or present life
- Identify morphological and textural indicators of life
- Detect and characterize any inorganic indicator of past and present life
- Determine the origin of sampled material
- Determine if living organisms persist in sampled materials

3. Proposed scientific instruments:

The implementation of the JEM science plan is based on the joint operation of scientific investigations on two complementary platforms: a lander and a carrier/orbiter. We provide now a preliminary description of the instrument suite required on each of these platforms to meet our measurement requirements. For each instrument the technical information needed for mission design can be found in Blanc et al. (2019a).

3.1. The Orbiter instrument suite.

To meet our measurements requirements, the Orbiter shall carry the following instruments, some of them to be operated during a minimum of 35 days simultaneously with Lander data relay, then all of them during the subsequent 3 months of nominal orbital science, and again some of them during the final descent to Europa's surface. To accommodate and operate this instrument suite on the Orbiter Science Platform will take the following estimated resources:

Orbital Science Platform projected required resources						
Facility/Instrument	**Outside the vault**	**Inside the vault**				
Core payload		Mass (kg)	Volume (m^3)	Total (kg)	Power (W)	TRL
Gravity Science Investigation (GSI)	-	3.4	0.006	3.4	22	5
Magnetometer (MAG)	0.1	0.1	0.001	0.2	0.4	8/9
Laser Altimeter (ELA)	11	9	0.08	20	40	5-6
Ion Mass Spectrometer + Electron Spectrometer (IMS/ELS)	7	3	0.006	10	11	5
Ion and Neutral Mass Spectrometer (INMS)	3.2	3	0.006	6.2	16	5-6
Dust Analyser (SUDA)	7.5	2.6	0.003	10.1	9.7	5-6
Total for core payload	28.8	21.1	0.102	49,9	99.1	
Augmentation: Langmuir Probe (LP)	1.6	3	0.004	4.6	6	5-6

Table 1. proposed orbiter instruments and required resources

The added complexity of the extreme radiation environment at Jupiter drives the orbiter instrument architecture. We make the choice of decoupling the sensor heads from their part of their electronics. This allows flexibility in their accommodation, easier radiation mitigation and full integration of the scientific capabilities of each of them. This ensures optimum science return while keeping the total resources low.

3.2. The Lander instrument suite.

The instrumentation proposed for the lander is composed of the Astrobiological Wet Laboratory instrument package (described in section 4.3.3), three geophysical sensors (geophone, magnetometer and laser reflector), a GCMS, a Raman spectrometer, a microscope and a context camera. All of them are suggestions from European institutes. The final payload will have to result from a discussion with NASA, which will propose its own choice of lander instruments.

To accommodate and operate the instrument suite on the Surface Science Platform will take the following estimated resources:

AWL Surface Science Platform projected required resources			
Facility/Instrument	**Mass (kg)**	**Power (W)**	**TRL**
AWL sensors MPAS	0.15	1.4	3-4
AWL sensors MPP	0.1	1	3-4
AWL sensors VISTA	0.09	0.24	5-6
Total for AWL (cf. 4.3.3.2)	11 (incl. 7 for shielding)	17.4 Whr	
MAG	0.6	0.8	8/9
Laser Reflector	0.0025	-	-
Geophone	0.3	0.5	5-6

Table 2. proposed lander instruments (including AWL) and required resources

4. Proposed mission configuration and profile

4.1. JEM orbits and science sequences.

Addressing the science objectives of JEM will rest upon instruments deployed synergistically on its two space platforms. These 2 platforms will be used to perform 3 sequences of scientific observations:

- **A.** A **surface science sequence** involving the lander instruments, planned to last about 35 days on a selected site;
- **B.** An **orbital science sequence** involving the orbiter instruments. This sequence will first overlap in time with the surface science sequence;
- **C.** A **descent science sequence** will correspond to an additional period, after the end of sequence B, during which the orbiter will explore regions of the exosphere/ionosphere very close to the surface, below the lowest altitude to be covered by Europa Clipper, to search for biomolecules in the densest layers of the exosphere.

