Life, the universe and microfluidics

Bradley M. Stone† and Andrew J. de Mello ponder the fundamental question of the 'origin of life' in the universe, and discuss whether miniaturised analytical instruments could be put to use within instrument payloads in upcoming space missions that aim to search for biogenic precursor molecules

The search for the origin of life

One of the holy grails of modern physical and biological science has been to understand the nature of the origin of life. In the present day context, this is often qualified by 'in the universe', or at least, 'within the galaxy', as opposed to 'on the early Earth'. This modern perspective has evolved due to the increasing confidence by many scientists that, given that we already have one data point that tells us that life originated (most probably) on Earth, life must have originated elsewhere in the galaxy as well. The rationales put forward in favour of this viewpoint are typically based on the following arguments: the statistical improbability that life only originated in about one star system in a galaxy of approximately 300 billion stars; the ubiquitous nature of life on our own planet, even in extreme environments that would seem to be hostile to life; and the increasing evidence for the existence of some biogenic precursor molecules throughout our galaxy. Furthermore, a significant and ever growing inventory of organic molecules have been identified in the interstellar medium,[1] in interplanetary dust particles[2] and meteorites,[3] and are believed to be present on comets.[4] Therefore, many members of the 'origin of life' community now envision a scenario in which the substances necessary for the commencement and evolution of life were delivered to the early Earth by comet and asteroid impacts that occurred at an elevated rate in the early solar system compared with the present day.

The current mission statement of the National Aeronautics and Space Administration (NASA) in the USA includes the following: "To explore the universe and search for life". More specifically, the Space Sciences Division of NASA poses the following questions in regard to fulfilling its role within the context of the NASA mission: (1) How did the universe begin and evolve? (2) How did we get here? (3) Where are we going? (4) Are we alone? While the third question might be considered separately, the other three are directly linked together by the question "How did life originate in the universe (galaxy)?" Consequently, attempting to find answers to this question is of the highest importance.

In examining the possibilities of answering this question, at least in part, in the near term there are a number of possible exploratory missions that have been considered by NASA (and other space agencies) that could potentially shed light on the origin of life question. Here follows a brief, and certainly not exhaustive, summary of some of the possibilities.

1. Mars

Long thought to be the most likely extraterrestrial body in the solar system to harbour life, Mars has been an intriguing candidate for performing origin of life experiments for decades. In fact, the notion that life might exist on Mars certainly dates back to the 19th century (*e.g.* H. G. Wells in his classic novel "War of the Worlds"). Current mainstream thinking is that life most likely does not now exist on Mars given the present extreme conditions there (surface temperatures averaging only −60 °C, lack of significant atmospheric pressure, lack of O_2 in the atmosphere and no significant H_2O on surface—save possibly at the south pole, no liquid water

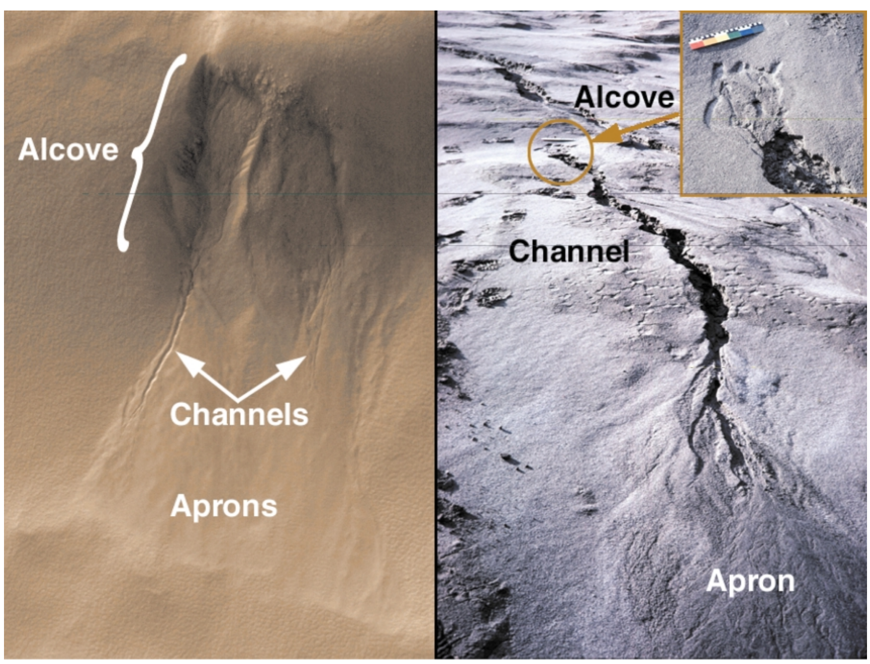

Fig. 1 Recent image of the Martian surface (left), taken by the Mars Orbital Camera on board the Mars Global Surveyor Spacecraft, showing erosion features strikingly similar to those seen on Earth due to water (right). Source: NASA/JPL/Malin Space Science Systems MGS MOC Release No. MOC2-234, 22/6/2000.

† Bradley M. Stone is Professor of Chemistry at San Jose State University. He is presently the University Co-Director of the NASA Faculty Fellowship Program for NASA's Ames Research Center and Dryden Flight Center.

