Origin of the solar system
The astrobiology point of view
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Workshop Report

This document present the report from the fourth AstRoMap workhsop held in Rome on 19-20 November 2014.

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Definition of science goals

Timeframe: ST= existing and planned infrastructure, MT= mission feasible with available techno, LT mission requiring massive technology and/or infrastructure development

Main objective of the workshop: From the state of the art (science and European capacity), identify current overarching scientific challenges and open questions related to to the study of the origin of solar system from an astrobiology point of view and define a stepwise approach to address them (with well-identified ST/MT/LT achievements) and technology and infrastructure development requirements and suggested investigations (lab, telescopes -ground and space-, space experiments, modelling, philosophy) required to progress on these issues.

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Some points to think about and develop:

In order to understand the origin of our Solar System and how life could develope and thrive on Earth we can now make comparison with many other Solar System. The study of extraterrestrial sysems is fort his reason an essential component of the study of our Solar System. Missions devised to study extraterrestrial planets are henceforth of interest fort the study of our Solar System.

- To be considered:
    - Programmatic aspects and how science policy can support/catalyse addressing the issue
    - How addressing the challenge can help to i) maintain European leadership and ii) develop complementary skills, competencies and expertise –
- Cross cutting issues:
- Technology: Which new technologies need to be developed for space missions whose objectives are to answer the questions defined in the workshop?
- Earth analogues: How Earth analogues can contribute to the study of the origin of Solar System?
- Planetary protection: What are the conditions and requirements for planetary protection and planetary ethics?

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The discussion started from revisiting the history of the Solar System using the expanded timeline prepared by K. Tsiganis, based on the one shown by D. Turrini the first day of the workshop. The discussion focuses mainly on three aspects: the dynamical evolution of the giant planets and the implication for the redistribution/delivery of water and organics at different times in the life of the Solar System; the formation of the planetary bodies (both giant and terrestrial) in the Solar System and their initial budget of water and of the elements needed for the rise of life; the timescales and the conditions for habitability on the Earth.

The discussion continued with a comparison of the different scenarios proposed for the formation and migration of the giant planets in the Solar System. The main outcome of the comparison was that water and volatile elements are delivered to the region of the terrestrial planets in all scenarios due to the action of the giant planets. In the classical scenario, the formation of Jupiter is sufficient to inject ice-rich planetesimals into the inner Solar System even in absence of orbital migration through the mechanism of the Jovian Early Bombardment (JEB). A moderate-to-marked migration (~0.25-1 au) of Jupiter in the outer Solar System during the JEB appears to reduce the flux of ice-rich planetesimals to the inner Solar System, favouring their ejection toward the outermost regions or their trapping into mean motion resonances. The latter mechanism (the resonant trapping of the ice-rich planetesimals) is however responsible for the delivery of water to the inner Solar System in the "Grand Tack" scenario. This scenario proposes that the giant planets crossed inward and outward the region of the terrestrial planets, with Jupiter reaching the current heliocentric distance of Mars: such extensive migration brought the ice-rich planetesimals trapped into the resonances into the inner Solar System and left there part of them during the outward migration of the giant planets. As a result, in all scenarios presently proposed for the early evolution of the Solar System (i.e. the first ~10 Ma) the presence of water and volatile elements inside the water ice condensation line appears to be a natural by-product of the appearance of the giant planets. It is presently unclear, however, how much of these volatile elements would actually survive the formation process of the terrestrial planets. The same holds true for the organic material originally present in the ice-rich planetesimals: did they survive the impacts that incorporated them in the growing terrestrial planets or were they destroyed?

If terrestrial planets may have already possessed the necessary budget of water and organic elements needed to give rise to life since their very formation, the immediate question is: why life appeared only several hundred millions years after they formed? The Earth and the Moon completed their formation about 4.4 Ga ago (i.e. about 40-60 Ma since the beginning of the life of the Solar System), yet life on Earth appeared only 3.5 -3.9 Ga ago. The appearance of life on Earth is temporally located immediately after the event known as the Lunar Cataclysm or the Late Heavy Bombardment (LHB), which should have occurred about 3.9 Ga ago. The near-coincidence between the end of the LHB and the appearance of life on Earth suggests that there might have been a correlation between these two events. The exact nature of this correlation is however uncertain. Did the LHB play a role in resupplying the terrestrial planets of the organic material and water that got lost during their formation process? Or was the LHB the final event of the most violent phases of the life of the Solar System and life appeared on Earth as a result of the more quiescent post-LHB environment? Before it is possible to address these questions, however, it is necessary to shed light on the environment on the Earth before the appearance of life. When exactly the Earth became habitable? Which factors influenced the most the habitability on Earth? From this point of view, the role of impacts is particularly important. Impacts can have both destructive and catalytic effects due to the energy released and the formation of craters, but it is currently unclear which effect is dominant and under which conditions. Another poorly constrained important factor is the influence of the radiation and the solar wind emitted from the young Sun, its interplay with the primordial atmosphere of the Earth and the implication of both for the habitability of the Earth's oceans and surface.

As a result of this discussion, several questions to be addressed at European and international level by the astrobiological community in the coming years were identified:

- What is the distribution of volatile and organic materials and, more generally, of the different elements and molecules in the circumsolar disk?
- Can organic materials present on/in planetesimals survive the impacts during the planetary formation process and the late bombardment events?
- Which is the role of impacts in creating sites favourable for the appearance/diffusion of life?

Which is instead their role in erasing or resetting organic materials and the first traces of life?

