MARS
EXPLORING
THE RED PLANET

CONTENTS

2 A fresh look at Mars
Seven spacecraft work to uncover Mars’ mysteries.

8 Curiosity’s latest findings from Mars
Curiosity continues its mission of discovery on the Red Planet.

14 How moon dust will put a ring around Mars
What will happen when Phobos is shredded into a ring?
Fourth rock

A fresh look at MARS

Mars—the latest international hotspot. Although that designation might seem a bit far-fetched, it seems less so if you consider the seven spacecraft now operating at the Red Planet and the five more being readied to go as scientific tourists. Robotic emissaries from Earth have occupied Mars continuously since 1997, and the missions currently active date back to 2001. This is the busiest, most fruitful, and most exciting time in the history of Mars exploration. The armada of spacecraft delivers a steady stream of data to planetary scientists that has led to important discoveries but also raised intriguing new mysteries.

The ground truth

Two rovers—Opportunity and Curiosity—continue to return sensational scientific information from the surface. Opportunity, which landed in January 2004 and celebrated its 4,000th martian day, or sol (one sol equals about 1.03 Earth days), in April 2015, surpassed the 26.219-mile (42.195 kilometers) distance of a marathon a month earlier. The rover’s science team, working on the planet’s surface virtually through the robot, is now exploring the eroded rim of an ancient impact crater called Endeavour. NASA orbiters previously had detected evidence for clay minerals on the rim of this 14-mile-wide (22km) crater. Opportunity has sampled those clays and found abundant evidence for mineral-filled veins containing gypsum. Both substances provide further proof that groundwater and perhaps even surface water once existed on this part of Mars. The clays, in particular, suggest that some of this water could have been comparable to fresh water on Earth rather than the mildly acidic water inferred from Opportunity’s earlier discoveries at Eagle, Endurance, and Victoria craters.

Even though Curiosity is the new kid on the block, having landed in August 2012, it surpassed its 1,000th sol in late May 2015. The sophisticated rover is now exploring the lower slopes of Mount Sharp, the looming 3-mile-high (5km) mountain of layered sedimentary rocks inside Gale Crater that drew the rover team to this landing site. Mount Sharp’s layers record important parts of Mars’ early warmer and wetter history. Curiosity’s mission is to decipher that record in detail, layer by layer if need be, to learn as much as possible about the Red Planet’s potential past habitability.

Like its predecessors, Opportunity and Spirit (which ceased transmissions in March 2010), Curiosity has found and continues to find ample evidence that both surface and groundwater once flowed on Mars. Recently revealed signs of that water include swarms of mineral-rich veins created when moving groundwater deposited materials that filled fractures in rocks. Other fresh discoveries of ancient water involve the detection of the iron-oxide mineral hematite,

by Jim Bell

Seven spacecraft—two on the ground and five circling above—continue to scour the Red Planet for signs of ancient water and conditions conducive to life.

by Jim Bell

NASA’s Curiosity rover poses for a selfie on Mount Sharp in January 2015. This vista combines dozens of images captured by a camera that sits at the end of the rover’s robotic arm. (Ground controllers positioned the arm so it would be out of the mosaic’s frames.) The rim of Gale Crater appears at the top right of this image, and the peak of Mount Sharp is at the top left. (NASA/JPL-Caltech/MSSS)
formed when water alters basaltic volcanic rock, and jarosite, an iron- and sulfur-bearing mineral that can arise when volcanic rock interacts with mildly acidic water. These kinds of mineral discoveries coupled with spectacular images of finely layered sandstones and mudstones (fine-grained sedimentary rocks that typically form in water’s presence) are beginning to paint a clearer picture of Mount Sharp. Scientists now suspect it is an enormous accumulation of sediments deposited in an ancient lake that periodically filled Gale Crater early in the planet’s warmer and wetter history. It’s an exciting hypothesis, but Curiosity needs to do a lot more climbing and sampling of additional layers to fully test it and tease out more details of the habitability of that possible ancient lake. Curiosity’s measurements of the martian atmosphere have been no less thrilling. A detailed search for methane early in the mission came up essentially blank, but in late 2013 the rover observed a shallow spike in the abundance of this gas followed by a quick return to near-zero levels. Are there localized sources of this simple organic compound on Mars, perhaps a byproduct of geological processes such as a reaction between water and subsurface rock? Or could it be from some subsurface biological process? Although the latter seems unlikely, mission scientists don’t want to discount any possibilities until they perform additional measurements and analyses.

The view from above
In the meantime, five active probes — three from NASA, one from the European Space Agency (ESA), and one from the Indian Space Research Organization (ISRO) — are plying the orbital seas above Mars. Using a variety of sophisticated instruments, these spacecraft are scouting the planet’s geology, mineralogy, and atmospheric composition as well as searching for landing sites for future rovers and surface probes. The most venerable of this quintet, and indeed the longest-operating spacecraft ever to explore the Red Planet, is NASA’s Mars Odyssey. Since arriving in polar orbit in 2001, Mars Odyssey has circled the planet nearly 60,000 times. In the process, it has discovered water ice in the south polar cap, found evidence that melting snow carved some geologically recent gullies, and helped find landing sites for Spirit and Opportunity.

