Mars: Science and Engineering (Week 4)

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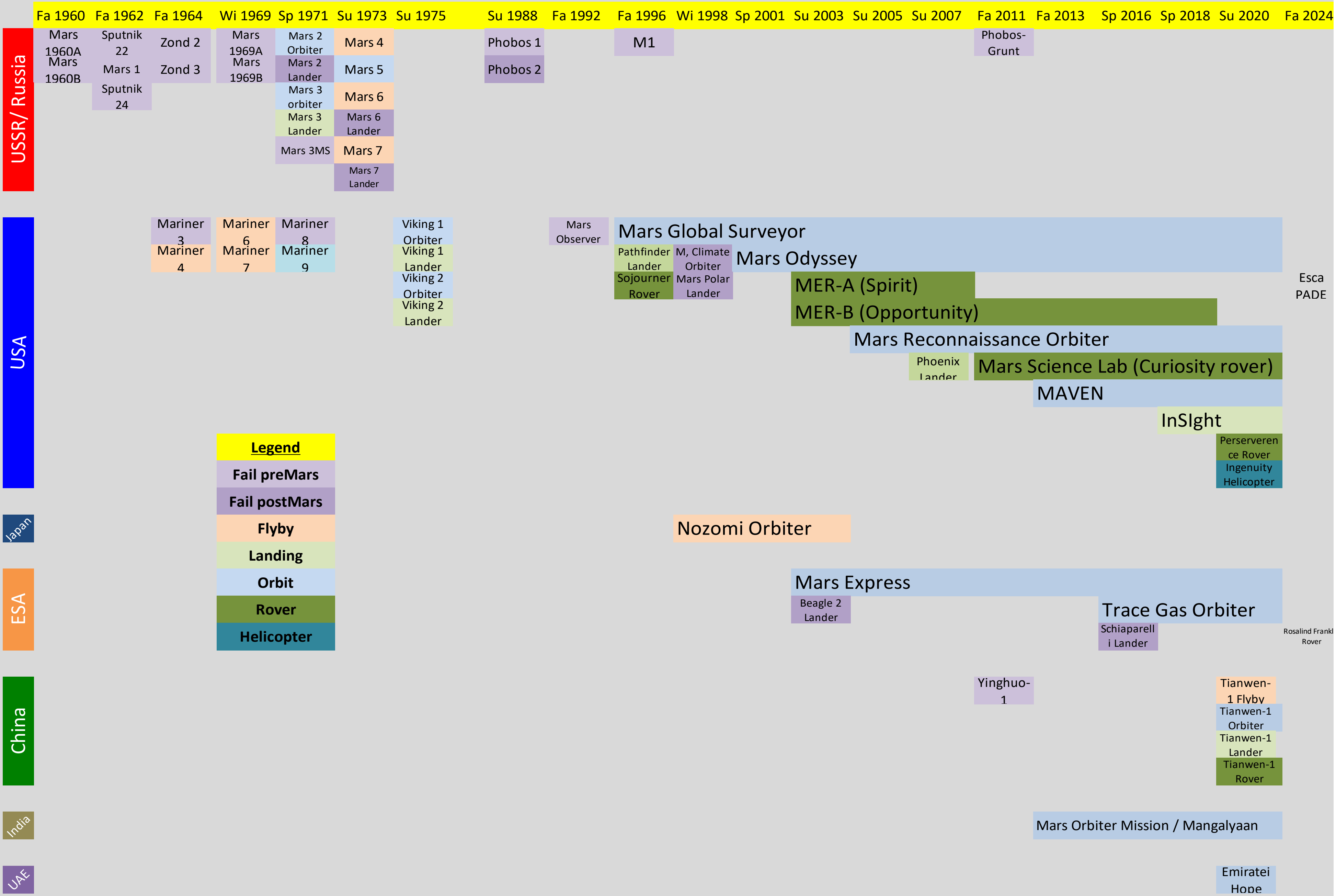
CMU Osher

Fall 2023

Course Outline

- Week 1
  - Astronomy background
  - Early flights with no or minimal success
  - Mariner Program
- Week 2
  - 1973: Soviet Mars program
  - 1975: US Viking program
  - 1990s: MGS, Pathfinder, Sojourner, Nozomi
- Week 3
  - Early 2000s: Odyssey, Spirit & Opportunity, Mars Express
  - Late 2000s: Mars Reconnaissance Orbiter, Phoenix lander
- **Week 4**
  - 2010s: Curiosity, MAVEN, Mangalayan, Insight
  - 2020s: Perseverance, Ingenuity, Tianwen, Emirati Hope
  - Future missions: Exo-Mars, EscaPade, sample return
  - Far future: humans on Mars