 DOI: 10.1039/b210360p

anywhere). However, there is a distinct likelihood that life did in fact evolve in ancient times, since the climatic and geological conditions are thought to have been similar to those of the early Earth. Recent photographic images of the planet's surface provide compelling evidence of channels and alluvial plains formed by ancient water flows (Fig. 1). Furthermore, the early Viking missions to Mars (*ca.* 1977) included an experiment designed to detect (indirectly) the presence of life (unfortunately the results were inconclusive).[5] More recently, evidence has been put forward for the existence of bacterial life on ancient Mars through the examination of the now-famous Allen Hills (ALH84001) meteorite known to have originated from this planet.[6] Future missions to Mars will undoubtedly follow up on this whole notion. The primary question is how to design better experiments that can provide conclusive answers. More importantly, what are the right questions to ask in the design of the experiments that will go on these missions?

2. Comets

If indeed comets were responsible for bringing necessary organic material to the early Earth, their continued study is of the highest importance. To this end, several missions to comets are currently planned or in progress. Most notable is the NASA Stardust mission, which is slated to bring back to Earth samples of a comet.[7] Launched in February 1999, the Stardust spacecraft is scheduled to encounter Comet Wild 2 in 2004, and return to Earth with samples in January 2006. The samples will be in the form of dust particles captured from the comet's tail, containing water and quite possibly complex organics that were formed in interstellar evolutionary processes. Of course, getting these samples back to Earth is only half the battle—the particles must then be analysed for the many possible organic molecules that could be present—not a trivial exercise. It is therefore essential to have the technological capability to discern the nature of the organic material trapped within the ices contained in these particles.

3. Europa

One of the bodies in the solar system most widely talked about today in terms of the 'origin of life' question is Europa—one of the Galilean satellites of Jupiter. Photographic evidence from the Voyager missions, along with remote spectroscopic studies, have revealed a world that some have speculated could harbour life. Europa's cracked, frozen oceans (giving evidence of geothermal processes) have stimulated the interest of many scientists who suspect that life may have originated in Earth's oceans near geothermal vents (Fig. 2). Possible missions to land on Europa, with the intent of investigating the origin of life issue, are currently in the early stages of planning.

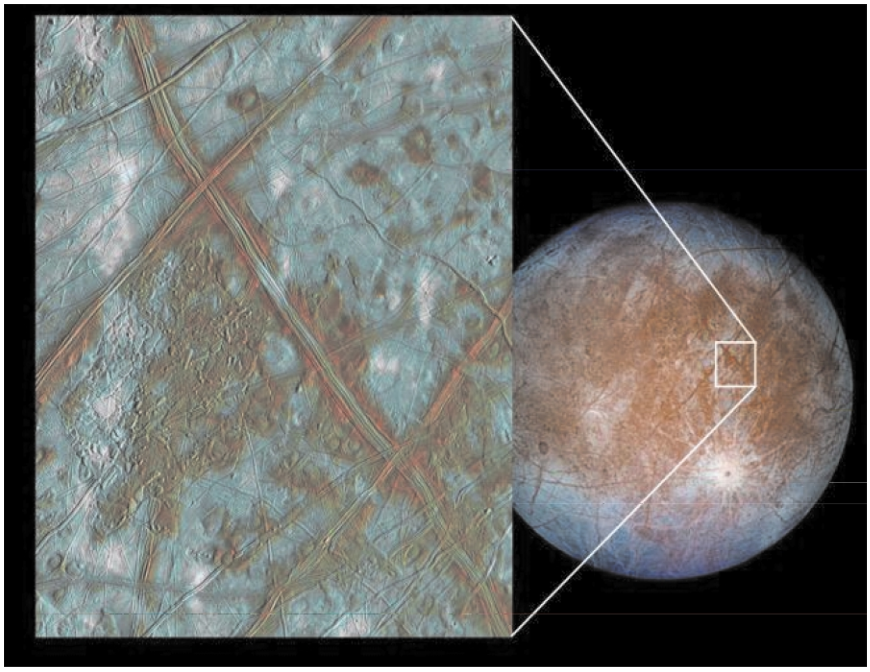

Fig. 2 One of the Galilean satellites of Jupiter: Europa. The striations appear to be cracks on the surface of a frozen ocean, indicative of ice flows that are seen on Earth in the polar regions. Source: NASA Planetary Photojournal Image ID: PIA03002 25/9/2000.

4. Titan

The rich photochemical haze that envelops Titan, the largest moon of Saturn, in its stratosphere has been thought to be evidence of a chemical factory for complex organic molecules (Fig. 3). Titan's predominantly N_2 and CH_4 atmosphere, together with interaction with short wavelength solar ultraviolet radiation, have been postulated to be responsible for this haze by the production of, and subsequent photopolymerization of, acetylene—forming aerosol particles of "polyacetylene".[8] The existence of N_2 in the atmosphere further suggests the possibility of nitrogen chemistry,[9–11] which has important consequences in the development of molecular species important for the initiation of life. Although not thought to be a potential habitat for life, either ancient or modern, Titan remains an interesting laboratory for the study of complex organic chemistry. The Cassini mission, with the Huygens probe due to enter Titan's atmosphere in 2004, will give us much more direct information regarding this moon, but the planning for future missions is inevitable.

