# Fluid Mechanics and Systems Biology for Understanding the Cosmic Distribution of Life: A Review

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**Abstract** Due to progress in instrumentation both in cryogenics and in space exploration, the 20th century witnessed the extension of fluid mechanics applications in two novel systems. While the major aim for the first of these two cases—low temperature physics—was to understand the underlying microscopic theory, in the second case of fluid mechanics in the outer Solar System the major problem was, and still is, one of instrumentation, rather than theory. This second kind of environments may provide hints regarding the central problem of astrobiology, namely the search for life outside our own planet. The Galileo Mission (1995–2003) allowed closer probing of the Jovian satellite Europa, both with imaging techniques, as well as with spectroscopy of its icy surface over a deep ocean that is covered with chemical elements. Other examples of oceans are found in Ganymede and Callisto, two other icy Galilean moons, but possibly these oceans are not in contact with a silicate core, as in the cases of the life-friendly world: the Earth. In addition, Europa, with possibly the same internal geological structure as our planet, is also potentially a life-friendly world. These appealing phenomena are currently the source of plans for the next European mission to Europa that will provide a baseline for the search of life. For this purpose knowledge of our oceans will guide us in the search of life in other solar system oceans. These possibilities have encouraged underlining technologically feasible proposals for delivering small missiles ("penetrators") with appropriate instrumentation. Whenever compatible with the available payloads, one objective of these instruments has been to identify bioindicators. We are interested essentially in understanding the surficial sulfur stains of Europa's icy surface. Although not included in the most recent approved mission for Europa, penetrators remain a valid alternative in lunar research that we have shown to be relevant to the basis of astrobiology. In

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this context we have argued that already existing miniaturized mass spectrometers are particularly relevant. The arguments of this work bring together fluid mechanics, systems biology, and feasible cutting-edge technology.

## 1 Introduction: Novel Applications of Fluid Mechanics

Generally fluid mechanics is understood as the response of fluids to forces exerted upon them. The fluids that first concerned this discipline were restricted to those that were easily observable, mainly liquid water. Interest in the field goes back to Classical Greece, to the well-known work of Archimedes (c. 290–280 BC-212/211 BC).

Since those early times significant changes have taken place in fluid mechanics, but we shall dwell especially on relatively recent events. For we will not concern ourselves with the details of the development by Leonhard Euler and Daniel Bernoulli in the 18th century, or with the work of G. G. Stokes and William Thomson in the 19th century, or even the definite steps forward taken by Ludwig Prandtl at the beginning of last century.

Instead, we wish to highlight briefly scientific disciplines in which fluid mechanics has been fundamental and those that are closely related to the main objectives of the science of astrobiology (the reader will find in Sect. 5 the relevant references). This is a relatively new science that studies the origin, evolution, distribution, and destiny of life in the universe. Astrobiology is flourishing in the present and our opinion is that it will continue to flourish at a faster pace in the future, due to the many space agencies including the European Union, the United States, Russia, Japan, the Popular Republic of China, India, and to these larger efforts other countries are beginning to join forces, including our own country for some time now 1999–2005 (Chela-Flores et al. 2000; Falcón and Loyo 2007). But let us begin firstly by returning to fluid mechanics on Earth. One evident example that is relevant to astrobiology is physical oceanography (as in the new environments provided by the icy satellites off Jupiter): this sub-discipline of oceanography is concerned with the properties of seawater including temperature, density and pressure, movement (waves, currents, and tides), and the interactions between the ocean water and its overlying atmosphere. In Sect. 5 we shall return to this topic in relation with the plumes that may reach the icy surface of Europa, the Galilean satellite of Jupiter. Oceanography is a wider discipline, since it deals with topics beyond fluid mechanics, including chemical oceanography, marine geology, and marine ecology.

Secondly, once again fluid mechanics is particularly relevant for atmospheric science (meteorology, climatology, and aeronomy). These disciplines are concerned with composition, structure, and dynamics of the Earth's atmosphere (Vallis 2006). Fluid mechanics is also needed in aeronomy, since this sub-discipline of atmospheric science studies the physics and processes of the upper atmosphere, information of which may be measurable in the middle term in worlds around other stars.