It also has built up an impressive collection of chemical and mineral maps of the surface that have helped scientists understand the distribution of ground ice as well as new details about the planet’s geology and mineralogy. Thanks to the mission’s longevity, the Mars Odyssey team recently was able to complete a global set of infra-red geologic maps at a resolution of around 330 feet (100 meters) per pixel. These are the highest-resolution maps of surface properties yet created for Mars and are helping researchers differentiate bedrock from sediments and dust-covered surfaces.

The second-oldest orbiter is ESA’s Mars Express, which went into an elliptical orbit around the planet in late 2003. The spacecraft’s instruments have been mapping the geology (in 3-D), mineralogy, and atmospheric composition and mineral chemistry of Mars during each close pass ever since. They have discovered minerals that can form only in the presence of water, vast amounts of water ice beneath the martian surface, and lava flows that might be only a few million years old. The High Resolution Stereo Camera continues to crank out spectacular topographic maps of mountains, craters, and canyons across the planet. The 3-D images are helping scientists understand the details of past geologic processes and adding key information to the search for future landing sites.

The Mars Reconnaissance Orbiter (MRO) ranks as NASA’s most prolific Mars orbiter yet. Since it arrived in its circular polar orbit in 2006, the spacecraft has returned more than 30 terabytes of data — more than all other Mars missions combined. MRO captures the sharpest details from orbit and has helped planetary scientists map Mars’ mineralogy and subsurface structure. The probe has found buried glaciers and the clay-rich minerals that led Curiosity’s science team to Gale Crater.

The mission’s Context Camera has imaged more than 90 percent of the martian surface at a resolution of about 20 feet (6m) per pixel. An even higher-resolution camera, the High Resolution Imaging Science Experimenter, helps scientists study intricate details in small gullies apparently created by seeping water, identify fresh impact craters formed within the past decade, and even spot alien spacecraft parts on the surface — most recently, the likely wreckage from the 2003 crash of ESA’s Beagle-2 lander.

The new arrivals
Two rookies recently joined these three veteran orbiters. ISRO’s Mars Orbiter Mission (MOM), also called Mangalyaan, is India’s first interplanetary mission. And when it entered Mars orbit in September 2014, that nation became the first to achieve success at the Red Planet on its first try. MOM’s primary purpose is to test basic spacecraft and instrument capabilities as well as ISRO’s ability to journey to Mars and operate successfully from orbit there. But in the process of demonstrating these technologies and skills, the spacecraft has captured some stunning color photos of the martian surface and atmosphere from its highly elliptical orbit.

NASA’s newest artificial martian satellite arrived two days before MOM. The spacecraft agency designed the Mars Atmosphere and Volatile Evolution (MAVEN) orbiter specifically to study the Red Planet’s atmosphere and especially the way it interacts with the stream of high-energy particles emitted by the Sun known as the solar wind. One of the mission’s main goals is to test the hypothesis that the solar wind slowly eroded ancient Mars’ thicker and warmer atmosphere, perhaps after the planet’s core solidified and its early magnetic field disappeared. Mars once had a

**Curiosity continues to explore the layered rocks on Mount Sharp’s lower slopes. In September 2014, the rover drilled its first hole on the mountain to collect samples for onboard analysis. The hole measures 0.63 inch (1.6 centimeters) across and 2.6 inches (6.7cm) deep, NASA/JPL-CALTECH/UCAL.

**The Mars Reconnaissance Orbiter captured Curiosity and its tracks as it trekked through layered deposits in April 2014. The rover (arrow) appears blue in this image’s exaggerated color.

**NASA’s newest artificial martian satellite arrived two days before MOM. The space agency designed the Mars Atmosphere and Volatile Evolution (MAVEN) orbiter specifically to study the Red Planet’s atmosphere and especially the way it interacts with the stream of high-energy particles emitted by the Sun known as the solar wind. One of the mission’s main goals is to test the hypothesis that the solar wind slowly eroded ancient Mars’ thicker and warmer atmosphere, perhaps after the planet’s core solidified and its early magnetic field disappeared. Mars once had a

**Scientists working with Mars Odyssey data recently created the highest-resolution global map of marital surface properties, in which warm areas appear bright and cool regions dark. This tiny section highlights the 4.0-mile-wide (6.9 kilometers) impact crater Gratteri.
ASTRONOMY • MARS: EXPLORING THE RED PLANET

The European Space Agency's Mars Express satellite captured this complex region of isolated hills and ridges in the southernmost section of Phlegra Montes in the planet's northern hemisphere. The probe's High Resolution Stereo Camera snapped this scene in October 2014 at a resolution of about 50 feet (15 meters) per pixel.

strong magnetic field, a discovery made by NASA's earlier Mars Global Surveyor mission, but no longer does. Will MAVEN find this is why Mars is no longer a snowball into the cold, dry world it is today?

Early science results from MAVEN include the surprising discoveries of an auroral glow lower in the atmosphere than scientists expected and a dust layer much higher in the atmosphere than expected. Some researchers have suggested that the absence of a shielding magnetic field could allow the solar wind to penetrate deeper before it initiates the aurora. The origin of the high-altitude dust remains a mystery, however. Is it dust from Mars lofted upward by strong atmospheric currents? Or could it be dust raining down from the Martian moons, Phobos or Deimos, or from streams of cometary dust? Scientists plan to test these and other hypotheses with additional MAVEN observations perhaps augmented by other orbiters.

