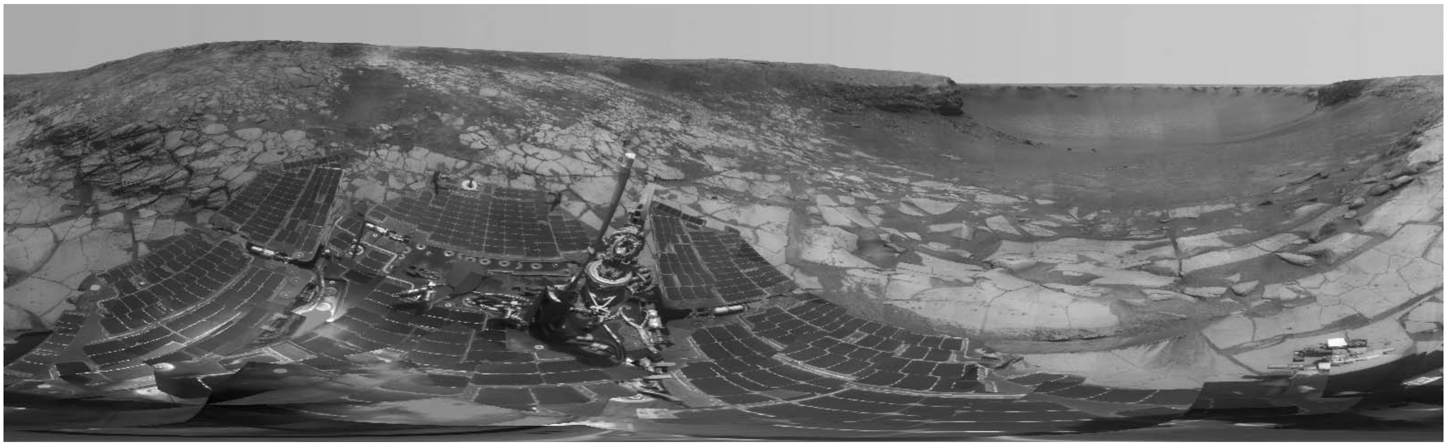


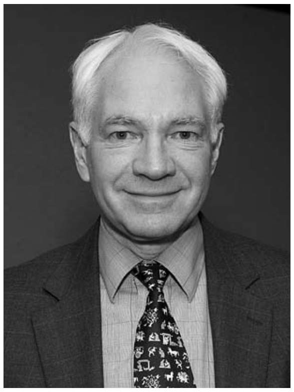
Panorama inside Victoria Crater, taken by a camera on the Mars Exploration Rover *Opportunity*. Image courtesy of NASA/JPL-Caltech/Cornell University.

Science Results from the Mars Exploration Rover Mission

Steven Squyres

Introduction by Claude Canizares

This presentation was given at the 1926th Stated Meeting, held at the House of the Academy on April 9, 2008.



Claude Canizares

Claude Canizares, a Fellow of the American Academy since 2004, is the Bruno Rossi Professor of Physics and Vice President for Research and Associate Provost at the Massachusetts Institute of Technology. He is also Associate Director of the Chandra X-ray Observatory Center and a Principal Investigator on NASA's Chandra X-ray Observatory.

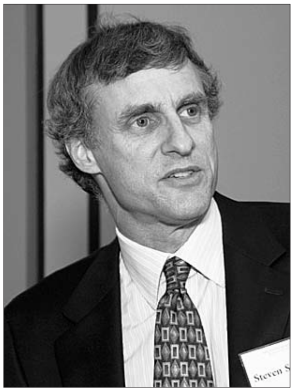
Introduction

It's a great pleasure, indeed an honor, to introduce my friend Steve Squyres. Just over four years ago I had the privilege of being at the Jet Propulsion Laboratory at the California Institute of Technology a few days after New Year's Eve, when the Mars Exploration Rover Mission reached Mars and went through the harrowing and exhilarating process known as entry, descent, and landing. This, of course, was wildly successful and it was the culmination of many years of effort by our speaker tonight, who is the Principal Scientific Investigator of this remarkable project. The two Rovers, *Spirit* and *Opportunity*, that are the scientific core of this mission have vastly exceeded by many times over their original design criteria and have returned an outstanding mother lode of information on Mars and its surface.