In Sect. 2 there is a brief description, by way of illustration, of how progress in instrumentation has extended the range of applications of fluid mechanics to include quantum fluid phenomena (superfluidity). But later on we shall underline how for astrobiology more relevant are oceanography, as well as atmospheric science. These two sciences are and, due to a series of possible space probes, will be increasingly more relevant in extra-terrestrial conditions, and in the short term, in an extra-solar context.

## 2 A 20th Century Application of Fluid Mechanics

Fluid mechanics has ventured into new pathways, of which one originated from improved low temperature instrumentation and the other was due to the exploration of the Solar System and will be introduced in the next section. But we underline here that technology has found applications for fluids firstly, at extremely low temperatures, and secondly additional applications arose in locations out of this world. Both of these unusual venues for fluids have concerned our research in the past. In the first case of "extreme fluids" the major difficulty was to propose the correct theory. In the second case the main issue was of a different kind, once the extraterrestrial fluids (oceans) were identified, the question was not a theoretical one, but the question that was called for was one of identifying, developing, testing, and challenging space agencies for approval of the appropriate instrumentation.

Returning to the first case, the development of advanced cryogenic technology at the beginning of the 20th century (in 1908) allowed to liquefy helium at (4.2 K) into a state that is called helium I. Special attention was paid to liquid helium when it cooled to near absolute zero (0 K [−273.15 °C]) in both of the stable isotopes of helium: $^{3}$He and $^{4}$He. It was in 1938 when an unusual set of properties was shown to occur in liquid $^{4}$He underneath a critical temperature. Hence, liquid helium I assumes different properties and we called this new state of condensed matter helium II, a true "superfluid". (One of the properties that first gave this liquid its name was the capability of displacing itself without viscosity). The major problem that raised by the discovery of superfluid $^{4}$He was to find its theoretical bases at a microscopic level. (Subsequently, in 1972, it was shown that the phenomenon also occurs in the second stable isotope $^{3}$He at temperatures that were even lower than in the liquid $^{4}$He).

Quantum mechanics gives a general understanding of superfluidity, since for $^{4}$He, the liquid state consists of atoms with null total spin angular momentum. Consequently, the distribution between their possible states is given by Bose statistics. Neglecting interactions between the $^{4}$He atoms, Bose condensation takes place (but the subsequent introduction of interactions does not change significantly the microscopic explanation). With the development of field theory, an alternative approach to fluid mechanics of superfluid $^{4}$He was suggested amongst various attempts (Chela-Flores 1975). As the temperature is lowered this field theoretic approach allows the subsequent estimate of the increment of the fraction of condensed atoms

(Chela-Flores 1976). The theory even allows an understanding of diffraction data, both X-rays, as well as neutron diffraction (Chela-Flores 1977). Although not discussed in these three papers, Bose condensation essentially applies also to the case of $^3$He superfluidity, where Fermi statistics are required for the $^3$He fermions. The insight that led to this further understanding was based on the earlier theory of superconductivity, where the fermions pair in structures known as Cooper pairs that have integral spin for which the correct statistics is, once again, that of Bose.

## 3 An Additional Application of Fluid Mechanics

We wish to underline that, once again, it is instrumentation, rather than theory (as in the above case of superfluidity of $^4$He) that now takes the central position of our enquiries for the new venue of the extraterrestrial fluids. Indeed, with the advent of advanced space technology the exploration of the outer Solar System was possible in the three decades that went from 1973 till 2003. Gradually it became evident that large bodies of liquid water were present in our cosmic neighborhood. Evidence began to emerge during the first steps of exploration of the possible presence of large oceans on the moons of the giant planets: Jupiter and Saturn.