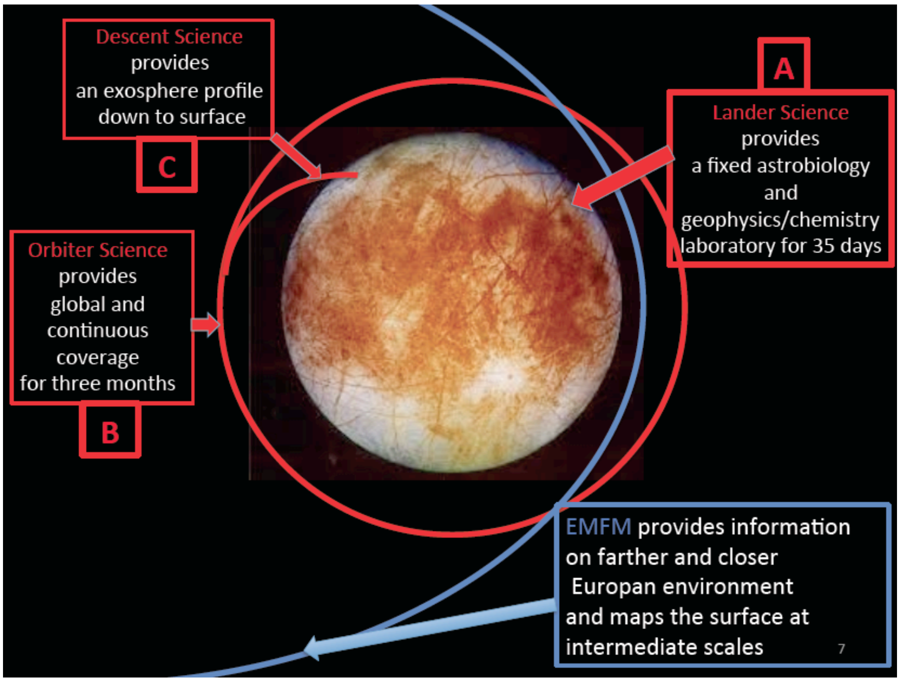

Figure 8: the three main science observation sequences of JEM: (A) 35 days of science operations at the surface; (B) a three-month continuous coverage of Europan planetary fields and plasma populations on a high-inclination orbit after an initial sequence on a halo orbit which will allow to study the structure of the Europan Alfven wings; (C) a short profile investigation of the exosphere before crash.

The choice of the orbital sequences to be used successively will be the result of a trade-off in the 3-D parameter space described by:

- the Total Ionizing Dose (TID) accumulated along the spacecraft trajectory, which gives directly the maximum operation time our platforms will be able to live through;

- the shielding thickness used to protect the equipment and mitigate radiation dose effects, which has a direct incidence on the weight of the platform and instruments;
- the total Delta V provided by the propulsion system, with direct impact on spacecraft total wet mass; taking into account the cruise time on each sequence.

Sequence	Sequence name	Mission function	Flight time	ΔV (m/s)	TID @ 2.5mm Al
S-1	Launch + cruise	Reach Jupiter System	4,9 years	800	~
S-2	JOI + PRM maneuver	Insert into the Jovian system	6,5 months	1000	~
S-3	Jovian tour to Europa vicinity	Phase the spacecraft with Europa	9,5 months	100	125 krad
S-4	EOI + Ejection to relay orbit	Insert into Europa, release the lander, reach relay orbit		700	~
S-5	Lander relay	Relay and downlink lander data	35 days	~	370 krad
S-6	Relay to LEO	Reach low-altitude quasi-polar orbit	1-3 days	400 (TBC)	12 krad/day
S-7	LEO operations	Support orbiter science mission	3 months	50	930 krad
S-8	Descent to surface				
S-9	Impact	End of mission			
Total			6,6 years	3,05 km/s	1,5 Mrad

Table 3: approximate flight time ΔV and TID (behind 2,5 mm finite Al slab shell)

To reach the Europan science operation orbits, starting from Earth with a SLS launch, the JEM flight complement will go through a succession of mission sequences. Table 2 shows one possible set of sequences, which is described in detail in the JEM reference article (Blanc et al., 2019a).

4.2. The JEM flight system.

4.2.1. <u>Global architecture: platforms.</u>

In its baseline configuration, the JEM flight system is composed of two platforms:

A soft lander platform developed by NASA:

This platform in the 350kg surface dry mass/ 35 kg payload mass class will perform investigations in astrobiology, ice characterisation and geophysics. We believe its design can be closely derived from the NASA Europa Lander SDT report (Hand, 2018). We propose that ESA and/or its member states provide a special science "sub-platform", the "Astrobiology Wet Laboratory" to this NASA platform.