Even those of us who have lived through our own space missions recognize that the degree to which this mission has captivated the world is almost unprecedented: We can only marvel at the incredible scale, both scientific and technical, of the achievement. Steve Squyres really stewarded this effort through many years of development. Now, after probably thinking he had only a few years of operations and then a release onto other things, Steve is being called back over and over again to plan the very detailed activities of the two Rovers as they scour the surface of Mars.

In 1977, when Steve was an undergraduate at Cornell, the *Voyager* spacecraft was launched to Jupiter and Saturn. He, probably even as an undergraduate but certainly as a graduate student (also at Cornell), ended up participating in the scientific team for that mission, which became a galvanizing moment for him and set his career toward the planets, both the outer planets but then the inner planets as well. He participated in the Magellan Mission to Venus and the Cassini-Huygens Mission to Saturn; he, too, has touched most of the missions to Mars: the Mars Observer, the Russian Mars '96, Mars Express, Mars Reconnaissance Orbiter, the Mars Odyssey Mission, and, of course, the Mars Exploration Rovers.

CBS News called Steve the Mars Ambassador. Now, I don't think they meant that he himself is a Martian. Rather, he has brought Mars to the Earth, and without any question he is Earth's ambassador to Mars. It gives me great pleasure to welcome Steve Squyres.



Steven Squyres

Steven Squyres is the Goldwin Smith Professor of Astronomy at Cornell University and the Principal Scientific Investigator of NASA's Mars Exploration Rover Project. He has been a Fellow of the American Academy since 2005.

Presentation

I face the challenge of trying to compress a combined 3,000 days on the surface of Mars into less than half an hour, so fasten your seatbelts.

The two Mars Rovers, *Spirit* and *Opportunity*, are effectively robotic field geologists. They have a two-part scientific payload. One part does remote sensing, which is supported by a mast with high-resolution color stereo cameras at the top and a Michelson interferometer and infrared spectrometer that live down toward the base; they use mirrors at the top of the mast to get the same view of the countryside as the cameras get. The second part is an arm in the front end of the vehicle, a five degree of freedom robotic manipulator, that includes a microscopic imager, an alpha particle X-ray spectrometer that does elemental chemistry, a Mössbauer spectrometer that tells us about the mineralogy of iron-bearing species, and a device called the RAT, or Rock Abrasion Tool, a diamond-tip tool that grinds away the outer layers of Martian rock and exposes the interior.

Spirit landed in the Gusev Crater. At 160 kilometers in diameter and 16 degrees south latitude on Mars, the Crater was chosen as a landing site because of a large, water-carved channel that empties into it. We went there seeking layered sedimentary rocks laid down long ago on a Martian lake that we believe once filled the crater. After we landed I managed to convince myself for about two days that this was what a Martian dry lake bed should look like, nice and smooth and flat. But when we started to look at the rocks we found that they were not sedimentary rocks at all.