The science of oceanography was untested in these novel environments, a situation that began to change at the very end of last century, as we will briefly refer to in Sect. 1. But within the 20th century the Galilean moons Europa, Ganymede, and Callisto were shown to be very likely the host of oceans of liquid water. These steps forward in the exploration of the outer Solar System have been a gradual process:

- Pioneers 10 and 11 were the first Jovian flybys: Pioneer 10 (1972) flew by Jupiter in December 1973. This was a major achievement for the period, since it was the first such mission. Pioneer 11 (1973) passed by Jupiter in December 1974.
- Voyager 1 went past Jupiter on March 5, 1979. Voyager 2 traveled more slowly and went by Jupiter on July 9, 1979.
- A decade later the Galileo mission built its success on the heritage from the much more modest missions mentioned above. Galileo was placed into Earth orbit in 1989, but from 1995–2003 the Galileo mission successfully explored the Jovian System, providing strong evidence for satellites, where life as it is known to have emerged on Earth, may have also have taken its initial steps providing an opportunity to identify a "second Genesis" using the suggestive phrase of Christopher McKay. (For a detailed discussion of the consequences of life on Europa, the reader should consult "A second Genesis: Stepping-stones towards the intelligibility of nature" (Chela-Flores 2009), especially Chaps. 8–12 and the Glossary, p. 199 for the original use of the suggestive phrase for the origin of life in an extraterrestrial context).

The Galileo mission has added insights, such as the presence on Europa of some form of 'ice tectonics'. The Jet Propulsion Laboratory, which handled Galileo for NASA, has released some images that suggest that part of the surface is understood in terms of shifting plates of ice. From all the information gathered from Voyager and Galileo, reasonable guesses have been put forward regarding possibly a substantial amount of liquid water between the Europan silicate crust and its icy surface. AQ1

## 4 New Paths for Fluid Mechanics in the 21st century

A preliminary proposal for a return mission to Europa and the Jupiter system was entitled LAPLACE. In February 2009 NASA and ESA took a preliminary decision to support a Jupiter mission with the name of the Europa-Jupiter System Mission (EJSM) replacing temporarily and extending our original Laplace proposal (Grasset et al. 2009).

The Jovian System exploration was reformulated by ESA as a European-led single spacecraft mission to the Jovian system, namely, the JUpiter ICy moon Explorer, JUICE (Dougherty et al. 2011). The timeline is launch in 2022, and arrival at the Jupiter system in 2030. The new mission is based on the design of the Jupiter Ganymede Orbiter, which is the ESA flight element of EJSM-Laplace Mission. Indeed, since three of the Galilean satellites are thought to host internal oceans, the JUICE mission will study the moons as potential habitats for life.

In this context an appropriate technology concerns the micro-penetrator. These instruments consist of small projectiles that can be delivered at high velocity to reach just beneath the surface of planets or their satellites for probing samples of surficial chemical elements, amongst other investigations. This type of instrumentation (the penetrators) has a long history of feasible technological development by several space agencies.

Although the limited payload constraints does not include penetrators in the JUICE mission, it is forcing a choice between penetrators and landers. Some advantages of the penetrator approach are nevertheless evident and remain a valid instrument for studying our origins in lunar research (Chela-Flores 2012). The low mass of these instruments, combined with their agility in deployment, makes them worthy complements to orbiter missions launched without landers. We have attempted to describe the feasibility of this technology both on the surface of Europa (Gowen et al. 2011), or on the Moon (Smith et al. 2012). The Europa's stained icy surface has been the focus of recent search for possible biomarkers. The science of biogeochemistry presents us the tantalizing option of inferring from the sulfur surficial patches tests of biogenic chemical elements. Several Earth-bound regions are good analogues of what may be happening in recent geologic times on Europa. These regions are on the Canadian Arctic (Damhnait et al. 2012) and in the Antarctic (Chela-Flores 2011).

Fluid mechanics provides a rationale for the mechanisms that could bring biomarkers from the seafloor to the icy surface. The original intention of some oceanographers was to understand the special changes in the Europa's surface in the Conamara Chaos Region (cf., Sect. 5). With the Galileo Mission we were able to retrieve detailed images of Europa's frozen and stained surface. One of the most intriguing and possibly significant was the Conamara Chaos.