Comet encounter

MAVEN and the other active spacecraft had front-row seats to one of 2014's most exciting astronomical events — October's close encounter between Mars and Comet Siding Spring (C/2013 A1). Although the comet’s icy nucleus would miss the planet, its extended envelope would pass right over the comet's icy nucleus would miss the daytime surface and not the nighttime sky. Their relatively short exposures didn't capture any meteors and rendered the comet as little more than a fuzzy blob.

Future exploration

Six national space agencies have now launched more than 40 missions to Mars since the first attempt in 1960. Only about half of these proved even partially successful, attesting to the difficulty in exploring the Red Planet. Despite the challenges, however, humans continue to send robotic emissaries and even have started thinking about plans for the first crewed missions, perhaps as soon as the 2030s.

Indeed, several missions in the works have direct connections to the eventual human exploration of Mars. In 2016, NASA will launch Insight, a lander based on the successful design of the 2008 Phoenix spacecraft. Insight will deploy a sensitive seismometer and heat-flow probe to search for signs of seismic or geothermal activity. Is Mars geologically dead or still active? Insight is designed to find out during its two-year primary mission, which will start in late 2016.

Also in late 2016, ESA, in cooperation with the Russian space agency, Roscosmos, will deploy the ExoMars Trace Gas Orbiter. This spacecraft will study methane and other minor atmospheric gases that might provide clues to the planet’s geologic and possible biologic evolution. As part of the mission, the orbiter will deploy an entry, descent, and landing demonstration module called Schiaparelli. ESA expects Schiaparelli to prove the agency’s ability to make a controlled landing on Mars’ surface. If it survives touchdown, the spacecraft will conduct a science mission lasting two to eight sols designed to study the landing site’s atmospheric conditions.

ESA will attempt its first Mars rover, once again in cooperation with Roscosmos, with ExoMars. Currently scheduled for a 2018 launch, the rover will use cameras, spectrometers (which analyze elemental composition), radar, and a drill to study the geological history of a past watery environment on Mars.

Understanding the detailed nature of the martian environment is also at the forefront of NASA’s plans for its next Mars rover, tentatively called Mars 2020 after the year of its planned launch. To save money, some 80 to 90 percent of the rover will be constructed from spare parts from Curiosity. NASA envisions Mars 2020 as a first step in a longer-term strategy of missions designed to bring samples back from Mars. The rover will feature high-resolution cameras, spectrometers, and drilling/coring systems that will allow it to physically sample a variety of surface materials and cache them for potential return to Earth on future missions.

Many planetary scientists believe that the next major leap in Mars exploration, and a critical step toward eventual human exploration of the Red Planet, will be to bring these carefully selected samples of soils and rocks to Earth for detailed geochemical and biological analysis. Are there chemical compounds in the soils that could degrade space-suit seals or other systems needed for life support? Is martian dust toxic to the human respiratory system in some unanticipated way? Can explorers extract resources such as oxygen and water from common Mars surface materials?

A primary goal of the Mars 2020 mission is to collect samples that can begin to answer such questions. Engineers are currently working on ways to cache these samples and decide the best way to return them to our planet.

I believe the human fascination with Mars stems in part from the fact that the deeper we look at it, the more we see parallels with our own world’s past. Early in its history, Mars was much more Earth-like than it is today. It was warmer and wetter — at least in places. Heat from the Sun, geothermal sources, and impacts provided abundant energy, and the rain of asteroid and comet impacts that pelted Mars and the rest of the planets provided a steady supply of organic molecules.

Water, energy, and organic molecules are the key ingredients needed for life as we know it. Past and present missions have helped us discover that Mars was indeed a habitable world long ago. Upcoming missions, including the first human explorers in the not-too-distant future, will be working to up the ante, trying to find out if Mars was — or still is — not just habitable, but inhabited.
Curiosity's latest findings from Mars

In August 2012, NASA’s newest rover landed in Mars’ Gale Crater. From finding ancient streambeds to analyzing hundreds of samples, the rover has kept busy helping scientists learn about the Red Planet’s habitability. by Sarah Scoles

M ore people tuned in to see the Curiosity rover land on Mars than watch CNN during Sunday prime time. When NASA’s most sophisticated, mobile, and outfitted robot touched down August 6, 2012, half a million viewers sat on the edges of their seats. A sky crane lowered Curiosity to a soft arrival on a planet it had traveled 552 million miles (887 million kilometers) to study. In the months since, the rover and the scientists who control it have been working hard to determine what Mars is like now, what it was like in the past, and what its past and present might mean for the past, present, and future of Earth.

A wild descent
Curiosity touched down in Gale Crater, a depression 96 miles (154km) across, near an alluvial fan that is called Peace Valles — a cone-shaped buildup of debris from, presumably, once-flowing water. “We didn’t just stumble into this area,” said John Grotzinger, Curiosity’s project scientist, in a press conference March 7, 2013. Scientists chose Gale Crater after much debate about balancing safety and science. After all, it doesn’t matter if interesting geology lies at the top of a boulder-strewn outcrop if your rover drives off a cliff. Gale Crater presented few such physical obstacles and appeared to offer diverse geology within a small area. Proximity is important: While the rover can move, engineers expect it to drive only 12 miles (20km) in its lifetime, making targets separated by 15 miles (24km) undesirable. Gale Crater is also home to Mount Sharp, a 18,000-foot-tall (5.5km) mountain that Curiosity currently is traveling toward. But it’s going to take a while to get there. Sharp is 5 miles (8km) from the rover’s landing site, and Curiosity’s longest day of driving has thus far been 464 feet (142 meters). The mound will be worth the wait, though, according to scientists. “Orbiting spacecraft suggest that the lower layers of this mound contain minerals formed in the presence of ancient water,” says Nadine Barlow, a Mars expert and professor at Northern Arizona University in Flagstaff, “while the upper layers appear drier and may contain evidence of more recent, but still distant, volcanic activity.”