A carrier/orbiter/relay platform:

This platform will fulfil the key functions of injecting the lander stack into an Europan orbit just prior to its de-orbitation, and of relaying the lander data to Earth. It will also carry a focused instrument suite to perform global high-resolution measurements of the gravity, magnetic field and topography fields and of the plasma/neutral environment along Europan orbits, as presented in section 2. This platform will conduct science operations from the relay orbit to end of mission. We are going to present a scenario to show that this platform could be provided by ESA with strong heritage from two of its previous developments: the JUICE mission, and the Orion capsule Service Module.

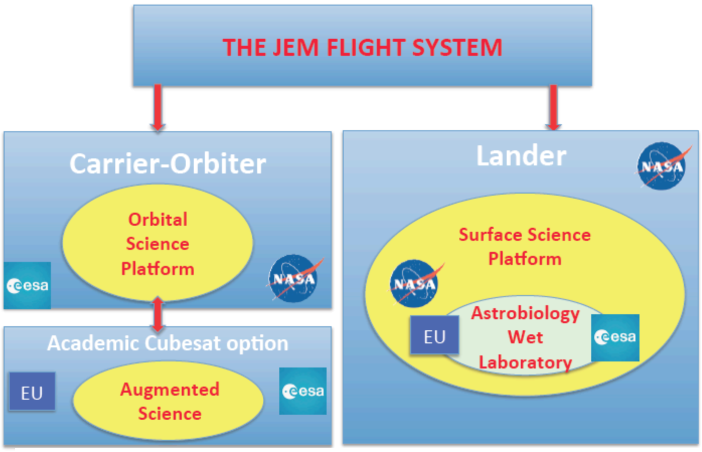

Figure 9: conceptual description of the JEM flight system JEM.

4.2.2. <u>*The carrier / orbiter / relay platform*</u>

Mission objectives, design drivers and proposed concept

The JEM orbiter platform will serve two objectives:

- To deliver the NASA lander in orbit around Europa, and to relay the lander scientific data to Earth during its 35 days at the Europan surface,
- To complement the surface science, carrying an instrument suite to perform global high-resolution measurements of the gravity, magnetic field and topography fields and of the plasma/neutral environment along Europan orbits.

The orbiter will conduct science operations during the lander mission and will continue operations for a minimum of three months after the end of the surface science operations.

The main design drivers of the orbiter are:

- To accommodate a 2,8 tons lander stack, to sustain the lander during cruise and to eject it with the highest accuracy and reliability,
- To accommodate a very large tank capacity to provide the required deltaV (~ 3 km/s) for a ~13 tons composite,
- To accommodate large appendages (large solar generator to cope with low solar flux and high radiation degradation, high gain antenna, instruments boom to support the orbiter's instruments suite),
- To maintain spacecraft resources and reliability in a very harsh environment (high radiation in Europan orbit, very cold temperature at Jupiter),
- To provide a sound mechanical interface with the Space Launch System (SLS).

The proposed JEM orbiter concept is inherited from two spacecraft currently developed by ESA:

- The European Service Module (ESM) of the Orion Multi-Purpose Crew Vehicle (MPCV), from which the mechanical and propulsion bus is adapted for JEM,
- The Jupiter Icy Moons Explorer (JUICE), which provides a relevant basis for the avionics of an interplanetary mission to Jupiter.

The ESM serves as primary power and propulsion component of the Orion spacecraft. It presents several advantages for the JEM mission: it is able to carry a very heavy payload (the Orion Crew Vehicle is in the 10 tons class), it is launched on SLS, and it is developed in a NASA / ESA collaboration framework, a key asset for the JEM mission.

The JUICE spacecraft, to be launched in May 2022, provides key assets for the other components of the JEM orbiter: a rad-hard avionics adapted to the specific constraints of an interplanetary mission and protected within a lead-shielded vault, and a power subsystem designed for LILT (Low Intensity Low Temperature) conditions.