The surface morphology can be understood in terms of oceanic plumes bearing chemical elements, including sulfur from hydrothermal sources in the oceanic bottom. A little beyond the present time technology will allow us to probe the atmospheres of planets beyond the Solar System, where the atmospheric sciences will be set in a new context (cf., Sect. 8) and this, once again, will allow fluid mechanics to explore a novel physical context, namely, the atmospheric structure of hot giants, Neptunes and super-Earths (Segura et al. 2010).

Several other instrumentation issues are also relevant. For instance, laser-induced breakdown spectroscopy (LIBS). This has been a technique for the analysis of elements by retrieving a unique elemental fingerprint spectrum. Since chemical elements are known to emit light of a given frequency when excited to sufficiently high temperatures, LIBS suggests itself for detecting all elements in a given target. There are advantages when planning the exploration of the Solar System.

LIBS shows potential for development instrumentation with characteristics typical of LIBS, but in addition rapid *in situ* analysis is possible with little or no sample preparation and the feasibility of automated spectroscopic analysis (Multari et al. 2010). But as in the case of the penetrators the payload constraint of, for instance the JUICE Mission, does exclude some of these relevant instruments.

## 5 Buoyant Plumes from the Underlying Seafloor

These are possibilities that can eventually be tested in the laboratories of fluid mechanics. The original intention was to simulate the circulation of Europa by solving the magneto-hydrodynamic equations of motion for a stratified incompressible conduction fluid in a rotating frame of reference. The argument was centered on the fact that the tidal forces can implement oceanic motions in the oceanic annulus generated by the other Galilean moons, by hydrothermal venting from crustal heating and by the intense Jovian magnetosphere. In addition, there will be oceanic stratification influenced by large-scale ocean circulation driven by hydrothermal venting from below and conductive cooling from above.

Such stratification is expected to determine the height of the hydrothermal plume rise, which if the conditions are given could be comparable with the ocean depth and modify the surficial ice. This was a phenomenon that could be observed by the space probes around Europa. This anomalous ice morphology began to be studied in terms of fluid mechanics around the time when Galileo Mission data from the Jovian System was available (Thomson and Delaney 1996).

Five years later, it was demonstrated that these plumes could indeed bear sufficient energy to alter the morphology of the surficial ice, as observed by the Galileo probe around the Conamara Region (Thomson and Delaney 2001). In detail, Thomson and Delaney interpreted this region as melt-through structures formed by oceanic plumes that rise to the base of the ice shell-surface from magmatically heated regions deep in the seafloor. But what is most interesting from our point of view is that these mechanisms of plume delivery from the hydrothermal vents could be the source of biomarkers.

On Earth the origin of life may have occurred around hydrothermal vents, where chemosynthetic bacteria may have flourished. In a similar manner, traces of living organisms could be part of the supply of the stained ice, where sulfur is a main chemical component. Mass spectrometry is the appropriate instrument that could decide whether the internal source of sulfur is of biogenic origin, as the fractionation produced by living organisms can be radically different from that produced by inorganic means (Dudeja et al. 2012).

## 6 Fluid Mechanics and a System-Level Understanding of Exolife

Systems biology has been a remarkable step forward in the life sciences, especially after we have learnt how to handle large data banks. The first steps in this direction were in the area of molecular biology with the genome and proteome projects. One specific area of impact has been molecular medicine. We have suggested extending systems biology to all areas of the life sciences, especially regarding "exolife" life, namely life elsewhere in the Universe, which is the main topic of the new science of astrobiology (Chela-Flores 2013a).

In fact, systems astrobiology is forced upon us, since our objective is not to reduce problems to first principles, but more modestly our main objective is to attempt defining a set of parameters that may lead to identifying the condition for the presence of complex life on an exo-world (exo-planets and exo-moons). The relevant parameters include amongst many others: an anomalous fraction of oxygen, the star class hosting the Earth-like planet, the age, the metallicity of the star, the position of the exoplanet in the habitability zone of its star, and the possible presence of an exomoon.