The mound will surely prove to be a gold mine. After spending 11 months investigating Gale’s depths, Curiosity set out for Mount Sharp on July 4. But what, exactly, did researchers hope to learn when they set metal feet on this planet? Which questions has the rover answered already, and which new questions has it brought up? As Grotzinger said at the press conference, “When you land on Mars, strange things can happen.”

While some of Curiosity’s discoveries have not been surprising, others have changed the public conception of Mars from a dead, dusty place to one that has been evolving for billions of years and continues, even now, to do so. When NASA launched Curiosity, it had biological, geological, and chemical goals. But the mission’s umbrella objective is to determine whether Mars was ever habitable. Grotzinger was quick to point out, though, that the rover is not there to determine whether metabolizing microbes actually were on Mars. “We are not a life-detection mission,” he said in March. Curiosity instead will determine whether life could have arisen and survived there. And the answer is directly applicable to us mammals and microbes: If Curiosity discovers that Mars used to be hospitable and has turned dusty but to one that has been evolving over millions of years, strange things can happen.”

During Curiosity’s 177th day on the Red Planet — February 3, 2013 — it took the dozens of images that, combined, make this full self-portrait. Soon after, the rover drilled into its first rock, becoming the first machine to sample the interior of another planet. NASA/JPL-CALTECH/MSSS

The first came March 7, when NASA announced that Curiosity had discovered a streambed in which life could have survived. “We have found a habitable environment that is so benign and supportive of life,” Grotzinger said at the time, “that, probably, if this water was around and you had been there, you would have been able to drink it.”

The location, Yellowknife Bay, was not just wet — it had Goldilocks conditions: salty but not too salty, not too acidi, not too basic, and full of porridge-like chemical energy for metabolism. These results came from the first rock Curiosity drilled, Febru- ary 8. The fine-grained rock, called John Klein, sits where streams appear to have descended from the crater’s rim, perhaps leaving standing water, and is covered in nodules and vents. The rover bored a 2.5- inch (6.4 centimeters) hole into it, sending samples to its Sample Analysis at Mars (SAM) and Chemistry and Mineralogy (CheMin) instruments, which investigate chemical makeup.

A month passed before NASA announced that the sample suggested a water-wet, life-friendly spot. When Curiosity touched down, said NASA’s mission manager, John Klein, life there. Sharp is 5 miles (8km) from the rover’s landing site, and Curiosity’s longest day of driving has thus far been 464 feet (142 meters). The mound will be worth the wait, though, according to scientists. “Orbiting spacecraft suggest that the lower layers of this mound contain minerals formed in the presence of ancient water,” says Nadine Barlow, a Mars expert and professor at North- ern Arizona University in Flagstaff, “while the upper layers appear drier and may contain evidence of more recent, but still dis- tant, volcanic activity.”

The mound will surely prove to be a gold mine. After spending 11 months investigat- ing Gale’s depths, Curiosity set out for Mount Sharp on July 4. But what, exactly, did researchers hope to learn when they set metal feet on this planet? Which questions has the rover answered already, and which new questions has it brought up? As Grotzinger said at the press conference, “When you land on Mars, strange things can happen.”

While some of Curiosity’s discoveries have not been surprising, others have changed the public conception of Mars from a dead, dusty place to one that has been evolving for billions of years and continues, even now, to do so. When NASA launched Curiosity, it had biological, geological, and chemical goals. But the mission’s umbrella objective is to determine whether Mars was ever habitable. Grotzinger was quick to point out, though, that the rover is not there to determine whether metabolizing microbes actually were on Mars. “We are not a life-detection mission,” he said in March. Curiosity instead will determine whether life could have arisen and survived there. And the answer is directly applicable to us mammals and microbes: If Curiosity discovers that Mars used to be hospitable and has turned barren, what does that mean for our planet? Christopher Edwards, a postdoctoral fellow at the California Institute of Technol- ogy and a member of the Curiosity science team, confirms, “[We’re] going to look for what happened on Mars, how that hap- pened differently on Earth, and how that allowed life on Earth to thrive.”

Red biology
Curiosity has been busy helping scientists piece the planet’s timeline together. During the rover’s first year at work, it collected 190 gigabits of data; took more than 36,700 full images and 35,000 thumbnail images; fired 197 images and 35,000 thumbnail images; fired 169 targets, and characterized rock samples; and drove more than 1 mile (1.6km).

The data are yielding serious results. The first came March 7, when NASA announced that Curiosity had discovered a streambed in which life could have survived. “We have found a habitable environment that is so benign and supportive of life,” Grotzinger said at the time, “that, probably, if this water was around and you had been there, you would have been able to drink it.”

The location, Yellowknife Bay, was not just wet — it had Goldilocks conditions: salty but not too salty, not too acidic, not too basic, and full of porridge-like chemical energy for metabolism. These results came from the first rock Curiosity drilled, Febru- ary 8. The fine-grained rock, called John Klein, sits where streams appear to have descended from the crater’s rim, perhaps leaving standing water, and is covered in nodules and vents. The rover bored a 2.5- inch (6.4 centimeters) hole into it, sending samples to its Sample Analysis at Mars (SAM) and Chemistry and Mineralogy (CheMin) instruments, which investigate chemical makeup.