JEM orbiter system design

<u>DeltaV and propellant budget.</u> Our launch and transfer strategy, based on NASA studies, features a large Deep Space Manoeuvre (DSM) and an Earth Gravity Assist to reach Jupiter. The SLS performance (Block 1 version) for this scenario is 13,3 tons. The deltaV budget during the Jupiter Tour is taken from the JPL design known as the "12-L1" Tour ("Jovian tour design for orbiter and lander missions to Europa", Campagnola et al, 2014). The total deltaV budget amounts to 3050 m/s. Assuming an orbiter dry mass of 2500 kg and a lander stack of 2800 kg, the propellant budget reaches 7900 kg. The composite wet mass (13,2 tons) is compatible with the launcher capability. The maximum dry mass requirement put on the JEM orbiter is therefore 2500 kg, including 20% system margin. Note that an additional gravity assist at Earth would allow to reduce the DSM intensity and provide significant additional mass margin at the cost of one additional year of transfer.

The deltaV budget is consistent with the NASA study mission profile (DV-EGA transfer, 12-L1 Jupiter Tour). The propellant budget fits within the Orion ESM capability (8600 kg) with margin.

Based on these key figures, it has been possible to perform a rough study of the JEM orbiter, which is described in the JEM reference article (Blanc et al. 2019a).

<u>Design for payload:</u>

A 5m magnetometer boom is used to provide a clean magnetic environment to the MAG sensors. The possibility to accommodate the JUICE recurrent 10.6m MAG boom will be investigated in Phase A. All design measures taken on JUICE to ensure the best EMC cleanliness performances are reused for JEM: the electronics vault provides an efficient Faraday cage to contain E-field radiation from electronics, a distributed single grounding point is implemented within the PCDU to avoid common mode perturbation, external surfaces (solar generator, MLI) are covered with an outer conductive coating to avoid charging, a magnetic shield is implemented on the most perturbating units (reaction wheels, motor drives). Two monitoring cameras will provide pictures of the lander's ejection. The overall resources allocation for the JEM orbiter is 50 kg and 100 W. The launch mass budget fits within the SLS capability and includes a 20% system margin on the carrier's dry mass.

The proposed JEM orbiter/carrier platform configuration is described in figures 10 and 11.

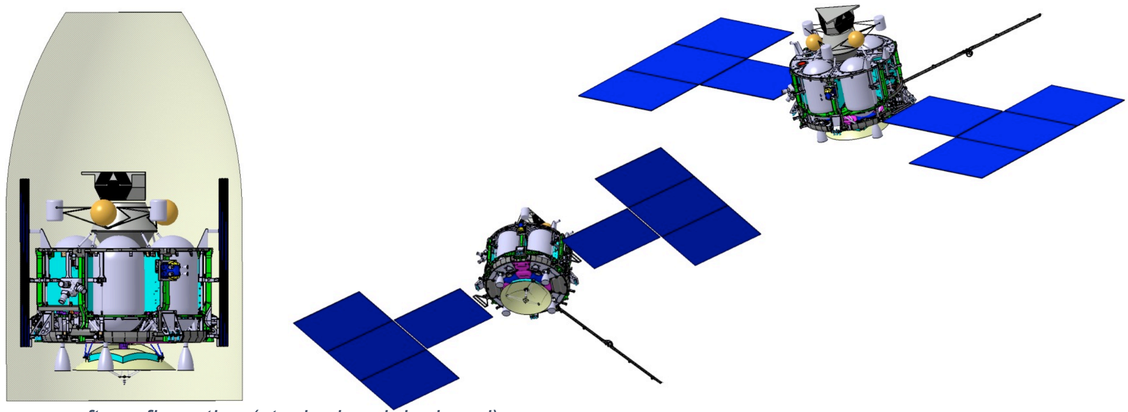

Figure 10: Spacecraft configuration (stacked and deployed)