Life in the Universe will emerge from statistical analysis of large data banks that are now rapidly beginning to accumulate. Our combined assumptions of convergence and the cosmos as a complex system imply that all the Earth-like exo-planets that will be in the habitable zone of their corresponding star will have an identifiable bioindicator (anomalous production of biogenic gases).

The signs of life are predicted to be a biologically produced atmosphere, largely fractionated towards one of the biogenic gases (in the case of the Earth the large fractionation triggered by biosystems is the 21 % of oxygen). Such atmospheres would not be the result of natural accretion processes in the processes that give origin to the planets, but instead, the emergence of the biogenic atmospheres would be the result of the innate phenomenon of life that the laws of biochemistry will allow in brief geologic times.

Systems astrobiology is analogous to systems biology, but it has to wait for its full implementation until after we have gathered enough data from the sector of our Galaxy. The practical reason why systems biology is a promising frontier for the future of astrobiology is that it is not easy to have access to information on these planets, except through the now incipient data banks of observable geophysical data, such as methane and oxygen atmospheres, as well as information on the presence of liquid water beyond the present data that has already been searched. In view of the large rate of data retrieval systems astrobiology needs to be formulated at present to prepare for its most convenient management and interpretation.

Since we are discussing how fluid mechanics has found a new area of application in the astrobiology of moons of our solar system, we shall dwell with some care on the question of the relevance of the moons for favouring the origin of life. The potential detection of exo-moons has raised the possibility of bringing the distribution of life in the cosmos closer to reality. The bases of exomoonology are the initial success of the CoRoT mission that was the first space mission designed to search for exo-planets similar to the Earth itself. It was launched with a Soyuz-Fregat rocket in December 2006. CoRoT is the French Space Agency (CNES) mission containing a small space telescope in a terrestrial orbit at a height of 900 km.

## 7 Distribution of Life in Other Solar Systems: Kepler Worlds

On the other hand, the Kepler Mission, unlike CoRoT, is in a solar orbit. It was launched on March 7, 2009 from Cape Canaveral Air Force Station in Florida. It has a capability to scan some 150,000 stars in the local neighborhood of our Galaxy for extrasolar planets (Kipping 2009a). Its main objective is to search for exo-planets, especially Earth-like planets. At the time of writing, Kepler now has selected out of the 150,000 stars a set of 2326 candidate transiting planets.

The search for exo-planets can be viewed as the first step in an eventual discovery of life as a complex cosmic system. Following the lines outlined above, we expect that a rationalization of life will eventually emerge from the data banks of a very large number of stars in our galactic sector. The geophysical data, rather than data banks of biological information, will provide a gradual emergence of the living phenomenon. The geophysical (atmospheric) bio-indicators point towards ecosystems that have evolved around stars producing measurable biomarkers in our galactic sector. Subsequently, with better missions and with improved instrumentation, this identification of life as a complex system can be extended from a sector of the Galaxy now being probed to other more distant parts of the Universe. It will be at that stage that the methods of computational biology are necessary.

## 8 The Moon's Influence on the Emergence of Habitability

The presence of an exo-moon would stabilize the magnetic axis of the exo-Earth and hence discard oscillations in the range 0–80° that would constrain the evolution of life from small anaerobic to large complex life capable of photosynthesis (Kipping 2009b; Chela-Flores 2013b). Although no exo-moon has been discovered so far they are in principle detectable with the Kepler data and, indeed, hints of an exomoon-forming region around exo-planets have been reported (Heller and Barnes 2012). On Earth the stability of the terrestrial magnetic axis is a well-known factor for the evolution of complex multicellular life. The Moon has stabilized the axis of rotation of the Earth, so that its axis of rotation stays in the same direction.

This has had a profound effect on Darwinian evolution, since drastic climatic changes would restrict the survival to only small, robust organisms to survive (Batalha et al. 2012). We have been presented with a remarkable discovery of several oceans in the moons of the outer solar system. The knowledge we are gathering from the moons of our solar system to which fluid mechanics has made a contribution (cf., Sect. 5), will in turn serve to understand the role of exo-moon in the emergence of life in systems of habitable environments around other stars.