A month passed before NASA announced that the sample suggested a water-wet, life-friendly spot. When Curiosity touched down, said NASA’s mission manager, John Klein, life there. Sharp is 5 miles (8km) from the rover’s landing site, and Curiosity’s longest day of driving has thus far been 464 feet (142 meters). The mound will be worth the wait, though, according to scientists. “Orbiting spacecraft suggest that the lower layers of this mound contain minerals formed in the presence of ancient water,” says Nadine Barlow, a Mars expert and professor at North- ern Arizona University in Flagstaff, “while the upper layers appear drier and may contain evidence of more recent, but still dis- tant, volcanic activity.”

The mound will surely prove to be a gold mine. After spending 11 months investigat- ing Gale’s depths, Curiosity set out for Mount Sharp on July 4. But what, exactly, did researchers hope to learn when they set metal feet on this planet? Which questions has the rover answered already, and which new questions has it brought up? As Grotzinger said at the press conference, “When you land on Mars, strange things can happen.”

While some of Curiosity’s discoveries have not been surprising, others have changed the public conception of Mars from a dead, dusty place to one that has been evolving for billions of years and continues, even now, to do so. When NASA launched Curiosity, it had biological, geological, and chemical goals. But the mission’s umbrella objective is to determine whether Mars was ever habitable. Grotzinger was quick to point out, though, that the rover is not there to determine whether metabolizing microbes actually were on Mars. “We are not a life-detection mission,” he said in March. Curiosity instead will determine whether life could have arisen and survived there. And the answer is directly applicable to us mammals and microbes: If Curiosity discovers that Mars used to be hospitable and has turned barren, what does that mean for our planet? Christopher Edwards, a postdoctoral fellow at the California Institute of Technol- ogy and a member of the Curiosity science team, confirms, “[We’re] going to look for
made of phosphates (phosphorus plus oxygen), carbohydrates (carbon, hydrogen, and oxygen), and nitrogen gases. In short, John Klein contains the ingredients necessary to whip up a batch of life. And the pH-bearing minerals — suggest the planet’s wet chemistry extended more than 15 inches (40cm) underground, making up between 1.3 and 3 percent of the total material.

**Remarkable Mars**

As temperatures on Mars changed, it was unable to hold on to its liquid water. Its atmosphere, which is now an inhospitable 95.95 percent carbon dioxide and 0.146 percent oxygen, according to Curiosity’s latest readings. Long ago, though, Mars’ atmosphere was different. Its many giant volcanoes were active, and they now act as roadblocks to the chemistry that potentially warmed Mars. And the more scientists study Mars, the more prevalent on Mars than they were in Earth’s atmosphere to that of the early solar system. In other words, the planet, which has low gravity in the solar system’s early years. In other words, the planet, which has low gravity and no significant magnetic field, can’t hang on to its lighter isotopes. It has evolved since its early years, losing lighter atoms. It actively continues to lose its less substantive substances today. And the more scientists learn about the planet, the more they see it as a generally dynamic place, rather than a Pompeii-style preservation of a bygone era.

**Water, water everywhere**

So how do we know Mars was, at some point, wet? But how long was the water there? How deep and extensive was it? Initial results from a third Curiosity instrument — the Mast Camera (MastCam), which uses near-infrared vision to detect iron- and water-bearing minerals — suggest the planet’s wet habitability was not limited to the resting place of a single rock but extended at least up to Mount Sharp. Scientists have long had solid evidence that water used to flow across the surface of the Red Planet. Data dating back to the Viking landers of the 1970s provided proof of the H2O molecule’s existence, but Curiosity is doing its part to show that the H2O came in the form of rivers, streams, and lakes. In addition to drilling rocks toward that end, the rover also has scooped soil at a sandbox called Rocknest, its SAM instrument heated the dirt to 932° Fahrenheit (500° Celsius), and evidence of water, sulfur, and chlorine compounds popped out. But the most satisfying answer came from close-up pictures the MastCam took of three rocks. The images are from the first 40 days of the mission, but analysis did not come right away. In June, scientists determined that “Goulburn,” “Link,” and “Hoth” — as the rocks are affectionately known — are glued-together pebbles. On Earth — and so, presumably, on Mars — sediments stick together like this when they are immersed in flowing water. To create deposits the size of Goulburn’s, Link’s, and Hoth’s, the martian stream would have been ankle- to hip-deep and flowing about 3 feet per second (1 m/s). Although water outlets of the streams in the past tense, Mars retains some of its water in frozen form. Curiosity found out just how much is there, searching for ice on-the-go as it traveled from Yellowknife Bay to its next big landmark: a three-terrain intersection called Glenelg. Its Dynamic Albedo of Neutrons (DAN) detector searched for slow neutrons, which indicate the presence of water. Cosmic rays constantly strike the planet’s surface, kicking neutrons out of their atoms. If the ejected neutrons interact with hydrogen atoms on their way out of the ground, they slow down. DAN looks for low-energy neutrons and, based on their abundance, can tell how full of water molecules the ground is. On its travels, Curiosity sometimes saw water merely on the surface, but other times the chemistry extended more than 15 inches (40cm) underground, making up between 1.3 and 3 percent of the total material.