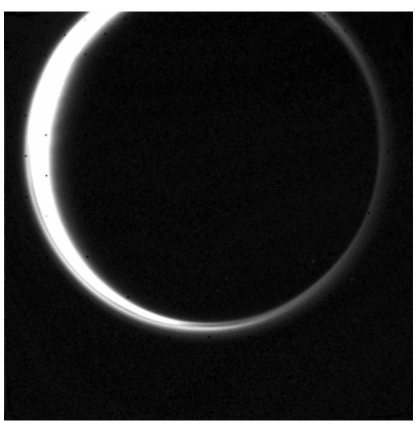

Fig. 3 Image of Saturn's largest moon, Titan, taken by the Voyager 2 spacecraft on 25th August 1981. The haze produced by aerosol particles in the upper atmosphere can be seen in the photo by looking at the limb of the planet. Source: NASA Planetary Photojournal Image ID: PIA02290 25/9/2000.

5. Other moons

There are other possibilities within the solar system for the presence of liquid water existing under an insulating layer of water ice. Other moons besides Europa, including Ganymede and Callisto (of Jupiter), Titan and Rhea (of Saturn) and Oberon and Titania (of Uranus), where water ice was previously know to exist,[12] are now thought to possibly have oceans existing under a thick layer of ice.[13] These worlds could also be the objects of future planetary missions with the intent of exploration for the possibility of life, or life's precursors.

6. Meteorites

One simple way to investigate extraterrestrial material is to examine meteorites that have fallen to Earth, as well as dust grains and micrometeorites that are collected in Earth's atmosphere. Material in these forms continuously rains down upon our planet, and can provide some key information regarding the extraterrestrial and possibly extrasolar inventory of organic species. Of course a key issue in examining these objects for organic material is to make sure that contamination by terrestrial materials is minimised, or at least can be discriminated against. Recently, Oliver Botta and Jeffrey Bada of the Scripps Institute of Oceanography have examined material extracted from the Murchison meteorite using a variety of standard analytical techniques.[3] An extensive inventory of families of organics (aliphatic and aromatic hydrocarbons, carboxylic acids, amino acids, sugars, DNA bases, quinones, fullerenes, heterocycles, *etc.*) has been identified.[1] The extraterrestrial nature of these organics was confirmed on the basis of the demonstration of isotopic and enantiomeric (for those compounds possessing chirality) ratios not consistent with those found in the terrestrial biosphere.

Missions to 1–5 above will all require instrumentation that will 'fit the bill' in terms of the various analytical techniques required to discern the many potential types of species that need be differentiated and analysed, along with the necessary miniaturisation so that the instruments can fit on the spacecraft and consume only as much power as allotted within the limitations of the spacecraft design. The concept of using microfluidic or lab-on-a-chip devices for the detection and analysis of chemical species on board interplanetary missions seems to be a natural fit. Ordinarily, instruments that end up on space missions are built to full scale first to test the concept. If successful, the instrument must then be engineered so that it will fit within the various design parameters of the spacecraft (most notably minimising volume, mass and power requirements). With chip-based instrumentation, miniaturisation, in terms of both reduced size and power requirements, has already been demonstrated. Consequently, the technology appears inherently appropriate for spacecraft missions, provided that the necessary chemical analyses can be performed. In this article, we survey some of the miniaturised and chip-based systems that have been suggested for future missions, and discuss possible future directions that this technology must explore to be chosen for upcoming missions.

What molecules do we look for?—biogenic precursors

Before discussing possible experiments and instrumentation for the detection of molecules associated with the origin of life, it is more instructive to discuss specifically what one would look for in such an experiment. The direct detection of living organisms by remote sensing is more problematic that it might initially appear. For example, our own spacecraft (designed for this purpose) landing on numerous sites (such as the Mongolian desert or Antarctica, for instance) back here on the Earth would have difficulty detecting life, despite the abundance of different organisms on our planet. Indirect sensing of life by looking for 'biomarkers' that would indicate the presence of life, for example the isotopic composition of CO_2 in the atmosphere, has been proposed.[14] However, the detection of so-called biogenic precursors—the molecules that must be present to initiate life, while more feasible, is still non-trivial. First, one must identify which species to detect, on the basis of their necessity in the origin of life scheme. Then, an analytical method must be chosen to positively identify those species, and distinguish them from any molecules that might interfere. In the proceeding section, we list some of the families of molecules that are most often discussed in terms of origin of life—the so-called biogenic precursors.

1. Amino acids

Amino acids are the essential molecular components of living organisms on Earth and are often at the top of the list of molecular species associated with life. Nevertheless, there are difficulties with the proposed mechanisms for their non-biotic origin on the early Earth. Their formation *via* Miller–Urey type (terrestrial) syntheses would be severely limited by the oxidizing conditions that are thought to have been prevalent on the early Earth. However, the detection of amino acids in meteorites has already been well established (see below). The idea that amino acids could have been delivered to Earth *via* comets and meteorites has been strengthened by recent studies published simultaneously in *Nature* by two research teams; one by a European group led by Mayo Greenberg[15] and the other spearheaded by Max Bernstein and Jason Dworkin at NASA's Ames Research Center.[16] In the former study, an interstellar ice analogue (containing water, methanol, ammonia, carbon monoxide and carbon dioxide) was irradiated with UV at 12 K. Analysis of the resulting residue (subsequent to hydrolysis by treatment with hydrochloric acid) by GC-MS demonstrated the existence of 16 amino acids, with all chiral products exhibiting enantiomeric separation, thus confirming the possibility of spontaneous generation of amino acids in the interstellar medium. In the latter study, a similar interstellar ice analogue (a mixture of water, methanol, ammonia and HCN) was irradiated with UV at 12 K. The residue, prior to hydrolysis, was analysed by HPLC and the authors report the detection of the amino acids serine, glycine and alanine (amongst other compounds). These two studies show that the synthesis of amino acids in the interstellar medium could be, at least in part, responsible for the existence of amino acids that were delivered to the early earth. However, it should be noted that Pascal Ehrenfreund *et al.* have recently demonstrated that the lifetime of amino acids in the interstellar medium may be limited due to the harsh ultraviolet radiation that these compounds would experience in that environment.[17]