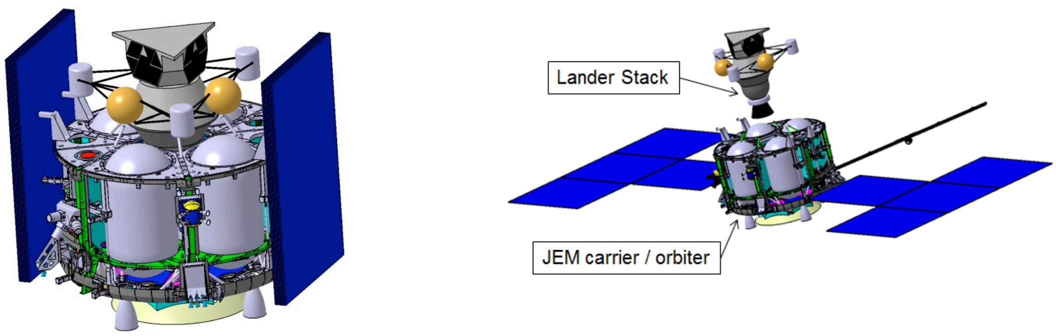

Figure 11: JEM carrier and lander interface

4.2.3. The JEM Lander complement.

4.2.3.1. The Soft Lander platform.

The soft lander platform is assumed to be delivered by NASA, based on its 2017 Europa Lander study. Figure 12 shows its architecture as described in the NASA 2016 report of the Europa Lander SDT (Hand et al., 2017). The soft lander will be the final element of the "lander stack" which also includes a propulsion stage and a skycrane following a concept similar to the Mars Science Laboratory sky-crane. With a total mass of 350 kg, the soft lander platform will carry a payload of 35 kg (including margins). The total power available for the entire 35-days mission from the on-board battery will be 2500 Whr, for a total data volume of 2700 Mbits. A gimbaled high gain antenna, co-aligned with the panoramic camera and mounted on the same articulated mast, will be used for the communications with the carrier-orbiter. The lander will be equipped, in addition to the payload, with a manipulator and a mast with panoramic cameras.

The analysis of samples of astrobiological interest will be performed by two complementary sample analysis facilities, one devoted to the analysis of solid samples, and another one dealing with liquid samples. The two facilities will be served by a common articulated arm. In addition to astrobiology investigations, the lander will also operate a geophysics station for the study of the planetary fields, the sounding of the sub-surface and the study of the properties of the surface ice.

We propose that the liquid sample analysis facility, called AWL for Astrobiology Wet Laboratory, be developed by ESA with sensor provided by its member states.

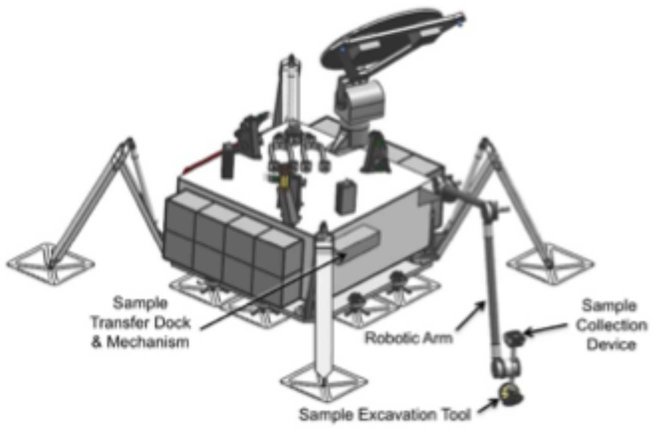

Figure 12: the latest NASA concept of a Europa Lander was given by the 2016 report of the Europa Lander SDT (Hand et al., 2017). It represents our reference in terms of the description of the lander component of the JEM

4.2.3.2. The Astrobiology Wet Laboratory (AWL)

We envisage two accommodation options for the AWL: at the own lander or at the surface. The latter option requires the arm hold the instrument and deposit it on the surface. The reason for selecting one of other option could be based on the arm design constrains but also the biochemical cleanliness conditions. The AWL detects large organics molecules (proteins, lipids, etc.) and to avoid false positives the level of biochemical cleanliness of the arm solid sampler should be stricter than if it only supplies samples to a GCMS or a Raman spectrometer. If the AWL works at the surface, it has its own sampler and if it at the lander only has a module for liquefy the sample. From an engineering point of view is more efficient to have the AWL at the lander. The AWL could also host the magnetometer with a small increase of mass (deployment boom, sensor head and electronic) and if it is on the lander could include also the thermogravimeter. In this case, the ESA contribution is a totally independent package, with clear interfaces with the lander.