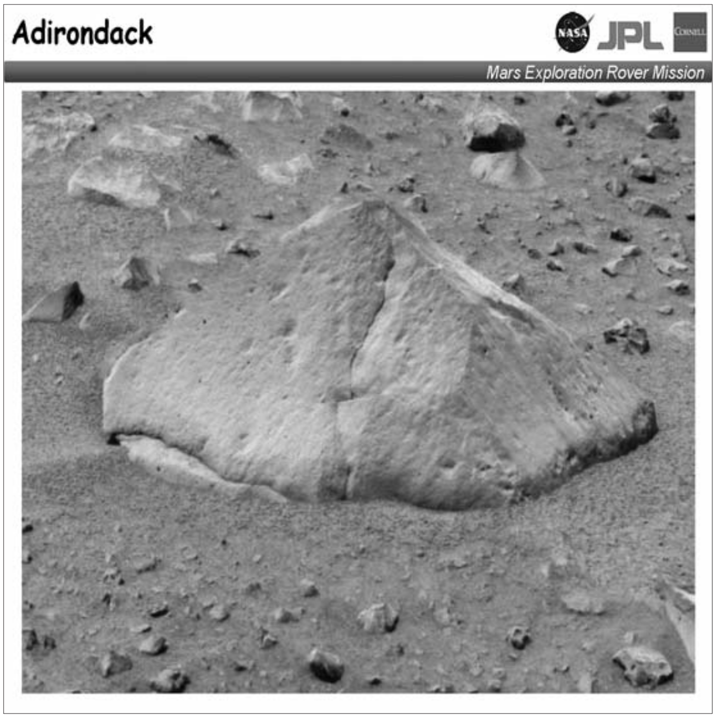


Figure 1

> *The two Mars Rovers,* Spirit *and* Opportunity, *are effectively robotic field geologists.*

We named the first rock that we looked at in detail Adirondack (see Figure 1). A Mössbauer spectrum revealed olivine, pyroxene, and magnetite, among other minerals, in the Adirondack rock. (Olivine and pyroxene are minerals that would be very common in basaltic lava on Earth.) Our infrared spectrometer also revealed olivine and pyroxene, as well as plagioclase, another mineral found in basaltic lava. The mineralogy inferred from elemental chemistry, as derived from the X-ray spectrometer, showed, again, plagioclase, pyroxene, olivine, and a bit of magnetite. All of the instruments tell the same story: Adirondack is a magnetite-bearing olivine basalt. It's an igneous rock that was erupted onto the floor of the Crater, burying whatever sediments were once there. Basically Mars faked us out; this was a disappointment at first.

Our vehicles were designed to last for 90 Martian days and drive 600 meters over their lifetime. When *Spirit* landed, we came to rest 2.5 kilometers from a spectacular range of hills that we named the Columbia Hills, after the *Columbia* space shuttle. Because of the longevity of the vehicle, we were able to get to the Columbia Hills and spend most of the mission there. The first hill that we chose to go after was one that we named Husband Hill, after Rick Husband, who was the commander of *Columbia* when it went down. We climbed over a period of about 400 days to the very summit of Husband Hill, which gives you a sense of the scale of that hill.

I have nowhere near enough time to describe to you the incredibly rich diversity of different geologic materials that are found on Husband Hill and all the geologic stories they tell. I'll tell you just one, drawn from the first rocks that we found as we arrived at Husband Hill, on the portion of it that we called the West Spur. In contrast to what we saw on the plains – massive lavas – we started to see layered rocks, even sub-centimeter layering within the rocks, at the West Spur. Typical rocks from the West Spur are granular, with individual grains within the rock. There's enormous variety in the size of the grains: some are tiny little things that approach the resolution limit of our camera (30 microns per pixel); others are millimeters in size. The combination of small and large grains points toward a very violent, energetic process involved in the formation of these rocks. A gentle process like flowing water or blowing wind tends to have a particular grain size that it transports most effectively, so grains tend to be well-sorted and more or less the same size. A violent process like an explosion will throw out fine and coarse grains all together, resulting in a jumbled-up rock like we found at the West Spur.

We took the composition of these rocks and ratioed them on an element-by-element basis to compare them with the lavas that we saw on the plains. For some of the elements, the composition is fairly similar, but there are a number of elements, notably phosphorous, sulfur, chlorine, and bromine – elements that tend to be present in salts – that are substantially enriched in this rock from the West Spur. (The rock is also significantly enriched in nickel, to which I'll return later.) Mineralogy from our Mössbauer spectrometer found goethite, an iron oxihydroxide. The hydroxide tells us that water had to be involved in the formation of this mineral.

Taking all of this together, we've come to the conclusion that these rocks are impact ejecta that have been altered by water. When an impactor from space comes in, hits the surface, creates an explosion, and throws a bunch of stuff in the air, it all falls out at once, with some of the impactor itself mixed in. Impactors tend to be rich in nickel; we think that's where the nickel comes from. And then there's clear evidence that water altered the rock: the presence of goethite and deposited salts (which produced the sulfates), phosphates, and chlorides makes this obvious.

