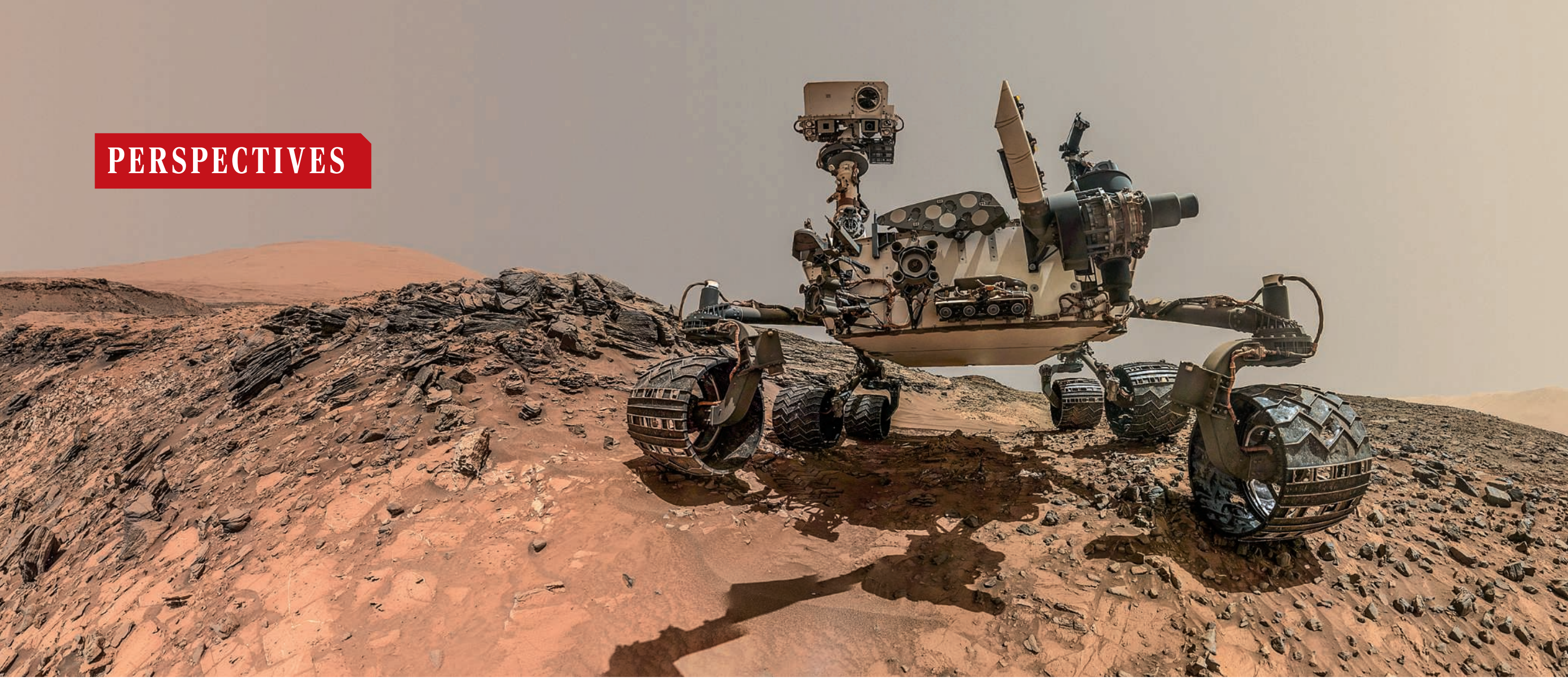

PLANETARY SCIENCE

Organic molecules on Mars

Data from the Curiosity rover provide evidence for organic molecules in ancient martian rocks and in the atmosphere

By **Inge Loes ten Kate**

On 6 August 2012, the Sample Analysis at Mars (SAM) instrument suite (*1*) arrived on Mars onboard the Curiosity rover. SAM's main aim was to search for organic molecules on the martian surface. On page 1096 of this issue, Eigenbrode *et al*. (*2*) report SAM data that provide conclusive evidence for the presence of organic compounds—thiophenic, aromatic, and aliphatic compounds—in drill samples from Mars' Gale crater. In a related paper on page 1093, Webster *et al*. (*3*) report a strong seasonal variation in atmospheric methane, the simplest organic molecule, in the martian atmosphere. Both these finding are breakthroughs in astrobiology.