Two different Mars rovers — Opportunity and Curiosity — have seen concretions (the small spheres pictured here) and cemented rocks. Geologic features that form in the presence of water. Opportunity’s Wowmey rock (top) appears to have formed in an acidic, inhospitable environment. Curiosity’s Sheepbed rock, however, formed in a neutral, non-salty environment with plenty of chemical energy. NASA/JPL-Caltech/Cornell/USGS

Scientists receive images directly from Curiosity — the raw files (left) — but from there, they have two options. They can process the pictures to show the view as it would look if you were standing on Mars (middle), or they can white-balance the photos so the scene looks as it would under Earth-lighting (right).
actually see how wind and water have played a role in martian history," she says. “To me that’s living, breathing.” The rover will have to travel up and over this lively surface in the coming months to continue its scientific work.

A time machine
Mars was more violent between 3.5 and 4.5 billion years ago. This time period, known as the Noachian Era, saw the formation of large impact craters, such as Gale, which are ready-to-use tools for scientists. Barlow phrases it more aggressively: “I like to refer to impact craters as ‘nature’s drills.’”

Because of their low-lying bottoms, crater floors collect material that flowed from higher elevations. If they were once wet, for instance, they retain sediments and deposits. Some rocks in Gale formed when flowing water cemented material together, while some rocks formed from volcanic activity. Curiosity can investigate both types.

Gale Crater showcases parts of Mars that are below the surface but used to be the surface. “The layers exposed in craters provide insights into past environments quite different from what we see on the planet today,” says Barlow. If Curiosity looks at the different strata — just like a scientist in the Grand Canyon might sample different elevations along the rock walls — it can help scientists learn more about the planet’s past.

Mount Sharp, where the rover is headed, also has rocky strata compacted together like a book of pressed flowers, if a book of pressed flowers contained flora from geological eras separated by millions of years.

It’s no Earth
While it’s unlikely that Mars ever had mammals, it was habitable, at least in spots. But like on Earth, conditions there vary from region to region, just as Earth is home to both the Badlands and the bayou. For instance, Curiosity has found that the planet’s relative humidity changes based on its location. The Rover Environmental Monitoring Station (REMS) saw the humidity drop from 69 percent to about 5 percent in the 0.25 mile (400m) between the landing site and the sandy area where the rover spent its 55th to 101st days on Mars.

The surface temperature, though, did not depend on the rover’s location, at least not on small scales. The average daily high has been a still-freezing 32°F (0°C), while the low averages -94°F (-70°C). On Earth, the average temperature is a comfortable 61°F (16°C), while Mars is only a frigid -31°F (-35°C).

Curiosity, so mindful of its own condition that it is almost self-aware, also uses REMS to determine how strongly the atmosphere is pressing down. The pressure between mid-August 2012 and late February 2013 — about a quarter of a martian year — slid upward by 0.029 pound per square inch. This seasonal change occurs because the spring sunlight causes carbon dioxide (CO2) to sublimate from the southern polar cap. The CO2 becomes part of the planet’s atmosphere, increasing its mass by 30 percent each time the season rolls around. But even the highest pressure is 0.0095 atmosphere, not even a hundredth the pressure we experience on Earth. So although the planet resembles Utah, remember Earth and Mars are still quite different. For one, everything Curiosity sees is gigantic. “The scale of features on Mars is massive,” says Edwards. “When I look at a crater, I always have to tell myself, ‘That crater is bigger than the entire Los Angeles Basin.’”

Secondly, everything Curiosity sees is old. “Look at a typical rock in your backyard,” Edwards continues. “It probably formed 100 million years ago. On Mars, rocks have been sitting on the surface for billions of years. You have an unadulterated record of rocks that often formed 3 billion years ago, a period that has been largely erased by large crater impacts.”

Sending a rover to Mars is like going back in time. When Curiosity samples a streambed, it peers into a period in the solar system’s history that we — earthlings who build structures on top of our wetter, more volcanic, more pressurized, and more hectic planet — cannot easily access.

Where to next? Curiosity is continuing its long trek toward Mount Sharp, and it will stop along the way whenever it comes into something interesting. So far, their plans have encountered only minor hiccups: Curiosity’s computer had a memory glitch February 28, it flipped into “safe mode” after a software malfunction March 16, and the rover popped a wheelie for a while in June. But the system generally works. In fact, it works so well that Curiosity sometimes operates without a baby sitter, reacting to obstacles without checking in with ground control.

The rover’s first year of results will help space agencies put astronauts’ boots on the ground — eventually. Astronomers need to thoroughly understand this desert planet if the United States is going to send humans there in 2020, as President Obama plans. Curiosity is pushing that agenda forward by learning where meltwater-ice supplies are and measuring how much radiation reaches the surface each day. With current technology, the level of radiation — about a CT scan’s worth every five days — is too high. But as long as scientists know that, they can work to innovate new protections.

Aside from the logistical investigations into whether humans can hack it on Mars, Curiosity is making inquiries into Earth’s prehistory. In September, scientists announced that they had found a rock, which they called Jake Matijevic, that was nearly indistinguishable from a certain kind of volcanic rock on Earth. The similarities suggest Mars’ interior may be more similar to Earth’s than anyone thought.