AWL/S description: In the AWL/S option it is composed of: i) a Sample Acquisition Module in charge of making a 10 cm hole to take a liquid sample, ii) the Data Processing Unit which controls the instrumentation and the communication with the lander; iii) a Power Unit composed by the batteries and circuit to regulate the power and distribute it to the other units; iv) a Communication Unit to establish physically the connections with the lander by an umbilical cable. An external structure support allows one to deploy the AWL with the lander manipulator. For the Sample Acquisition Module (SAM), we have evaluated different alternatives (Ulamec 2007, Biele 2011, Weiss 2011, Sakurai 2016) for drilling, taking into account the limitations on resources and trying to reduce as much as possible the use of any mechanism. The most promising option is the use of a drilling system based on laser. Sakurai (2016) has demonstrated the capabilities of this concept. The water sample is taken in two steps: i) the first 5 cm of ice (degraded by the radiation) are sublimated by the laser and ii) the tube is moved down by a pneumatic actuator and once in contact penetrates by 5 cm in the ice. The tube is pressurized and heated to provide conditions in which the water is stable. At this moment the sample is sucked by a syringe (controlled by a spring) to fill the sample deposit. From this deposit the instruments are filled. A single pressurized deposit (nitrogen TBC) is used for tube movement and pressurization. The most critical components of the AWL/S are the batteries. They are the heaviest element and need to be controlled above a determined temperature to maintain their performances. For radiation protection, the Warm and Shielding Box has a thickness of 18 mm Al to allow the use of space standard components. Figure 13 shows the AWL mechanical configuration. A warm and shielding box (WSB) is used to maintain the operational temperature and protect all the electronics for radiation. The WSB will guarantee by design bio-cleanliness after integration. The SAM will have an isolation lid that will be closed once at the end of the integration to maintain the biological cleanliness. An opening protected with an EPA filter will help the decompression during launch. The external structure supports the magnetometer boom and allows hanging to the lander articulated arm.

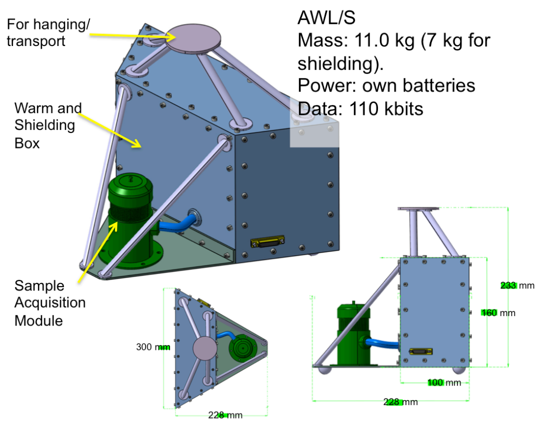

Figure 13: AWL/S mechanical configuration concept. A support structure allows it to be handled by the lander arm. A box protects the electronics, MAP and MPP. The isolation lid, below SAM, has a lateral movement to be open.

This configuration allows ejection from the lander if for some scientific reason it was recommended to explore some site far from it. The AWL side could be equipped with small airbags and following a similar concept implemented in the Pathfinder lander, a set of petals could guarantee that it stays always in the vertical orientation.

AWL/L description: The main difference with the AWL/L is the SAM, which in this case is reduced to a module to liquefy the sample and has no batteries, making the Power Unit much more simple. The process for obtaining the liquid sample is similar to the one proposed for the AWL/S.

- ✓ Drilling activities consumption 10 W for 1 hour.
- ✓ Additional sample processing 2.5 W for 3 hour.
- ✓ Data processing & control core consumptions 5W.
- ✓ Orbiter has the capacity to charge and monitor the battery (req. 85 W.hr)
- ✓ Battery should be maintained warmed to T > -20ºC
- ✓ No redundancy
- ✓ Standard flight EEE components
- ✓ Control based on a FPGA running a low frequency
- ✓ S/W in coded C and small program size < 64 KB
- ✓ Power conditioning based on COTS converter
- ✓ Orbiter has the capacity to charge and monitor the battery (req. 145 W.hr including AWL self heating).
- ✓ Battery configuration 5 series-cell & 5 parallel cells. Total weight < 1.5 kg.