The more challenging possibilities that we have to face include the example of a Neptune around an M2 star with a widely separated Earth-like Moon (Kipping et al. 2012). If a moon happens to be leading the planet, as it passes by, it will pull the planet across the face of the star a little faster than average. If it happens to be following, it will hold the planet back. Whether the moon is leading, or trailing, the silhouette of the planet and moon will be wider than that of a planet alone. The planet-moon system will block more of the star's light.

If the moon is directly in between the planet and the visual range of Kepler, on the other hand, or if it is between the planet and the star, more starlight will reach Kepler's sensors-and the moon itself will not be visible. After the planet passes around the star several times the changes in speed caused by a moon can be compared with an average speed, and so that moons that are completely hidden on one pass can have a chance to show themselves on the next.

It should be kept in mind that the feasible detection of exo-moons will add additional parameters for the emergence of habitability on their exo-planets, as it has happened in our own local environment (cf., Sect. 6). The Moon has been a stabilizing factor for the axis of rotation of the Earth. In the case of Mars, for instance, the lack of large satellites has allowed axis obliquity change. Consequently, the ice at the poles could in some moonless exo-planets be displaced to the equator. But the Moon has helped stabilize the Earth, so that its axis of rotation stays in the same direction, leading to less climatic change than if the Earth resembled the moonless planet Venus. The emergence of more complex multi-cellular organisms has been favoured compared to a planet where drastic climatic change would allow only small, robust organisms to survive.

With the advent of exomoonology (Kipping et al. 2012), the new batch of data to arrive will be particularly relevant for adding yet another factor in defining habitability and life, as suggested in a systems astrobiological approach. We will face with the Kepler data and the HEK Project a selection of data for discriminating those Kepler worlds that have more favourable options for habitability if they have companion satellites.

## 9 Insights from a System-Level Understanding

The systems biology approach should also give us insights into one of its branches, namely astrobiology, whose major problem is to understand habitability in alternative abodes for life. With its geophysical/astronomical data, astrobiology can follow up the tracks of genetics and biochemistry for solving fundamental problems that were intrinsic to these disciplines of the life sciences such as protein, or proteome folding. By having the option of focusing on how systems properties emerge in astrobiology, we can raise the question whether habitability can be interpreted as an emergent phenomenon. We suggest basing such an approach on different forthcoming projects:

### *9.1 The Kepler Mission*

This NASA mission is already producing valuable data related to over 2000 candidates for exo-planets (at the time of writing).

### *9.2 The FINESSE Mission*

The NASA Mission FINNESSE, Fast INfrared Exoplanet Spectroscopy Survey Explorer (Swain 2010) is to be launched in 2016. It is also a source of data in the near future. It would measure the spectra of stars and their planets.

FINESSE will analyze the planetary atmospheric components using a space telescope to survey more than 200 planets around other stars. This mission attempts to find the fraction of biogenic gases in exo-planet atmospheres and how the Solar System fits into the family of planets in the galactic neighborhood focused by the Kepler mission. FINESSE science objectives overlap the topic of our interest, since firstly, they intend to measure fundamental parameters in the exo-atmospheres to allow knowing the physical and chemical processes of their atmospheres.

Secondly, the science objectives once again overlap with one of the atmospheric science sub-disciplines—climatology—concerned with the weather in the same layers of the atmosphere over given periods of time. The second relevant FINESSE science objective is to trace the composition and temperature change with longitude and time. It is expected that the details of the day side-night side differences will allow the mission to determine insights into the exo-planet climate. A project now in its first steps, the “Hunt for Exomoons with Kepler”, (the HEK project mentioned in Sect. 8) aims at distilling the entire list of known transiting planet candidates found by Kepler.

This effort is pursued in order to track down the most promising candidates for hosting at least an all-important moon, whose interaction with the host planet is relevant for the pathway along which life evolves.

### 9.3 The TESS Mission

With Transiting Exoplanet Survey Satellite Mission, TESS (Foust 2012) the Kepler search for exo-planets will be extended to additional G, K type of stars up to the 12 magnitude, including over two million stars and M type (red-dwarfs) to about one thousand up to 30 parsecs.