More direct evidence of amino acid generation in extraterrestrial environments has been provided by analyses of meteorite samples (*e.g.* the Murchison and Murray meteorites).[3] Various studies have demonstrated the presence of amino acids in such samples. As noted, the discovery of amino acids on other planetary bodies would necessitate the inclusion of chirality analysis, as this is a central issue with respect to biological organisms. Amino acids in living organisms on Earth are of exclusively one enantiomeric form (specifically, all amino acids found in proteins are of the L-enantiomeric form[18]), in direct contrast to laboratory syntheses of amino acids, which result in racemic mixtures. Clearly, life as we know it has developed with a clear preference for one chiral form exclusively over the other—and this may prove to be an important "biomarker" when exploring amino acids of extraterrestrial origin.

2. Polycyclic aromatic hydrocarbons (PAHs)

Although not thought to be directly associated with the origin of life, there is now strong evidence that these multi-ringed molecules are an important source of carbon in the interstellar medium.[17] If one includes substituted PAHs and heterocycles in this category, then certainly this class of compounds may be an important precursor to many molecules of biological importance. PAHs have already been detected in interplanetary dust particles[19] and micrometeorites,[20] have been identified as the source of ubiquitous galactic infrared emission bands,[21] and there is a strong argument that these compounds are responsible for many of the so-called Diffuse Interstellar Bands[22] (DIBs, absorption bands that are observed due to species in the interstellar medium). In particular, cationic and anionic species appear to play an important role.[23,24] Recently Bernstein and colleagues at NASA have shown that alkyl substituted PAHs can be formed under interstellar conditions.[25] These molecules had been claimed to be biomarkers (*i.e.* evidence for early life) in the Allen Hills meteorite by McKay *et al.*,[6] but this work demonstrates that these compounds could have been synthesized on interstellar dust grains by the irradiation of the ice mantles coating these particles by ultraviolet radiation.

3. Purine and pyrimidine bases

Since DNA and RNA are so intimately associated with living organisms, as the keys to the genetic code and protein synthesis, the purine and pyrimidine bases that are the genetic information component of the nucleotides would be good candidates in the search for the origin of life (if we assume that life elsewhere is based on similar genetic systems). At the very least, we know that it was essential that these heterocyclic bases must have been available on the early Earth, and so a search for them elsewhere in the solar system seems reasonable. Purines and pyrimidines, along with other related, biologically important nitrogen heterocycles, are known to be present in meteorites.[26–28]

4. Hexamethylenetetramine (HMT)

Louis Allamandola and co-workers at the NASA Ames Research Center have investigated the formation of complex organic species in interstellar and cometary ice analogues for many years.[4,29] One intriguing species that is found upon the UV irradiation of these ices is hexamethylenetetramine (HMT).[30,31] Subsequent UV irradiation of HMT has been shown to form various nitriles. Furthermore, HMT is known to hydrolyse under acidic conditions to form, amongst other species, amino acids. Consequently, HMT may be an important biochemical precursor for the formation of biological molecules of importance on the early Earth and potentially elsewhere.

5. Quinones

Quinones are a group of molecules that "in many cases seem to take part in oxidation–reduction cycles essential to a living organism".[32] Recent laboratory results by Max Bernstein and co-workers[33,34] at NASA's Ames Research Center suggest that quinones might be readily formed by the UV irradiation of PAHs contained in H_2O ice mantles on interstellar grains.

6. Other molecular species

Of course, there are a host of other molecules associated with living systems. These include sugars (which have been detected in meteorites[35]) and other carbohydrates, carboxylic acids, alcohols, ketones, aldehydes. This means that there is an enormous range of experimental possibilities that could be utilised in an extraterrestrial mission. The key will be to identify the best experiment.

The use of chip-based instruments on future space missions

The idea that microfabricated analysis systems could be used in extraterrestrial environments is not new. In fact, the small size and low power requirements of the first silicon gas chromatograph fabricated by Stephen Terry and co-workers at Stanford University in 1975 were seen at the time as ideal characteristics for better utilising spacecraft resources.[36]

At a fundamental level, chip-based analysis systems have been shown to possess many distinct advantages over their conventional counterparts. Nevertheless, when designing an instrument for space flight purposes (as opposed to terrestrial-based instrumentation) many additional considerations must be taken into account.

Size

Probably the most obvious feature of typical chip-based instruments is the small instrumental footprint. Planar chips fabricated from glasses, silicon, ceramics, polymers or plastics are usually a few cm^2 in area, weigh a few hundred grams at most and have minimal volume. These characteristics are clearly desirable for 'in-the-field' measurements, but virtually essential for extraterrestrial applications, where the number and complexity of on-board instruments is determined by allowable spacecraft payload mass.