To appreciate the importance of these detections, we must go back to NASA's 1976 Viking mission and its search for life on Mars. Viking 1 and 2 were two stationary landers that studied the atmosphere and surface of their local environment with a range of instruments, including a gas chromatograph mass spectrometer (GCMS) dedicated to the detection of organic compounds. However, neither signs of life nor organic compounds were detected in the regolith samples analyzed during this mission (*4*). It is arguable whether not finding signs of life was surprising, but finding no evidence for organic molecules was unexpected. What makes organic compounds so special that we are still searching for them on Mars, more than 40 years later?

Nearly all molecules containing carbon are organic compounds, apart from a few such as CO and CO_2. Many organic molecules are not produced by living organisms. Organic molecules on Mars may have been formed abiotically on the martian surface, delivered from space, or produced by past or present martian life. Space missions to Mars are carefully cleaned to prevent accidental delivery of terrestrial organic molecules to the planet (*5*).

Throughout the Universe, organic compounds are produced abiotically (*6*) and delivered to planetary surfaces through impacts of comets, asteroids, meteorites, and interplanetary dust particles (*7*). They are therefore expected to exist on the martian surface. More speculative is the possibility of past or even present life on Mars. Life on Earth uses and produces four major types of organic compounds: carbohydrates, lipids, proteins, and nucleic acids. Each of these types is constructed from smaller organic molecules, such as sugars, amino acids, and nucleobases. Based on the assumption that hypothetical martian life would not greatly differ from terrestrial life, the search for martian life focuses on these building blocks.

The current influx of abiotically produced organic molecules to the martian surface, estimated from scaling the terrestrial influx to a martian scenario, combined with measurements of the martian atmosphere (*8*, *9*), is 100 to 300 metric tons per year. Most of the martian surface is billions of years old (*10*), so organic molecules should be abundant. Why did the Viking landers not detect any? Are organic molecules degraded on the martian surface, particularly by ultraviolet radiation (which has much shorter wavelength on Mars than on Earth) (*11*), ionizing radiation (*12*), or oxidizing compounds (*13*)? All such processes may eradicate organic molecules from the upper few centimeters or even meters of the surface (*12*).

But even if all abiotic organic molecules on the martian surface were degraded, their degradation products should still be detectable. Moreover, minerals such as sulfates and clay minerals that are present on Mars may store organic molecules in their crystal structure, protecting them from the destructive environment (*13*). It thus remained unclear how representative the regolith samples, and the analyses Viking performed on them, were of the organic inventory of Mars.

Clearly, there were still ample reasons to justify a second mission to Mars with an instrument dedicated to the search for organic molecules. SAM was inspired by Viking's GCMS. In the instrument, martian regolith samples are heated so that gases trapped in the samples, organic compounds adsorbed onto the samples, and compounds released by thermal breakdown of minerals are released. The gases are analyzed on a GCMS and a tunable laser spectrometer (*1*).

In 2015, the first analyses of SAM hinted at the presence of organic molecules on

A low-angle self-portrait of NASA's Curiosity Mars rover. SAM is safely hidden inside the rover, ready to analyze when samples are delivered from the top.

PHOTO: NASA/JPL-CALTECH/MSSS

Department of Earth Sciences, Utrecht University, Utrecht, Netherlands. Email: i.l.tenkate@uu.nl

Mars (*14*), but those measurements were hampered by the presence of perchlorate salts. These salts, present in martian regolith, break down upon heating within the SAM instruments to temperatures of 200°C. The oxygen and chlorine hereby released react with organic molecules. Leakage of reactive agents presented another challenge. Eigenbrode *et al.* overcame both challenges by only analyzing the gases released above 400°C. They can be certain that these gases are not a result of leaking reagent or reaction with perchlorate. The authors meticulously show all data obtained on Mars by the SAM instrument since its first measurements in 2013 and have thoroughly analyzed all potential contaminants and other signals that might have influenced the actual measurements. They thereby carefully avoid any bias toward hypotheses developed over the past decades. The results convincingly show the long-awaited detection of organic compounds on Mars.

