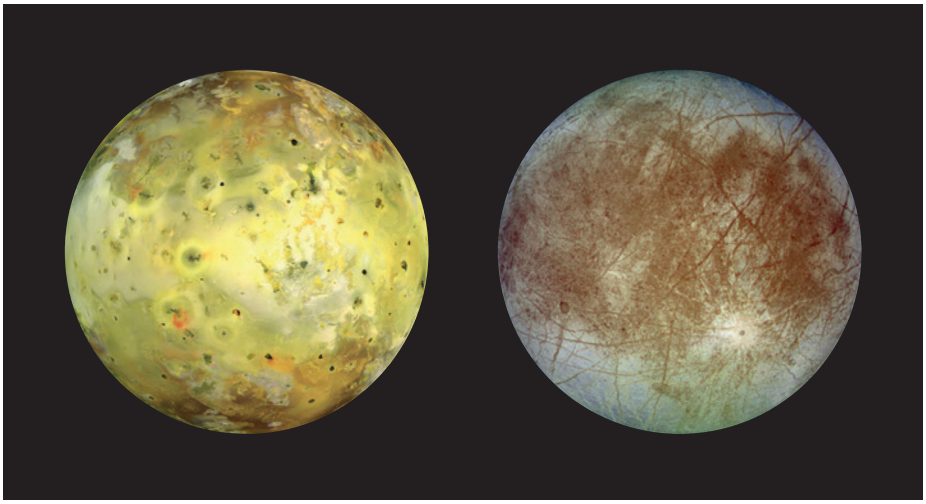
A chemist's guide to the Solar System

In the first of two essays that offer a chemistry-themed guided tour around the Solar System, **Bruce Gibb** looks at what sort of organic molecules are out there and just where you can find them.

In March 2004 the European Space Agency (ESA) launched the Rosetta spacecraft with a plan to slingshot it around the Earth until it caught up with a comet uninspiringly named 67P. Most of us probably forgot that fact until November of last year when the Philae lander — designed to touch down on the comet, essentially nail itself to the surface, and then perform a series of analyses — was detached from Rosetta to begin its descent. As reported widely in the media, Philae's landing did not go quite according to plan. To paraphrase the optimistic interpretation offered by the ESA: we didn't land once, we landed three times! (Or at least more than once.) Having bounced around the comet uncontrollably, the lander came to rest in a shady alcove where its solar panels are not currently able to receive enough sunlight to recharge the battery. Nevertheless, even in the short time that it remained fully operational, Philae did at least one thing that piqued the interest of organic chemists; it detected as-yet-undisclosed organic molecules on the surface of the comet.

This finding raises two interesting chemistry-related questions: how many organic molecules have been detected in space? And what are they?

These are important questions for astronomers of an organic chemistry bent — such as planetary scientists — and astrobiologists contemplating the existence of life in other parts of the universe. Not all astrobiologists are, however, wedded to the necessity of organic life; some think that alien life might be, well, weird[1]. And I mean really weird… like the sesame-seed-sized intelligent life-forms that live on the surface of neutron stars and rely on metabolisms based on nuclear chemistry[2]. As I said, weird! For those whom such a scenario is a little too far-fetched, then it all comes down to the unique complicatedness and complexity of organic molecules and what they do in water; or if you want to get just a little bit alien, an alternative solvent with properties similar to water — such as ammonia.



LEFT: NASA/JPL/UNIV. ARIZONA; RIGHT: NASA/JPL/DLR

Io (left) and Europa (right), category IV and II astronomical bodies, respectively (not to scale).

The number of different organic compounds that have been detected in space is currently around 110; at least according to André Brack of the CNRS in France[3]. A significant number of these have been identified by spectroscopic analysis of the more than 2,000 exoplanets that have been pinpointed so far. Exoplanet discovery is a pretty hot topic in itself at the moment, and with new instrumentation such as the James Webb Space Telescope coming online in the next few years, its future — unlike the apparent magnitude of these objects — is very bright indeed. With potential confirmation of the likes of ocean planets, super-Earths such as GJ 1214 b, and goodness knows what sort of new discoveries around the corner, planetary sciences looks very healthy.