5. Technology challenges of the JEM mission

Use of a heavy launcher:

The estimated wet mass of the orbiter/lander composite to be injected into interplanetary orbit, over 13 tons, requires the use of a Heavy Launcher of the SLS class. Including such a launcher in the flight concept of JEM will be its first technology challenge.

Planetary protection:

According to the COSPAR Planetary Protection policy, a general requirement for every mission to Europa has to be applied in order to reduce the probability of inadvertent contamination of a subsurface ocean by viable terrestrial microorganisms or their spores to less than 1×10^{-4} per mission (1 viable microorganism / 10,000 missions). Meeting this requirement will be the second technology challenge of JEM.

Radiation:

The inner magnetosphere of Jupiter where Europa orbits is the most severe radiation environment in the Solar System. This presents significant challenges for operating a spacecraft and its science instruments at Europa. The phases when the mission elements are in orbit around Europa are by far the most constraining ones in terms of radiation doses. Low-altitude orbits around Europa however have a clear advantage in terms of reduced radiation doses when one takes into account the complex trajectories traced by charged particles in the combined Jovian and Europan magnetic fields (Truscott et al., 2011). Designing space and instruments electronics that can survive this harsh environment will be the third major technology challenge of JEM.

AI and smart technologies for the landing sequence:

The lander composite, after release from the carrier platform, will have to execute an automatic sequence of partly propelled descent and soft landing to the Europan surface. Given the complex topography of Europa and our lack of knowledge of it at its hectometric scale, a smart navigation system capable of observing the landing zone, fine tuning the choice of the landing site and guiding the lander to the chosen area is mandatory. This will require a high level of autonomy and Artificial Intelligence on board. This will be the third major technology challenge of JEM.

Development of a smart bio-signature characterization package:

Finally, developing a “winning” strategy in our search for bio-signatures will be the ultimate, and in a way the most important technology challenge of JEM. We have offered in the White Paper a novel approach, combining analysis in the gas phase with an analysis in the liquid phases performed by a special “Astrobiology Wet Laboratory” (AWL), to meet this challenge.

6. Proposed international collaboration schemes:

The design and planning of JEM will be able to rest on the unique asset of several missions to the Jupiter System to be flown by ESA and NASA before 2035. With the arrival of Juno at Jupiter on July 4th, 2016, Jupiter system exploration has entered a new phase in which the successive missions under planning will address a sequence of complementary high-level scientific questions. Juno (NASA) focuses on the origin and formation of Jupiter itself, and on the coupling of Jupiter with the other components of the satellite system: tidal coupling to the satellites, via the measurement of Jovian tidal waves; magnetospheric coupling of Jupiter to its magnetodisk, via the first in-situ study of the polar and high-latitude magnetosphere.
JUICE (ESA), to be launched in 2022, will first study the Jupiter system in general, and the Galilean satellites Europa and Callisto in particular. Once in orbit around Ganymede, it will provide an in-depth investigation of Ganymede as a geophysical body and as a Class IV habitat. NASA’s Europa Clipper, to be launched in 2022 as well, will provide a first approach to an assessment of Europa’s habitability. It will not go into Europan orbit, but the host of data on Europa it will return during its 45 fly-bys will provide the basis for a lander mission. However, the findings expected from Europa Clipper in terms of geophysics and of characterization of Europa’s internal structure will be limited by its fly-by approach and currently envisaged science payload: flying an orbiter mission, even with a limited duration, in polar orbit, will remain a must for a comprehensive characterization of Europa’s habitability. Finally, CNSA is currently working on a China-led mission to Jupiter, to be launched in

the 2030 time frame, which will focus on the origins of the satellite system (with Callisto and the irregular satellites as its main targets) and/or on the “workings” of the Jupiter system, with Io as its main target (e.g., Blanc et al. 2019).
Coming after these previous missions that will investigate the origins and the workings of the system, study Ganymede in great detail with the unique power of a polar orbiter and provide a first assessment of Europa’s habitability, JEM will be in ideal position to perform a comprehensive description of Europa as a habitable world and to search for life at its surface. **We believe that *this very challenging objective should be reached in the 2035-2050 time frame***. We also believe that ***the major scientific and technological challenges of such an endeavor can be met if ESA (with its expertise on the Jupiter system gained with JUICE) and NASA (with its long and deep investments in the science and technology of a Europa Lander) join forces to search for life at Europa***.