“You can think of planets as giant laboratory experiments set up 4.5 billion years ago,” says Bandfield. “Each has slightly different proportions of rock, water, etc. How did those slightly different proportions lead to such radically different results? Specifically, how did they produce Mars — a planet that may have been habitable, but not inhabited, in the distant past — and Earth, a geologically similar planet now teeming with everything from upright mammals to archaeabacteria?”

“We study these other planets to reflect on ourselves,” says Edwards. “It’s a system, right? Our solar system.”
Red Planet mayhem

How moon dust will put a ring around MARS

Phobos, a moon of Mars, is destined to be shredded, changing the Red Planet forever.

by Joel Davis

Someday, Mars’ moon Phobos will slip past a certain point in its deteriorating orbit and get ripped apart by tidal forces, forming a ring. This illustration depicts Phobos midway through that process, overlooking the Red Planet.

© 2016 Kalmbach Publishing Co. This material may not be reproduced in any form without permission from the publisher. www.Astronomy.com
Lord of the rings

While we know of thousands of exoplanets, only one exoplanet system has been found. J1407b is a massive planet with rings so large they block out their parent star’s light. It has a total of 30 systems in its rings, and the system has mass comparable to the mass of Mars. In fact, the system is around our Sun, it would stretch all the way past Venus and fall a bit short of Earth’s orbit. J1407b is massive enough that it may not technically qualify as a planet, and may instead be a brown dwarf, a class of objects encompassing failed stars. This object is estimated to be 20 times more massive than Jupiter.

It appears the process of coming apart at the seams has already begun. Images of Phobos taken by the Viking orbiters and other spacecraft show a network of grooves in the tiny moon’s surface. At first they appeared to radiate from near Stickney Crater, and geologists assumed that the grooves were cracks caused by the ancient impact. Some certainly are just that, but not all. In 2015, Terry Hurford of NASA’s Goddard Space Flight Center and his colleagues reported a new analysis of the grooves. Most of them actually radiate from the side of Phobos that constantly faces Mars; tidal forces caused by Mars’ gravitational pull are deforming Phobos. Hurford believes the grooves are stretch marks, a visible sign of the inexorable grip of tidal forces on the moon.

The future martian ring will not be the only one in the solar system, of course. Nor will it be the only ring whose existence depends on a moon. — J. D.

SATURN

The ring arcs are — like the future ring around Mars — all intimately linked to moons and moonlets. The existence of Saturn’s much more massive ring system is linked to Saturn having lost its large primordial inner moons, Canup explains. “Jupiter retained its large inner moons, [while] its dusty ring system is vastly less massive than the ring system at Saturn.”

Creating a martian ring

Phobos doesn’t easily be the size of a planet, but many of the same mechanisms will drive its destruction. Its companion moon Deimos is about 7.8 miles (12.6 kilometers) in diameter and orbits Mars at an average distance of 14,580 miles (23,460 km), far enough away to avoid Phobos’ fate. Phobos is 16 miles (26 km) in diameter. It circles the planet at an average speed of 5,827 miles per hour.

Phobos, it seems, is not long for this universe — at least on the large cosmic timescale.

Astronomers have long known that Phobos, the larger and nearer of the two martian moons, is slowly spiraling inward to a predictable end. The end result won’t be pretty: Phobos will slip closer and closer toward Mars, then strike a gravitational line where the planet’s tidal forces will be strong enough to rip it apart. The rubble pile like moon will break into smaller boulders, rocks, and dust, and will spread out in orbit around Mars. Mars will join the gas giants in having a spectacular feature: a ring system. It could be 25 million years from now. It could be up to 75 million years. Recent discoveries about the little moon’s composition and density, however, make it far more likely that its death dive will happen sooner. The pieces that don’t form a ring will fall to the surface, smashing with enough force toocknock Mars with new craters. “A lot of planetary science focuses on what happened in the past and what’s happening now,” says planetary scientist Benjamin A. Black. “It’s not often that we look at the future, at what will happen.” Black, a City University of New York professor, and graduate student Tushar Mittal from the University of California, Berkeley, have carried out a detailed examination of the eventual fate of Phobos.

It could be 25 million years from now. It could be up to 75 million years. Recent discoveries about the little moon’s composition and density, however, make it far more likely that its death dive will happen sooner. The pieces that don’t form a ring will fall to the surface, smashing with enough force to knock Mars with new craters. “A lot of planetary science focuses on what happened in the past and what’s happening now,” says planetary scientist Benjamin A. Black. “It’s not often that we look at the future, at what will happen.” Black, a City University of New York professor, and graduate student Tushar Mittal from the University of California, Berkeley, have carried out a detailed examination of the eventual fate of Phobos.

Jupiter’s four faint and dusty rings probably formed by a different mechanism than Saturn’s — and more recently — but its moons still play a vital role. Amalthea and Thebe are the likely sources of the material in Jupiter’s outer two “gossamer” rings. These outer rings are dustier and fainter than the inner rings, and are the sources of the dust grains making up the main and innermost halo rings. Some force works against the rings, keeping them relatively thin. Electromagnetic forces, a phenomenon called plasma drag, and even pressure from sunlight (called the Poynting–Robertson effect) continually remove the micron-sized particles from the rings. But particles dropped off the moons by meteoroid impacts create dust and continually replenish the rings. The 13 known rings of Uranus are unlike those of Jupiter or Saturn. All but the innermost and two outermost of the rings are quite narrow, ranging from just 0.6 to 59.6 miles (1 to 96 kilometers) wide. Their particles are larger than those in Jupiter’s rings, but there’s little dust. Instead, they’re largely made up of ice with organic chemicals mixed in to give the dark appearances, unique among the other solar system rings.