But coming back down to Earth — or at least getting a lot closer to it — what sort of organic molecules have been detected in the Solar System? And where are they? So with a nod to *bona fide* astrobiologists and a wink to Douglas Adams, here's a personal guide to our Solar System from an organic chemist; a compendium not just of organic molecules, but also a few inorganics of interest to organic chemists (and potentially astrobiologists too). After all, it is hard to put together such a compendium by ignoring strikingly alien (but mostly inorganic) worlds such as Jupiter's Io.

It's best to start by defining where organic molecules do not figure prominently. Such an evaluation is inevitably tied to the 'plausibility of life (POL) on other worlds' scale defined by Irwin and Schulze-Makuch[4]. In their minds, the three necessary and sufficient criteria for life are (i) a fluid medium, (ii) a source of energy and (iii) constituents and conditions compatible with polymeric chemistry. Based on these factors they invoked five categories of heavenly body: category I (essentially equivalent to Earth); category II (evidence of liquid water, a source of energy and organic molecules); category III (a combination of the three requirements outlined for category II objects, but in such a way that could only result in exotic forms of life); category IV (possibility of an environment favourable to life in the distant past, but changes to the climate of the body make it unlikely that any life that was there still is); category V (forget it!).

There is, of course, only one category I body in the Solar System; but that's off-topic here. Jumping to the other extreme, for different reasons there are lots of category V bodies; the Sun is too hot, Mercury is too hot (mostly) and too small to retain much of an atmosphere. Some water-ice can be found in the various recesses of craters that are never exposed to direct sunlight, but Mercury seems to be free of liquid water and organic molecules. There are also many bodies in the Solar System that are too small to hold on to any atmosphere or volatile compounds, and so are very unlikely to build up any significant amounts of organics.

Hence we can mostly classify small moons as barren rocks and put them in category V on the POL scale. With these taken care of, we can turn to the more interesting category II and IV planetary bodies; we'll deal with category III bodies next time.

Let's start with those that are mostly devoid of organic molecules: category IV objects. First up is the hell-off-Earth Venus. Maybe there was more to this planet at one point, but the exceptionally high atmospheric temperatures and pressures — along with the CO_2 atmosphere and sulfuric acid clouds — make for a very organic-unfriendly world. To Star Trek fans, Venus is definitely a real-world, class Y (demon class) planet. However, it is possible that Venus was the victim of a run-away greenhouse effect and, at one point, was a lot more hospitable than it is today.

Hell comes in many different forms of course, so we should include beautiful Io in our discussion of category IVs. The innermost Galilean moon and fourth largest natural satellite in the Solar System, Io has over 400 active volcanoes. These are powered by tidal heating brought about by Io's erratic orbit, which is induced by orbital resonance with Europa. Such volcanic activity results in plumes and lava flows that paint the surface in gorgeous hues of yellow, red, white, black and green. Precisely which molecules give rise to all of these different colours is unknown, but ignoring the run-of-the-mill silicates, sulfur rules on Io — as a variety of allotropes and compounds. And if Io's turbo-charged volcanism is not a dynamic enough surface for you, consider also that because of its iron or iron sulfide core, the spinning of Io in the magnetosphere of Jupiter means that it acts as an electric generator, releasing ions that enhance the magnetic field of Jupiter. Combined with the intense ionizing radiation from Jupiter itself, Io loses 1 ton per second of its ionized atmosphere, which mainly consists of SO_2, SO, NaCl, and atomic sulfur and oxygen. Demon class indeed! Nevertheless, modelling does suggest that, at some point in its past, Io was a lot more conducive to organic chemistry and life; perhaps being water-rich and averaging −23 °C rather than having 2,000 °C lava spilling out onto a −113 °C surface[4].