### 9.4 The EChO Mission

With the Exoplanet Characterisation Observatory Mission, EChO (Tinetti et al. 2012), exo-moons down to $0.33R \oplus$ would be detectable for our target stars, providing a complementary set of information from what is being searched from the Kepler data (Kipping et al. 2012). In addition, ECho will be able to analyze the atmospheres of super-Earths in the habitable zones of their host stars. One of their objectives is to measure the spatial (vertical and horizontal) and temporal variability of the thermal/chemical atmospheric structure of hot giants, Neptunes, and super-Earths orbiting bright stars.

## 10 Discussion and Conclusions

From the point of view of the comparatively recent science of astrobiology (Chela-Flores 2011), we have aimed to illustrate a novel area of application of the time-honoured discipline of fluid mechanics. Since ancient times fluid mechanics has been relevant in a context of our civilization. An extraordinary new venue for fluid mechanics emerged early in the 20th century for macroscopic quantum phenomena of the quantum liquids.

These relatively new applications became even broader, due to the technological revolution in instrumentation that we are going through at present. This on-going revolution is to be materialized with the forthcoming extension of aeronomy from its present Solar System constraints to planetary systems around other stars, since as mentioned in Sect. 2 aeronomy is concerned with the physics and processes of the upper atmosphere. Now we are in a position to anticipate that the upper exo-atmospheres will be measurable with the coming step forward in instrumentation with the missions FINESSE, EChO, and TESS (cf., Sect. 9).

An underlying hypothesis in the previous work (Chela-Flores 2013a) has been evolutionary convergence, namely, independent evolution of similar genetic or morphological features. Assuming both biochemistry (Pace 2001) and biology (Dawkins 1983) to be universal sciences, evolutionary convergence has been assumed to be possible, even in other lines of biological evolution elsewhere in the universe (Conway-Morris 1998, 2003; Chela-Flores 2007). For a more careful detailed discussion of evolutionary convergence we refer the interested reader to Chap. 12 in "The Science of Astrobiology" (Chela-Flores 2011).

The eventual verification of the validity of the fluid mechanics theory that has been applied to the internal ocean of Europa (cf., Sect. 5) does not have to wait for long-term technological developments. We originally proposed with our JPL co-workers instruments of the kind of cryobots and coupled hydrobots that may penetrate the icy cover to probe directly the oceanic phenomena that were to be modelled by fluid mechanics (Horvath et al. 1997). However, it is clear now that the surficial probing that can be performed with the help of the micro-penetrators would suffice for extracting most of the relevant information from the upper layers of the icy Europan surface (Gowen et al. 2011).

Finally, a point that we would like to highlight is that the new venues for the science of astrobiology have been suggested by older approaches that come from the life and physical sciences. Indeed, systems chemistry is a physical science clearly outlined (Anderson 1972), in which an interdisciplinary approach focuses on complex interactions in chemical systems, using a new point of view, holism rather than reductionism, where collective phenomena are the main ingredient in basic research of chemical systems. It attempts to produce a more holistic understanding of biochemistry, especially the question of folding in proteins.

On the other hand, systems biology is a life science in which an interdisciplinary approach focuses on complex interactions in biological systems, using a new point of view. It attempts to produce a more holistic understanding of biology, especially genetics. The new approach aims to construct a network of interacting processes that can be related to the information sciences (Buchanan et al. 2010). A major aim is to discover emergent properties of a system that would be understood by focusing on its complex interactions and relying on the information sciences. These computational techniques have given rise to systems astrobiology, where the new space science is also considered as a branch of biology (Chela-Flores 2013a).

Instead of applying the new methodology of systems biology to genetics, it is applied to other biologically relevant questions, namely the origin, evolution, distribution, and destiny of life in the Universe. The distribution of systems of habitable worlds with their biomarkers will be testable in the short term with forthcoming space missions mentioned above. This would justify subsequent use of quantitative systems biology methods that are already available in other branches of biology.

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