After time in the West Spur, we climbed all the way to the summit of Husband Hill and came down off the summit to a place called Home Plate, where we've been for a while. Home Plate is a plateau of layered volcanic rocks that is about two or three meters high and about 80 or 90 meters across. Right now we are on the north side of it, our solar rays tilted toward the north with the sun low in the northern sky, riding out our third winter on Mars. We hope to explore more with *Spirit* when springtime comes.

The right front wheel of *Spirit* no longer turns; it died about 800 days into the mission. The other five wheels work fine, but in order to drive the vehicle we have to drive it backward, dragging the broken wheel through the soil. While this does make *Spirit* hard to drive, it digs a trench, hundreds of meters long, through the Martian soil, turning up something wonderful every so often.

There's clear evidence that water altered the rock.

Opportunity came to rest in an impact crater we named Eagle Crater. We spent 60 Martian days there and then drove over to a much larger crater called Endurance Crater and spent a couple of hundred Martian days exploring there, including deep down into the crater. The *Opportunity* landing site was chosen not because of its topography but because of its chemistry. Data from an infrared spectrometer – the thermal emissions spectrometer that was in orbit around Mars on the Mars Global Surveyor spacecraft – show not only basaltic lava at the *Opportunity* landing site, but also hematite. Hematite, an iron oxide, is a mineral that sometimes forms as a consequence of the action of liquid water.

The rocks at Meridiani Planum, near where *Opportunity* landed, are all made of the same materials: they are sandstones, composed of sand-sized grains that are extremely rich in sulfate salts (see Figure 2). Embedded within them are little round spherules, things that we've come to call 'blueberries,' which turn out to be extremely rich in hematite. By mass, sulfate salts account for roughly 40 percent of the rock: 20 percent magnesium sulfate, 10 percent calcium sulfate, and 10 percent of an iron sulfate called jarosite.

When we mapped the composition with our infrared spectrometer we found a lot of sand made of basalt. The soils in many places are very rich in these hematite blueberries, but everywhere you have bedrock exposed, the rock is sulfate rich. The mineralogy derived from the infrared spectrum tells the same story as elemental chemistry: 10 percent jarosite, 20 percent magnesium sulfate, 10 percent calcium sulfate. The Mössbauer spectrometer sees only iron-bearing minerals, so it shows the jarosite as well. You need water to make this jarosite, a particularly environmentally informative mineral because it only forms at low pH. The pH has to be less than about four or five to form jarosite, and, on Earth, jarosite typically forms around a pH of three or two. This helps to make it clear that when people talk about the Meridiani Planum and the presence of water on Mars, they should more accurately be talking about sulfuric acid on Mars.

At Endurance Crater, the larger of the two craters where we took *Opportunity*, we drilled with our rock abrasion tool a total of eleven rat holes over a stratographic distance of about seven meters, working our way down into the crater. This is the first stratigraphic section ever put together on another planet. We saw some substantial changes in the nature of the rock as we went down. Toward the surface the rock preserved the lamina-