But there are similarities: Like Jupiter’s and Saturn’s rings, Uranus’ rings are intimately associated with moons and moonlets. Primordial moons the size of Puck, 100 miles (162km) in diameter, or larger would have had a good chance of surviving for several billion years. But not all would ascend to form rings. Computer simulations show that the 11 inner moons of Uranus are likely the remains of original larger moons broken up by cometary impacts. What’s more, the current rate of meteoroid impacts among moons and other icy bodies at Uranus’ distance is enough to create all the observed rings and dust bands circling that planet. Because the rings appear to be young, probably not more than 600 million years old, the material in the rings must be continuously renewed. Particles blasted off the tiny moons and still-unseen moonlets by collisions and meteoroid impacts continually add material to the rings, while the dust continues to dissipate.

Neptune’s free rings and various dust bands are probably even younger than those of Uranus, and the same processes are likely responsible for them and the moons that orbit in or near them. Naiad and Thalassa orbit in the gap between the innermost Galilean and Le Verrier rings, and Despina orbits just inside the Le Verrier ring. Galatea lies slightly inside the outermost Adams ring. These tiny moons are likely rubble-pile objects, agglomerations of fragments from earlier neptunian moons, weakly held together by gravity. The ring particles are material continually blasted off the moons by meteoroid impacts. Unlike the uranian rings, the rings of Neptune are quite dusty, thanks to the destruction of a satellite at least 20 percent of the material is in the size of smoke particles, and in some of the rings, that rise to 70 percent.

The Adams ring also has five distinct clumps or arcs of dust spanning 40° in longitude. How they can exist for any length of time is a mystery, as these tenuous rings should have faded away. One explanation, by planetary ring expert Carolyn Porco, leader of the Cassini orbiters imaging team, is that a resonance caused by Galatea’s eccentric orbit may act to keep the particles in the arcs from spreading out and dissipating. — J. D.
Astronomy

the early solar system. Phobos is not only a rubble pile with a weak density, and complex organic molecules such as amino acids, but also a tiny moon with a liquid ocean. Geysers at the moon’s south pole eject water into space, forming the ring.

As Phobos spirals inward, it will reach a distance, called the Roche limit, where the moon will be pulled apart by Mars’ gravity. The end result will be a temporary ring around Mars. Someone is standing in the way.

The line dividing the two moons is called the Roche limit, the point at which the gravitational force of Mars is sufficient to tear apart any material not bound to Phobos. As Phobos descends through this limit, it begins to spin more rapidly, eventually becoming a ring.

Several studies confirm that Phobos’ inward spiral will lead to its destruction in 25 to 75 million years. Eventually, the rocky rubble left behind will meet a quicker, more dramatic end. It will plummet down along slanting paths to impact the surface of Mars and leave a string of elongated craters across the planet’s equator.

Other once and future rings

It is possible that Mars possessed a ring system in its distant past. “We’re not certain,” says Black, “but it would be worth investigating whether past inwardly migrating moons may have existed. Some fraction of moons might be expected to have an orbital configuration similar to that of Phobos and Mars.”

Some planetary scientists think Mars once did have more than two moons. Researchers have identified 258 elliptical craters on Mars formed by objects hitting the surface at grazing angles. At least some of them could well have been made by oblique impacts of ancient martian moons. If so, others may have broken up before hitting the atmosphere, leaving short-lived rings of rocks and dust around Mars.

There’s no evidence that Mercury or Venus ever possessed ring systems. Earth did, though, for an extremely brief period during the formation of the Moon 4.5 billion years ago when our planet was struck by a Mars-sized body dubbed Theia. Much of Theia merged with Earth, but the “Big Splash” would have blown the remaining material into space. Computer simulations indicate about 20 percent of Theia’s mass would have gone into orbit around Earth as a ring. About 10 percent of the ring’s material then quickly coalesced into the Moon, with the rest eventually falling back to Earth. The ring would not have lasted long, perhaps as little as a month but probably no more than 100 years.

Curiously, our Moon also could end as it began, according to astronomer Lee Anne Willson, university professor emerita at Iowa State University. As part of her research on the fate of Earth as the Sun expands into a red giant, she found that the Moon stood a chance of becoming a ring around Earth.

The Moon is receding from Earth at a rate of about 1.6 inches (4cm) per year. Left uncheckered, the Moon will eventually migrate out to a distance where it will take 47 days to orbit Earth. By then, Earth’s rotation also will have slowed to 47 days. The two will then keep the same face to each other, as Pluto and its moon Charon do today.

Before this happens, though, some 5 billion years from now, the Sun will enter its red giant phase. It will start expanding in size, and swallow up Mercury and Venus. As the Earth-Moon system orbits through the Sun’s expanded outer atmosphere, drag forces will cause the Moon’s orbit to begin decaying. The Sun will probably continue to expand, and destroy both Earth and the Moon. On the other hand, if the Sun should blow off about 20 percent of its mass first, the Moon will continue to spiral down to its Roche limit. Tidal forces will tear it apart, just as they will destroy Phobos.

And then, 9 billion years after the Moon’s birth from a ring of molten impact ejecta, and nearly 5 billion years after the birth and death of the ring around Mars, Earth will once again have a ring.