Power requirements

As an example of the typical power requirements for extraterrestrial missions, let's consider the joint NASA and ESA (European Space Agency) Cassini mission, presently on its way to Saturn. Cassini carries with it the Huygens probe, built by the ESA,[37] which will separate from the Cassini spacecraft and descend into the atmosphere of Titan to conduct experiments during a 150 min journey to the surface, upon which it will crash and be destroyed. The Huygens probe carries a payload of six experiments, which collectively require 1800 W during the lifetime of the spacecraft. This power will be supplied by five $LiSO_2$ batteries. Amazingly, this is slightly less that the power used by a typical electric kettle in the UK! Even so, further reductions in instrumental power consumption will allow a more diverse number of experiments to be performed in such a situation. Chip-based analysis systems typically exhibit extremely low power consumption. For example, microfabricated electrophoresis systems can provide for high efficiency separations of a range of molecular species with power consumptions much less than 1 W. Similarly microfabricated heaters for chip-based systems can be used to effectively control sample temperatures with power requirements of only a couple of watts.

Integration and automation

Since all interplanetary missions in search of life are unmanned, instruments must be operated remotely. Normally a 'wake up' signal transmitted from Mission Control will be used to activate or prime a given instrument. The instrument will then operate automatically for a given period of time, transmitting data back to Earth. The logistics of this scenario are complex and require that a given instrument operates efficiently after long periods of inactivity (*e.g.* almost 7 years in the case of instruments aboard the Huygens probe). Due to the high levels of integration and automation possible within chip-based systems and the lack of components with moving parts, microfabricated analysis devices are potentially good candidates for such uses. Furthermore, the effects of system failure can be minimised by building redundancy into each instrument. Microfabrication procedures allow for the facile construction of parallel devices within a monolithic substrate. Consequently, if a single device fails another is on hand to take on its function. Although this approach is theoretically feasible using conventional technologies, cost, power and weight limitations render this technically formidable.

Technical advantage

The ability to perform rapid measurements during a limited time period is key to many current space missions. The Huygens probe, for example, will only have approximately 150 min to make its measurements and transmit the data back to Earth before it is destroyed. This means that measurements must be rapid and efficient to maximise information output. It is well established that microfluidic systems can afford both high analytical performance whilst maintaining high analytical throughput. Small volume and low-concentration samples may be analysed with high sensitivity, and laminar flow regimes may be used to effectively control reagent motivation or chemical reaction. Perhaps more importantly, the ability to integrate novel components and formats within a planar device may often generate new functionalities not attainable in conventional instruments and allow new types of experiment to be performed. This may be especially important for many situations where the time available for measurement is limited.

Based on these simple observations microfluidic systems appear to hold much promise as future instruments for interplanetary space missions. Indeed the possibility of using chip-based devices as part of a spacecraft instrument package, for the analysis of organic material of possible biological and/or prebiological significance, has recently been proposed by a number of groups. We will briefly discuss a few of these. Our intent is not a comprehensive review of proposed experiments utilising microfluidic technology, but rather some examples to demonstrate the feasibility and potential advantages of such techniques.

Microfluidic systems for chromatography, capillary electrophoresis, mass spectrometry, DNA sequence analysis, DNA amplification, chemical synthesis and process control have been intensively studied and developed over the past decade. Consequently, a bedrock of analytical methods is available for the identification of biogenic precursors in extraterrestrial environments.[38]

Experiments utilizing microfluidic technology have previously been proposed for spaceflight. Many of these form the heart of experiments that are designed to take advantage of the microgravity environment on the Space Shuttle or the International Space Station. An ESA consortium recently designed and built a miniature space bioreactor for the culturing of yeast cells in microgravity.[39] The bioreactor fabricated using conventional micromachining methods provides controlled growth conditions and allows on-line delivery of biological parameters. The bioreactor has already flown on two space shuttle missions (Spacelab, Second International Microgravity Laboratory in 1994 and in the Spacehab, in the Shuttle to Mir Mission in 1996). Results from these missions demonstrate the feasibility of such devices for space-based applications and the demonstration of biological effects in microgravity environments. Further experiments are planned on board the International Space Station. More generally, the development of instrumentation for use in space missions at NASA is driven by the goals of superior performance, faster response times and lower cost. New generation instruments are designed to weigh less than 1 kg, occupy volumes less than 2 L and consume less than 5 W. All these requirements naturally lead to an interest in microfabricated technology and consequently much current research is focussed on the development of MEMS based technology for robotic planetary exploration.[40]

More relevant to the current analysis, Jeffery Bada at the Scripps Institution of Oceanography at the University of California, San Diego has recently discussed the development and characteristics of modern day instruments for detecting extraterrestrial life (or at least some of the biogenic precursors for life).[41,42] Bada supports the use of microfluidic devices (specifically microfabricated electrophoresis devices) for the detection and identification of amino acids that might be extracted from Martian soils. An ideal instrument would have the capability of distinguishing between the enantiomeric forms of the amino acid, and would therefore allow for the possible distinction between amino acids associated with living (with a complete bias towards one enantiomer) *vs.* non-living systems (racemic mixtures). To this end, Bada along with Richard Mathies from the University of California, Berkeley, have described a microfabricated capillary electrophoresis (CE) device that can determine amino acid composition and also provide chiral resolution of relevant enantiomers.[43] A chip-based CE system incorporating a folded separation channel (19 cm long × 150 µm wide × 20 µm deep) was used to separate a number of derivatised amino acid enantiomers in less than 4 minutes. Furthermore, chiral amino acid separations were performed on hot water extracts taken from the interior and exterior of the Murchison meteorite (Fig. 4). Results from this study yielded enantiomeric resolution comparable to conventional HPLC and GC/MS methods, but in ultra-short times and using only a 100 µL of sample. Although the results from this feasibility study are impressive, the authors note that the development of a