We propose the following share of responsibilities between ESA and NASA: (1) The lander will be provided and operated by NASA with the support of ESA; (2) NASA will study with ESA the possibility of deploying from that platform a small ESA-provided « Astrobiology Wet Laboratory (AWL)» as an option; (3) ESA will take a major responsibility in the delivery of the carrier/orbiter/relay platform, ranging from the delivery of the full platform to the delivery of an integrated « science investigation platform » and of critical subsystems; (4) The proposed selection of scientific investigations on the different flight elements will be validated by ESA for the carrier/orbiter (see section 3 for proposed payload), by NASA for the lander and will likely include contributions from the U.S. and European scientific communities. ESA will support the developments required to reach TRL6 during the study phase for the AWL, the MPAS and the MPP sensors. ESA will initiate early in the project the planetary protection plan and its implementation.

6°/ Summary and conclusions

In this White Paper we propose that ESA works with NASA and other potentially interested international partners to design and fly jointly an ambitious and exciting planetary mission to characterize Europa’s habitability and search for bio-signatures in the environment of Europa (surface, subsurface and exosphere). By choosing the Jupiter system as our destination, we can build on the advanced understanding of this system which the missions preceding JEM will provide: improved understanding of its origin and formation (Juno), of its evolutionary mechanisms (JUICE) and a preliminary comparative understanding of the habitability of its different moon by ESA’s JUICE and NASA’s Europa Clipper. We propose the following **overarching goals** for the JEM mission:

Understand Europa as a complex system responding to Jupiter system forcing, characterize the habitability of its potential biosphere, and search for life in its surface, sub-surface and exosphere.

We described the observation strategy we propose to address them, which combines three scientific measurement sequences: 1- measurements on a high-latitude, low-latitude Europan orbit providing a continuous and global mapping of planetary fields (magnetic and gravity) and of the neutral and charged environment during a period of three months; 2- in-situ measurements to be performed at the surface, using a soft lander operating during 35 days, focusing on the search for bio-signatures at the surface and sub-surface using advanced analytical techniques in the solid and liquid phases, and the operation of a surface geophysical station whose measurements will complement those of the orbiter; 3- measurements of the chemical composition of the very low exosphere, to be performed near the end of the mission during the final descent phase.
These observation sequences will be performed by two science platforms: a soft lander to perform all scientific measurements at the surface and sub-surface and an orbiter to perform the orbital and descent sequences. In this concept, the orbiter will carry the lander stack from the Earth to a Europan orbit on which it will release it for its descent, before providing the data relay during the 35 days of lander operations. Using its instrument platform, the carrier will perform science operations during the relay phase, before moving to its final Europan science orbit for three months.

For the orbiter scientific platform, our proposed payload suite includes seven well-proven instruments to characterize the planetary fields and the plasma, neutrals and dust environment, fitting within our projected allocated mass.
Our lander science platform is composed of a geophysical station and of two complementary astrobiology facilities dedicated to bio-signature characterization experiments operating respectively in the solid and in the liquid phases. The design and development of the liquid phase laboratory, called AWL for "Astrobiology Wet Laboratory", could be a specific European contribution to the surface science platform. The two astrobiology facilities will be fed by a common articulating arm operating at the platform level that will collect the samples at the surface or sub-surface and will deliver them to the analytical facilities.
To fly JEM while making this mission an appealing and affordable joint exploration venture for both ESA and NASA, we propose an innovative distribution of roles; ESA would design and provide the carrier-orbiter-relay platform while NASA would provide an SLS launcher and the lander stack. We showed that this ESA contribution is technically possible, most likely as an M- or L-class mission, taking advantage of a double heritage of European developments: the JUICE spacecraft for the JEM orbiter avionics, and an adaptation of the ORION ESM bus to the specific needs of JEM for its structure. Following this approach, JEM will be a major exciting joint venture to the outer solar system of ESA and NASA, working together to share one of the most exciting scientific endeavors of the XXIst century: to search for life beyond our own planet.

Final note and acknowledgements:

A more comprehensive description of the JEM mission concept, science objectives, scientific payload and mission scenario is given in Blanc et al. (2019a).

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