As Webster *et al.* show, methane has also been conclusively detected in the martian atmosphere (*3*). During 5 years of analysis, SAM has found not only a stable methane background, but also local seasonal peaks. It may be that the gas is released from a large subsurface reservoir, but neither the source of that methane nor the driving force of its release is understood. Although many geological processes produce methane, its possible link with biological processes warrants further study to fully understand the martian methane cycle.

The detection of organic molecules and methane on Mars has far-ranging implications in light of potential past life on Mars. Curiosity has shown that Gale crater was habitable around 3.5 billion years ago (*15*), with conditions comparable to those on the early Earth, where life evolved around that time. The question of whether life might have originated or existed on Mars is a lot more opportune now that we know that organic molecules were present on its surface at that time. ■

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ORGANISMAL BIOLOGY

Honey bees zero in on the empty set

Honey bees join a select number of animals shown to understand the concept of nothing

By **Andreas Nieder**

The number zero is central to contemporary mathematics and to our scientifically and technologically advanced culture (*1*). Yet, it is a difficult number to understand. Children grasp the symbolic number zero long after they start to understand, at around the age of 4 years, that "nothing" can be a numerical quantity—the empty set—that is smaller than one (*2*). Scientists therefore assumed that the concept of "nothing" as a numerical quantity was beyond the reach of any animal. Recent studies on cognitively advanced vertebrates challenge this view, however. Monkeys and birds can not only distinguish numerical quantities (*3*) but also grasp the empty set as the smallest quantity on the mental number line (*4*, *5*). On page 1124 of this issue, Howard *et al.* (*6*) show that the honey bee, a small insect on a branch very remote from humans on the animal tree of life, also belongs to the elite club of animals that comprehend the empty set as the conceptual precursor of the number zero.

Honey bees have a reputation as smart insects. They possess elaborate short-term memory to consider upcoming decisions (*7*), understand abstract concepts such as sameness and difference (*8*), and learn intricate skills from other bees (*9*). Bees can also estimate the number of up to four objects (*10*, *11*). But Howard *et al.* demonstrate even more astonishing number skills in these insects. The researchers report that honey bees can not only rank numerical quantities according to the rules "greater than" and "less than" but they can also extrapolate the less-than rule to place empty sets next to the number one at the lower end of the mental number line.

For their experiments, the authors lured free-flying honey bees from maintained hives to their testing apparatus (see the figure) and marked the insects with color for identification. They rewarded the bees for discriminating displays on a screen that showed different numbers (numerosities) of items. The researchers controlled for systematic changes in the appearance of the numerosity displays that occur when the number of items is changed. They thus ensured that the bees were discriminating between different numbers, rather than responding to low-level visual cues.

First, the researchers trained the bees to rank two numerosity displays at a time. Over the course of training, they changed the numbers presented to encourage rule learning. Bees from one group were rewarded with a sugar solution whenever they flew to the display showing more items, thereby following a greater-than rule. The other group of bees was trained on the less-than rule and rewarded for landing at the display that presented fewer items. The bees learned to master this task with displays consisting of one to four items; they were able to do so not only for familiar numerosity displays but also for new displays.

Next, the researchers occasionally inserted displays containing no item. Would the bees understand that empty displays could be ranked with countable numerosities? Indeed, the bees obeying the less-than rule spontaneously landed on displays showing no item, that is, an empty set (see the figure). In doing so, bees understood that the empty set was numerically smaller than sets of one, two, or more items. Further experiments confirmed that this behavior was related to quantity estimation and not a product of the learning history.

The bees' accuracy in performance improved as the magnitude of difference between two respective numerosities increased. They found it hard to judge whether the empty set was smaller than one but were progressively better when they had to compare two, three, or larger numbers with an empty set. With this behavior, the bees demonstrated the numerical-distance effect with empty sets, a hallmark of number discrimination. The series of experiments (*6*) therefore demonstrates that bees grasp the empty set as a quantitative concept.

The findings are all the more exciting when considering the phylogenetic remoteness of insects and vertebrates. Their last common ancestor, a humble creature that barely had a brain at all, lived more than 600 million years

Animal Physiology Unit, Institute of Neurobiology, University of Tübingen, Auf der Morgenstelle 28, 72076 Tübingen, Germany. Email: andreas.nieder@uni-tuebingen.de

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Inge Loes ten Kate

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