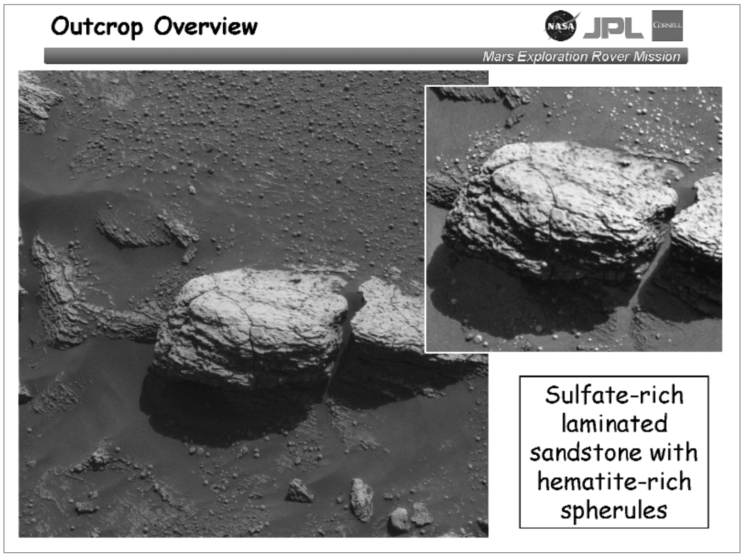
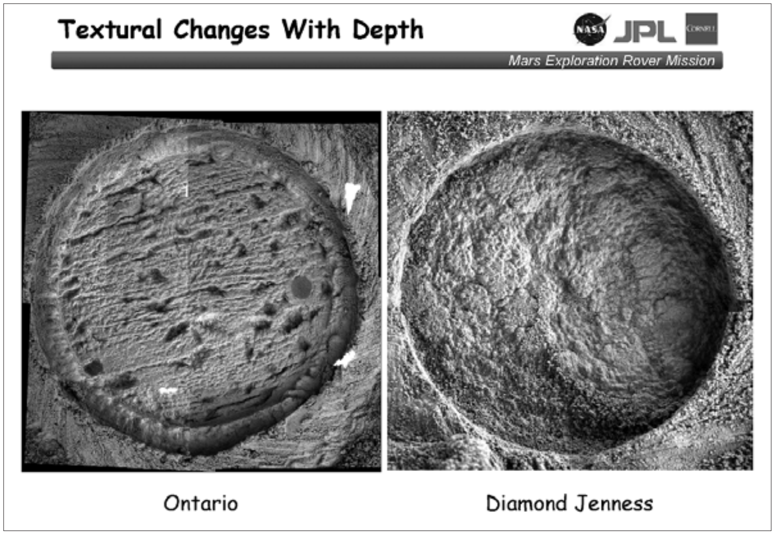


Figure 2



Textural Changes With Depth

Mars Exploration Rover Mission

Ontario

Diamond Jenness

Figure 3

tions very nicely in the original layering in sandstone. But when we got deeper in the crater that changed completely. The layering goes away, replaced by a lumpy texture, which, we believe, is a consequence of recrystalization (see Figure 3). These are soluble rocks; magnesium sulfate in particular is highly soluble in water. If these rocks are soaked in water for long enough, recrystalization occurs, destroying the original textures. That is what you see deep in the crater.

The Opportunity *landing site was chosen not because of its topography but because of its chemistry.*

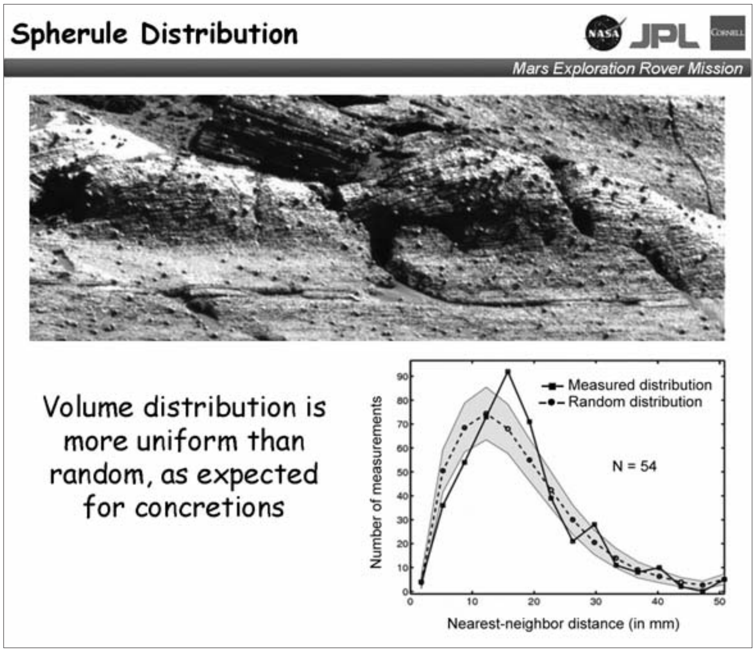
The chemistry changes as you go down-section as well. As you get deeper the chlorine increases sharply (precipitation of chloride salts is taking place below a certain level), but both sulfur and magnesium decrease. They follow each other beautifully, which tells us that the compound made of mostly magnesium and sulfur – magnesium sulfate – is the soluble material that gets dissolved away. The point at which the texture changes is the same point of depth below which the chemistry begins to change.