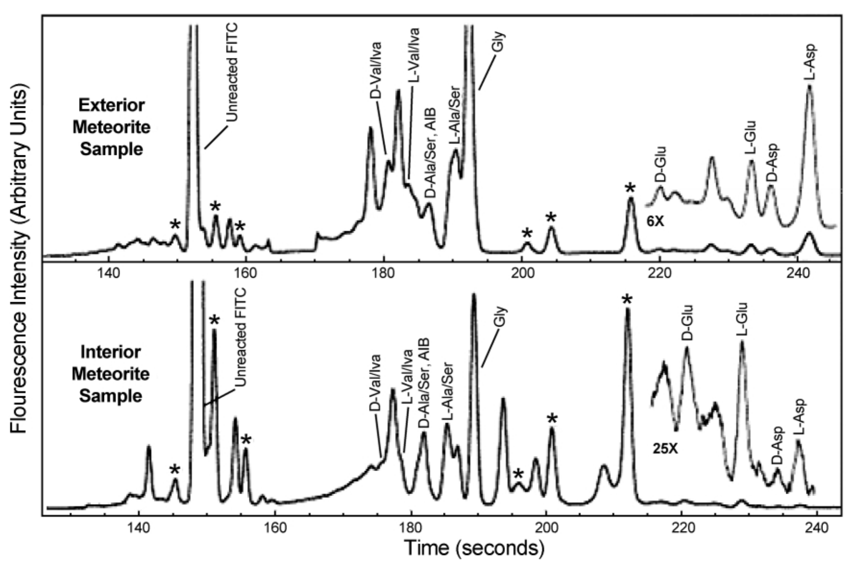

Fig. 4 Electropherograms of FITC-labelled amino acid extracts of samples taken from the interior and exterior of the Murchison meteorite performed on a glass CE microdevice. Channel dimensions: 190 mm long × 150 µm wide × 20 µm deep, separation voltage: 550 V cm^{-1}. Adapted with permission from ref. 43, © 1999 American Chemical Society.

fully integrated chip-based system for *in situ* measurements is non-trivial due to the need for additional processing stages such as amino acid extraction, extract purification and derivatisation. To address this issue, the researchers are developing a scheme to extract and deliver materials directly into CE microdevices. This involves formation of an aqueous extract by heating samples in hot water for an hour, followed by freezing and sublimation of the extract at Mars ambient pressures onto a cold finger. The sublimed ice/amino acid mixture is then delivered directly to a reservoir interfaced to the microdevice.

Additionally, Ronald Crawford and colleagues at the University of Idaho and NASA demonstrated, by a series of terrestrial-based experiments, the feasibility of searching for extraterrestrial life based on the thermodynamics of electron transport, *i.e.* the detection of redox-active molecules (*e.g.* quinones) that might supply the necessary energy to support life.[44] Using a number of analytical techniques (such as solvent extraction, filtration, HPLC, CE and ESI-MS) on a series of representative electron transport compounds, bacterial cultures, and soils the team demonstrated the viability of the approach. Based on these results the authors have proposed a conceptual design for a chip-based device for inclusion in a "'life detection module" as part of a spacecraft payload. The envisaged device includes an extraction module (designed to handle traditional solvents and supercritical CO_2), a variety of separation and detection elements, ESI-MS for structural determination, and control electronics. Development of this concept is ongoing.

Over the past two decades Mass Spectrometry has developed into one of the most powerful tools for molecular detection and identification. To this end, there has been much interest in miniaturised or microfabricated mass spectrometers for in-the-field applications.[45] For extraterrestrial applications, miniaturised mass spectrometers are highly desirable due to their inherent simplicity and ability to provide for high-information content measurements in short times. For example, Tim Cornish and co-workers at Johns Hopkins University have developed miniature time-of-flight (TOF) mass spectrometers for use in remote locations (one might argue that using these instruments on other planetary bodies in the solar system may seem to "fit the bill").[46] Interestingly, they have recently described a miniaturised laser TOF-MS for elemental, isotopic and organic analysis of unprepared soil samples. The beauty of this approach stems from the omission of complex sample preparation stages, and importantly, the instrument can be miniaturised to the size of a soda can without any loss in performance. Ara Chutjian and colleagues at NASA's Jet Propulsion Laboratory in Pasadena have recently reported the construction and operation of a miniature quadrupole mass spectrometer array (and gas chromatograph) for NASA flight missions.[47] The mass spectrometer is approximately 5 cm long and forms part of a shoebox system weighing approximately 5 pounds (Fig. 5). The instrument has been refined for the analysis of N_2, O_2, hydrazines and ammonia, and is planned for use in both manned or robotic spaceflight. Current mass spectrometers used in the Cassini mission to Saturn and the Galileo mission to Jupiter weigh between 20 and 24 pounds and consume about 25 watts of power, whist the quadrupole array system consumes approximately half that. Although the system is currently being targeted at the analysis of ammonia leaks in the International Space Station, the team plan further miniaturisation and micromachining to reduce weight, size and power consumption, whilst improving resolution. These improvements will hopefully allow the system to be used in both planetary atmospheres and on planet surfaces. A more detailed assessment of miniaturised and microfabricated mass spectrometers can be found elsewhere.[48]