- Which is the role of endogenous activity of moons and terrestrial planets in creating sites favourable for the appearance/diffusion of life?
- How is the collisional environment on the primordial, pre-LHB Earth (fractures, crater saturation, ejecta blancketing, micrometeoritic flux)? Is the impact flux strong enough to reset any organic or life sign that formed in that period?
- Which is the oldest appearance of life on Earth and how does it temporally relate with the timespan covered by the LHB?
    - Does the LHB represent the mechanism to deliver organic and/or water to a sterile Earth or does it instead represent the last violent enough event to reset the prebiotic chemistry or destroy the first forms of life apperaring on an already habitable Earth?
    - Could have prebiotic chemistry/life appeared and disappeared (several times?) in the timespan between the formation of the Earth and the LHB?
- Which is the role of the Moon in stabilizing the climate and supplying energy to the primordial Earth's oceans through tides?
- Which is the role of the primordial atmosphere of the Earth in protecting the prebiotic chemistry?
- Which is the role of stellar evolution of the young Sun and its more violent stellar radiation/solar wind in affecting the habitability of the primordial Earth and its pre-biotic chemistry? Does it oppose pre-biotic chemistry, destroying it, or does it act as a catalyst, supplying energy for chemical reactions?

The discussion then evolved in identifying which interactions are needed with the scientific and technological communities dealing with planetary science, exoplanets, star formation and circumstellar disks in order to gather all the data needed to address the previous questions:

- *CIRCUMSTELLAR DISKS*: ALMA recently reached a resolution high enough to resolve circumstellar disks and observe the gaps created by forming giant planets. It is necessary to verify with the ALMA community and, more generally, with the scientific community involved in circumstellar disks to which extent it is possibile to use current observational facilities to produce resolved compositional profiles of the main molecules/elements in disks.
- *EXTRASOLAR PLANETS*: ESA M3 mission is Plato 2.0, whose goal is to search for terrestrial planets in the habitable zone of their stars. Plato will also provide accurate measurements of the stellar ages. One of the ESA M3 mission candidates was the Exoplanet Characterization Observatory (EChO), which aimed at characterizing the atmospheric compositions of exoplanets (both giant and terrestrial). To which extent is it technologically possible with existing facilities to characterize the atmospheric composition of terrestrial exoplanets? If so, will the data provided by Plato allow the selection of a sample of young terrestrial planets (< 1 Ga) to study their atmospheres as analogues of the primordial atmosphere of the Earth?
- *METEORITES AND EXTRATERRESTRIAL SAMPLES*: extraterrestrial samples collected in situ and brought back to the Earth are essential to improve our understanding of the sources of the elements necessary for pre-biotic chemistry and life, as the volatile components of meteorites are generally not preserved following the atmospheric entry and the exposition to the atmosphere up until the specimens are collected.
    - The collection of Mars samples requires to address the issue of planetary protection of the Earth upon return.
    - Europe is currently lacking a curation facility (during the discussion it is agreed that there is little point in creating national curation facilities, it is more efficient to think in terms of shared european facilities).
- *SPACE MISSIONS*: given the pivotal role that space missions play in providing extrasolar analogues (see above), in exploring habitable environments in the Solar System and in

collecting and returning samples, it is necessary to interact with the space mission community (both scientific and technological) to assess whether the financial instruments at their disposal are adequate for the development of new instruments and technologies of astrobiological interest (penetrators, sample collectors, nuclear power systems, etc.). In case such financial instruments proved inadequate, AstRoMap can act as intermediary/spokeperson on behalf of the community with the EU and ESA.

  - Two kinds of technologies proved high-priority in the discussion: enabling technologies (see the list above) and low-cost technologies for multiple identically missions to different targets (see e.g. Mars Express/Venus Express).

During the discussion several actions that the AstRoMap consortium can undertake on behalf of the astrobiological and planetary communities were suggested:

- Creation of a European Virtual Astrobiology Institute to coordinate and unify the different national astrobiological and planetary science communities.
- Recommend in the Roadmap that every mission to the outer Solar System should assess the possibility of performing fly-bys of target of opportunity during the crossing of the asteroid belt, during the cruise phase (NEOs, Centaurs, comets, Trojans) and upon entrance into satellite systems (irregular satellites of the giant planets) to gather the needed information to characterized the minor bodies continuum in the Solar System and its astrobiological potential.
- Recommend to ESA the development of pivotal enabling technologies:
  - nuclear power systems (solar technology is inefficient beyond the orbit of Jupiter);
  - ground-based communication network (achievable data rate significantly limit the potential of missions to the outer Solar System).
- Creation of a common European newsletter of astrobiological and planetary science results and activities for professionals and the general public. The newsletter can also act as press agency in english language for the relevant communities to advertise European results and activities.
- Solicit/support the creation of a European educational network involving countries with and without national space agencies (evaluate the possibility to propose/support a Marie Curie action for funding a training network as the first step of this action; the network can later be expanded and incorporated into the Europlanet project).
- Assess the opportunity to support ESA M4 (and later) mission proposals/themes of astrobiological interest.
- Assess the opportunity of recommending/supporting observational activities at European level and in collaboration with international partners for the characterization of the inner Oort Cloud through occultation surveys (either from ground or space).
- Contact the community of meteorite hunters at European level to involve it and assess their needs for support.
- Contact the network for fireball identification/alert and assess the opportunity of supporting the expansion of the network in the Roadmap.
- Involve in the AstRoMap community and the European astrobiological community the geological/biological communities already involved in the search of ancient rocks and microfossils. The aim is support and coordinate the efforts to identify the first appearance of water and life on Earth (to improve the constraints on the evolution of habitability on our planet).
- Recommend, support and/or initiate capacity building activities in third party countries by the European astrobiological and planetary science communities. Such activities should be coordinated with similar activities already performed by IAU.