We found a place that we called the Berry Bowl, where a bunch of the so-called blueberries have come together (see Figure 4). We measured their composition and found them to be at least 50 percent hematite by mass – probably closer to 70 or 80 percent actually. We have concluded that they are concretions, which, on Earth, form in sedimentary rocks that are saturated in water. With a concretion, some mineral wants to precipitate out, so it finds a nucleation point and starts to solidify. It adds layer upon layer upon layer, growing a hard, spherical nodule (sort of like the way an oyster builds a pearl), which is dispersed through the rock. One interesting thing about a concretion is that as it grows, it draws fluid from a body of fluid around it within the rock and carves out a space for itself. This volume it creates for itself within the rock means that statistical analysis of the special or the volumetric distribution of concretions within a rock reveals a distribution that is not a poisson dis-

Measuring Spherule Mineralogy

Mars Exploration Rover Mission

Figure 4



Spherule Distribution

Mars Exploration Rover Mission

Volume distribution is more uniform than random, as expected for concretions

Figure 5

tribution, not spatially random but more uniform, because the concretions space themselves out; nearest-neighbor statistics of their distribution confirm this uniformity (see Figure 5).

Informed by data from experiments performed by Dave Rubin of the U.S. Geological Survey at Menlo Park, California, we have also found evidence in a few places that water not only saturated the ground but came to the surface. Rubin found that when water flows over sand that is 40 centimeters across it leaves behind highly sinuous crested ripples, at a scale of five to ten centimeters. Computer simulations (again, the work of Rubin) of a ripple crest propagating downstream show that what gets left behind in the geologic record are concave upward festoons or trough geometry cross-bedding structures, indicating that these ripples propagated downstream at very small scales and proving that water was the fluid that did it. We discovered concave smiley shapes within the rock, up to ten centimeters across, in a number of places, including a rock we named Cornville, which is chock full of these shapes (see Figure 6). So not only did water soak the ground here, but it also occasionally came to the surface.

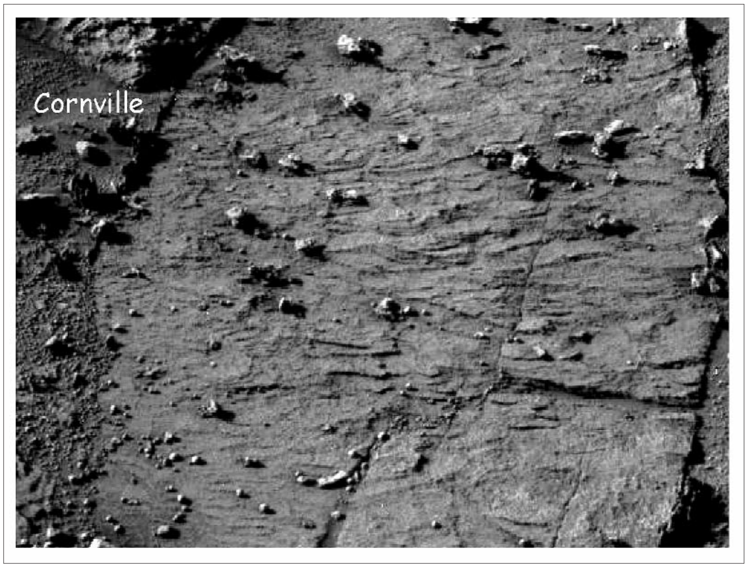


Figure 6

I would be doing you a grave disservice if I gave you the sense that the science that I just described to you was science that was done by me. I am one member of a team of 170 scientists; I had 57 coinvestigators. It's an extraordinary team of scientists, and I'm very fortunate to be part of it. I also have to give a lot of credit to a fabulous team of engineers that built vehicles that were designed to last for 90 days and have lasted more than 1,500 days on the Martian surface. For every one of us who has been part of this mission, it has been, in the very literal sense of the phrase, the adventure of a lifetime.

When people talk about the Meridiani Planum and the presence of water on Mars, they should more accurately be talking about sulfuric acid on Mars.

Questions and Answers

Question: Where is the water now?