Now let's move on to category II planets and moons. There are a surprisingly large number of Solar System bodies that fit the definition of category II; however, this is more because of the presence of large amounts of water rather than large amounts of organics. Consider, for example, our next-to-nearest planetary neighbour — Mars. There's a lot of water locked up in the poles of the red planet, enough apparently to flood the complete planet to a depth of eleven metres. However, with a much thinner atmosphere than that of Earth (the atmospheric pressure on the surface of Mars is less than a hundredth of that found at sea-level on Earth), liquid water can only exist at the very low elevations, and even then only transiently. Nevertheless, the countless dry ravines and deltas suggest that water did at one time flow freely over the terrain (based on this assumption Mars could be classified as a category IV body).

In terms of organics, what has been found on Mars has been fairly limited. The most prevalent organic compound is atmospheric methane, the existence of which is somewhat of a conundrum because unless it is being continuously produced, it should have disappeared long ago. There are three plausible explanations for its presence: (i) the ice at the poles is a mixture of normal ice and ice filled with methane (methane clathrate), and these two forms of ice are continuously emitting and absorbing methane to produce a steady-state concentration of the gas; (ii) it is being generated by the reaction of water, CO_2 and minerals such as olivine $(MgFe)_2SiO_4$; or (iii) it is produced by methanogenic microbial life. Needless to say, the last of these possibilities would have considerable ramifications. As for bigger 'organic' molecules, there seems to be small quantities of formaldehyde, ammonia and perhaps aromatics such as chlorobenzene[5], but whether there are larger molecules still is unclear because the instrumentation so far sent to Mars has only been designed to detect relatively small molecules. Bearing in mind this caveat, with the exception of methane there aren't any obvious large quantities of organic molecules. Continued exploration on the ground and in the sky will tell us more.

There are, however, more intriguing category II bodies in our Solar System than Mars. Moving further out, we can stop off at the Galilean moons once again: specifically Ganymede and Europa, and include in this section of our tour Saturn's moon Enceladus. What these moons have in common — at least at a very general level — are hot iron-rich cores (powered by radioactive decay and/or tidal heating induced by their gas-giant parents), surrounded by a thick water mantle[6–8] and an outer crust of water-ice, clay and organics. We're confident of the existence of saltwater oceans under the surface crust of these moons for several reasons, not least because in the case of Europa and Enceladus they are leaking! The Hubble Telescope spotted this first on Europa, but the recent Cassini–Huygens Mission to Saturn has included several flybys — and even fly-throughs — of the plumes of Enceladus[9].

In the case of Enceladus the water plumes contain mainly CO_2, CH_4 and NH_3. Whether larger organics are present in the plumes remains to be determined by further analysis and more advanced probes, but there are certainly more-complex molecules on the surface of these worlds[10]. The stains on their surfaces seem to be a combination of clays and tholins. Tholins — a term coined by the late great Carl Sagan and his colleague Bishun Khare — are heteropolymers derived from the photochemical reaction between simple alkanes, such as methane, and nitrogen. The simplest products of such reactions are ethane, acetylene, methylacetylene, diacetylene, hydrogen cyanide, cyanogen, cyanoacetylene, dicyanoacetylene… you get the picture. The precise composition of tholins is likely to be complicated and system specific, but we are learning more about them by studying their formation in the lab; and from my admittedly biased perspective, it's good to see supramolecular chemistry — in the guise of crown ethers — helping out in this regard[11].

The implications of such category II systems are obvious. Energy, warm water, and complex organic molecules are a heady brew for the astrobiologists. And when you throw many different inorganic salts and oxygen (formed by the interactions of cosmic rays and ice) into the mix, you can understand why Europa is a prime future target in the search for extraterrestrial life[12]. It may look like a beat-up marble (it's actually the smoothest body in the solar system), but it's got a lot going for it. And even if there are no fish, plankton or bacteria, the organic soup potentially hiding under the surface of Europa would be a veritable treasure-trove of fascinating chemistry. What exotic processes can occur in such an alien environment? The mind boggles. And we haven't even got to the really exciting organic chemistry yet! For that you'll just have to wait for the second essay in this two-part series. ❐

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