Another analytical technique of great utility for the detection of biogenic precursor molecules is gas chromatography. Again, there have been many examples of miniaturised and micromachined systems for portable applications,[49] and so their use as instruments in future space mission is to be expected. As an example, Krzystof Malecki and co-workers at Wroclaw University of Technology in Poland have developed a silicon-glass gas chromatograph based on micromachined technology that is specifically designed for in-the-field applications. Indeed, the authors are currently focussing on the development of microfabricated GC systems for the analysis of astronomical objects in extraterrestrial environments.[50]

Fig. 5 Image of minature quadrupole mass spectrometer array. Source http://technology.jpl.nasa.gov/gallery/microchips/micro_index.html

The future

Although the studies presented herein are small in number, and far from comprehensive, they clearly demonstrate that the use of microfluidic systems as analysis tools in extraterrestrial environments is under serious consideration. The small instrumental footprints, high levels of functional integration and low power consumption typical of microfabricated analysis devices have been foremost in attracting the attention of mission scientists. The simple combination of these features could potentially facilitate the creation of 'space laboratories' equipped with dozens of distinct analytical instruments, whilst maintaining low payload masses and minimal power requirements. Due to the long timeline for the development of instrument payloads for spacecraft (the time duration from the initial inception of the idea to launch of the spacecraft will typically be on the order of many years) and the relative infancy of the microfluidic system development, few chip-based instruments have actually been used or tested in recent interplanetary missions. Nevertheless, a number of MEMS based technologies, including microgyroscopes, micro-propulsion devices, biomedical devices, adaptive optics and micro-instruments, are currently under development by NASA and ESA teams for forthcoming missions.[51] The successful implementation of chip-based systems in future missions will in large part be dictated by achievable degrees of functional integration. Although many unit functions such as filters, sample extraction units, heaters, separation columns and chemical reactors can be integrated within a planar chip format, other components such as light sources, detectors, control electronics, signal transmitters must also be integrated within the instrument footprint. Although feasible, this remains and will continue to remain a technical challenge, especially when considering the stringent requirements of instrumental payloads. Furthermore, since a typical instrument remains dormant during the vast majority of an extended interplanetary cruise (apart from its wake up clock) redundancy must be built into each unit operation to avoid rather costly instrument failures.

In conclusion, this discussion is intended to stimulate the interest of at least some to consider the enormous potential that exists for the application of microfluidic technology to the space program, and to missions geared towards the understanding of such fundamental questions as the origin of life. The development of new instruments on the micro and nano scales with these purposes in mind will be a fruitful field for years to come—as we believe that we are just at the tip of the iceberg in terms of the use of chip-based devices in this capacity.

Acknowledgement

We acknowledge Dr Max Bernstein of the Astrochemistry Group at NASA Ames Research Center, Moffett Field, California and The Center for the Study of Life in the Universe, SETI Institute, Mountain View, California for invaluable comments and suggestions relating to the content of this article.