Squyres: We think that a substantial amount of the water is down in the ground, frozen as permafrost. There is a spacecraft called the Mars Odyssey Orbiter that carries a gamma neutron spectrometer which is able to detect ice deposits down to a depth of roughly 50 centimeters or a meter. Poleward of about 60 degrees latitude on Mars the ground is saturated with ice down to that depth. You can't see below that, but there's probably more down there as well. So a good bet is that a lot of it soaked into the ground and froze.

You have to realize that the Martian crust is a consequence of many events: it is a consequence of lots and lots of impact cratering. That cratering breaks up the rocks and causes a lot of fracturing and void space, much more than you would expect, perhaps, in terrestrial rocks. That provides a subsurface reservoir where a fair amount of water can be hidden.

Question: As you command the vehicle from mission control there are so many minutes, one-way transit time, before the vehicle hears the command and so many minutes for us to interpret the optical images that I presume get sent. What's the frequency at which these commands are issued? What's the experience like? What's happening in between communications? And how fast does the vehicle go?

Squyres: We operate the vehicles by sending a set of commands to them once a day. The sun rises on Mars and falls on the solar arrays, waking the vehicle, typically, at 10:30 in the morning, local solar time on Mars. We transmit to the vehicle a complete set of instructions, everything we want it to do that day. It works until about 4:30 in the afternoon, when the Mars Odyssey Orbiter flies overhead. At that point the Rover transmits to the Orbiter what happened that day, and the Orbiter relays the data back to Earth. We have roughly 18 hours to look at the data and images, figure out what we want to do next, and send the next set of commands to the vehicle.

I'd love to control the Rover via joystick, but we don't do it that way. When I talk about Rover "drivers," nobody has a steering wheel or throttle. Instead, we write hundreds of lines of computer code telling the Rover what to do each day. As for the speed of the vehicle, it can go six centimeters a second, but we don't typically go nearly that fast. The Rover has to spend a lot of time assessing the safety of the terrain. It has a set of cameras that it will use to build up a three-dimensional range map of the topography in front of it and figure out what it is safe to go over and what it has to go around. You can actually program different levels of courage or cowardice into the vehicle, depending on how scary you think the terrain is. Our all-time record was 220 meters in one day. In comparison, the *Sojourner* Rover on Mars Pathfinder did, I think, 106 meters over its entire lifetime. So 220 meters in a day is pretty good. Our all-time record for *Spirit* is 125 meters in a day. In good terrain a typical number is 20 or 30 meters in a day. For *Spirit* these days, with that busted wheel, 5 meters is a good day.

Question: I'm under the impression that it's pretty cold on Mars. I wonder if you saw any evidence that the water ever froze. Were there places where you might have expected it to freeze and you saw something different?

Squyres: We've thought a lot about that, and I think our data do not enable us to answer that question. Features that we've seen, including those little ripples that speak of surface water, could form perfectly well under an ice cover. Water can flow under a cover of ice; I see that in Ithaca, New York, in the winter. So I don't think that our mission has really addressed that. I have not seen anything that is uniquely attributable to ice, nor have I seen anything that I think rules it out.

Question: How confident can you be that your extrapolations from what you've seen in this tiny surface would be true elsewhere?

Steven Squyres: I worry about that one a lot. I feel pretty confident about our interpretations at these two little pinpricks on the surface of Mars. However, the combined surface area of Mars is equal to the combined surface area of all the continents of Earth together. *Spirit* has gone 7.5 kilometers; *Opportunity* has gone 12 – there's a lot of Mars we haven't seen. Mars is incredibly diverse geologically. We know that from images that we see from orbit – just look at how different our two landing sites are, for example. It would be reckless to try to extrapolate too far from these two little spots on the surface. We are trying to characterize these two places and then interpolate as best we can using orbital data. But if you put a dozen of these Rovers down on a dozen places on Mars you'd get a dozen different stories; that's the nature of the business. ■

Margaret Geller (Harvard-Smithsonian Center for Astrophysics) and Scott Kenyon (Harvard-Smithsonian Center for Astrophysics)

Elaine Musgrave (Wiley-Blackwell Publishing) and Michael Wood-Vasey (Harvard-Smithsonian Center for Astrophysics)

Linda Gelb, Arthur Gelb (Four Sigma Corporation), and Leslie Berlowitz