References

1 P. Ehrenfreund and S. B. Charnley, *Annu. Rev. Astron. Astrophys.*, 2000, **38**, 427.
2 S. Messenger, *Nature*, 2000, **404**, 968.
3 O. Botta and J. L. Bada, *Surv. Geophys.*, 2002, **23**, 411.
4 S. A. Sandford, L. J. Allamandola and M. P. Bernstein, *Sci. Am.*, 1999, **281**, 42.
5 H. P. Klein, J. Lederberg, A. Rich, N. H. Horowitz, V. Oyama and G. V. Levin, *Nature*, 1976, **262**, 24.
6 D. S. McKay, E. K. Gibson, K. L. Thomas-Kerpta, H. Vali, C. S. Romanek, S. J. Clemett, X. D. F. Chillier, C. R. Maechling and R. N. Zare, *Science*, 1996, **273**, 924.
7 http://stardust.jpl.nasa.gov/.
8 T. W. Scattergood, E. Y Lau and B. M. Stone, *Icarus*, 1992, **99**, 98.
9 F. Raulin, P. Coll, N. Smith, Y. Benilan, P. Bruston and M.-C. Gazeau, *Adv. Space Res.*, 1999, **24**, 453.
10 D. W. Clarke and J. P. Ferris, *Icarus*, 1997, **127**, 158.
11 B. M. Stone, S. Clegg and T. W. Scattergood, unpublished results.
12 V. Kotwicki, *J. Hydrol. Sci.*, 1991, **36**, 49.
13 J. Ruiz, *Nature*, 2001, **412**, 409.
14 T. B. Sauke and J. F. Becker, *Planet. Space Sci.*, 1998, **46**, 805.
15 G. M. Munoz Caro, U. J. Meierhenrich, W. A. Schutte, B. Barbier, A. Arcones Segovia, H. Rosenbauer, W. H. P. Thiemann, A. Brack and J. M. Greenberg, *Nature*, 2002, **416**, 403.
16 M. P. Bernstein, J. P. Dworkin, S. A. Sandford, G. W. Cooper and L. J. Allamandola, *Nature*, 2002, **416**, 401.
17 P. Ehrenfreund, M. P. Bernstein, J. P. Dworkin, S. A. Sandford and L. J. Allamandola, *Astrophys. J.*, 2001, **550**, L95.
18 C. K. Matthews, K. E. van Holde and K. G. Ahern, *Biochemistry*, Benjamin Cummings, San Francisco, 3rd edn., 2000, p. 130.
19 S. J. Clemett, C. R. Maechling, R. N. Zare, P. D. Swan and R. M. Walker, *Science*, 1993, **262**, 721.
20 S. J. Clemett, X. D. F. Chillier, S. Gillette, R. N. Zare, M. Maurette, C. Engrand and G. Kurat, *Origins Life Evol. Biosphere*, 1998, **28**, 425.
21 E. Peeters, S. Hony, C. Van Kerkhoven, A. G. G. M. Tielens, L. J. Allamandola, D. M. Hudgins and C. Bauschlicher, *Astron. Astrophys.*, 2002, **390**, 1089.
22 F. Salama, *J. Mol. Struct.*, 2001, **563**, 19.
23 X. D. F. Chillier, B. M. Stone, C. Joblin, F. Salama and L. J. Allamandola, *J. Chem. Phys.*, 2002, **116**, 5725.
24 R. Ruiterkamp, T. Halasinski, F. Salama, B. H. Foing, L. J. Allamandola, W. Schmidt and P. Ehrenfreund, *Astron. Astrophys.*, 2002, **390**, 1153.
25 M. P. Bernstein, J. E. Elsila, J. P. Dworkin, S. A. Sandford, L. J. Allamandola and R. N. Zare, *Astrophys. J.*, 2002, **576**, 1115.
26 R. Hayatsu, E. Anders, M. H. Studier and L. P. Moore, *Geochim. Cosmochim. Acta*, 1975, **39**, 471.
27 J. Shi, G. Shen, F. Lan, N. Su and H. Zhou, *Geochimica*, 1978, **1**, 57.
28 W. Van Der Velden and A. W. Schwartz, *Geochim. Cosmochim. Acta*, 1977, **41**, 961.
29 L. J. Allamandola, M. P. Bernstein, S. A. Sandford and R. L. Walker, *Space Sci. Reviews*, 1999, **90**, 219.
30 M. P. Bernstein, S. A. Sandford, L. J. Allamandola, S. Chang and M. A. Scharberg, *Astrophys. J.*, 1995, **454**, 327.
31 M. P. Bernstein, L. J. Allamandola and S. A. Sandford, *Adv. Space Res.*, 1997, **19**, 991.
32 R. T. Morrison and R. N. Boyd, *Organic Chemistry*, Prentice-Hall, Englewood Cliffs, NJ, 6th edn., 1992, p. 985.
33 M. P. Bernstein, S. A. Sandford, L. J. Allamandola, J. S. Gillette, S. J. Clemett and R. N. Zare, *Science*, 1999, **283**, 1135.
34 M. P. Bernstein, J. P. Dworkin, S. A. Sandford and L. J. Allamandola, *Meteoritics Planet. Sci.*, 2001, **36**, 351.
35 G. Cooper, N. Kimmich, W. Belisle, J. Sarinana, K. Brabham and L. Garrel, *Nature*, 2001, **414**, 879.
36 S. C. Terry, J. H. Jerman and J. B. Angell, *IEEE Trans. Electron. Devices.*, 1979, **ED-26**, 1880.
37 http://saturn.jpl.nasa.gov/cassini/english/.
38 D. R Reyes, D. Iossifidis, P. Auroux and A. Manz, *Anal. Chem.*, 2002, **74**, 2623; P. Auroux, D. Iossifidis, D. R. Reyes and A. Manz, *Anal. Chem.*, 2002, **74**, 2637.
39 I. Walther, B. van der Schoot, M. Boillat and A. Cogoli, *Enzyme Microb. Technol.*, 2000, **27**, 778.
40 http://mems.jpl.nasa.gov/.
41 J. Bada, *Proc. Natl. Acad. Sci. USA*, 2001, **98**, 797.
42 J. L. Bada, *NASA Technical Reports*, Rept-97-1103R1.
43 L. D. Hutt, D. P. Glavin, J. L. Bada and R. A. Mathies, *Anal. Chem.*, 1999, **71**, 4000.
44 R. L. Crawford, A. Paszczynski, Q. Lang, I. F. Cheng, B. Barnes, T. J. Anderson, R. Wells, C. Wai, G. Corti, L. Allenbach, D. P. Erwin, J. Park, T. Assefi and M. Mojarradi, *Icarus*, 2001, **154**, 531.
45 A. de Mello, *Lab Chip*, 2002, **1**, 7N.
46 T. J. Cornish, S. Ecelberger and W. Brinckerhoff, *Rapid Commun. Mass Spectrom.*, 2000, **14**, 2408.
47 A. Chutjian, M. R. Darrach, V. Garkanian, S. P. Jackson, T. D. Molsberry, O. J. Orient, D. Karman, P. M. Holland and D. Aalami, *A Miniature Quadruple Mass Spectrometer Array and GC for Space Flight: Astronaut EVA and Cabin-Air Monitoring*, Society of Automotive Engineers, Inc., 2000-01-02300.
48 E. R. Badman and R. G. Cooks, *J. Mass. Spectrom.*, 2000, **35**, 659.
49 A. J. de Mello, *Lab Chip*, 2002, **2**, 48N.
50 L. Nieradko and K. Malecki, *Proceedings of Shaping the Future; International Forum for Graduates and Young Researchers at EXPO 2000*, University of Hanover, Hanover, Germany, July, 2000, p. 11.
51 http://mems.jpl.nasa.gov/files/MEMS-SPIE.pdf.