Fa 1960
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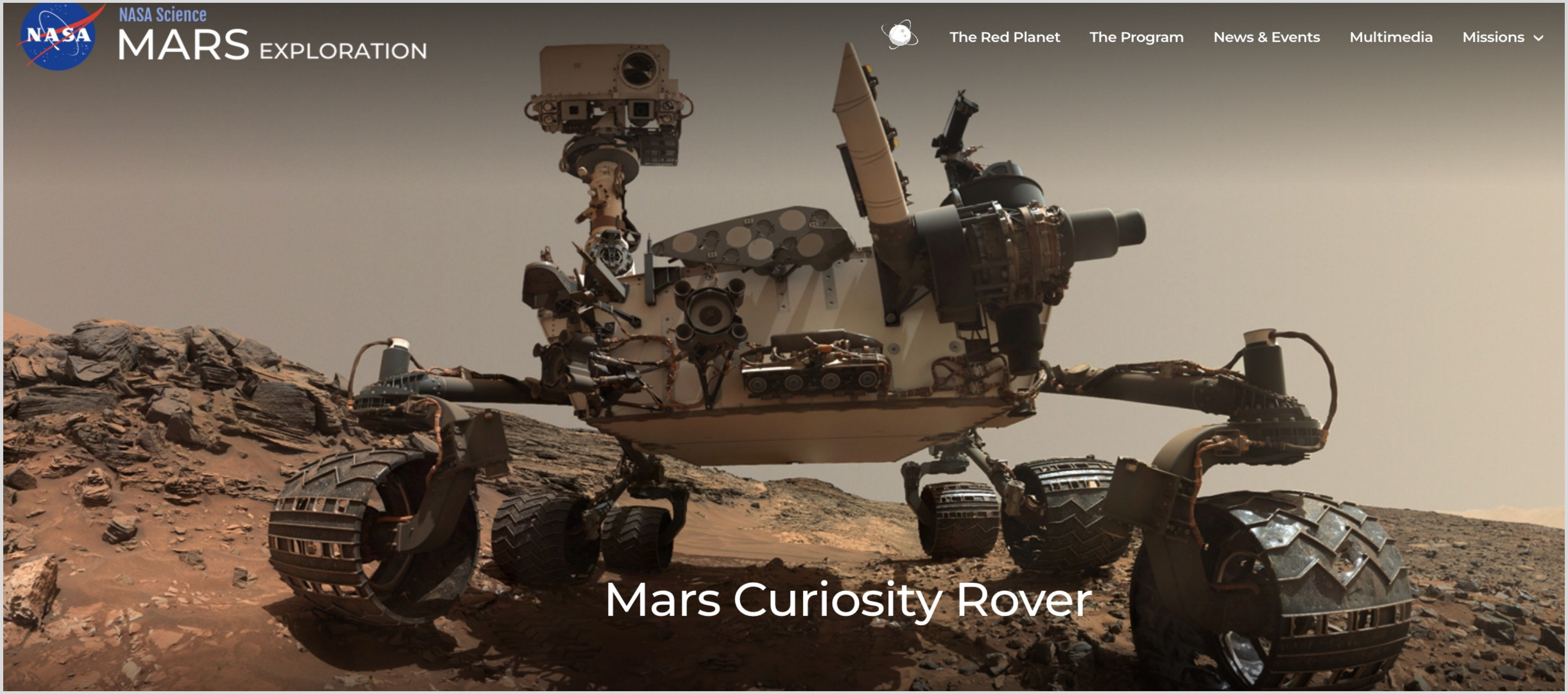
USSR/ Russia
Mars 1960A
Mars 1960B
Sputnik 22
Mars 1
Sputnik 24
Zond 2
Zond 3
Mars 1969A
Mars 1969B
Mars 2 Orbiter
Mars 2 Lander
Mars 3 orbiter
Mars 3 Lander
Mars 3MS
Mars 4
Mars 5
Mars 6
Mars 6 Lander
Mars 7
Mars 7 Lander
Phobos 1
Phobos 2
M1
Phobos-Grunt
USA
Mariner 3
Mariner 4
Mariner 6
Mariner 7
Mariner 8
Mariner 9
Viking 1 Orbiter
Viking 1 Lander
Viking 2 Orbiter
Viking 2 Lander
Mars Observer
Mars Global Surveyor
Pathfinder Lander
Sojourner Rover
M, Climate Orbiter
Mars Polar Lander
Mars Odyssey
MER-A (Spirit)
MER-B (Opportunity)
Mars Reconnaissance Orbiter
Phoenix Lander
Mars Science Lab (Curiosity rover)
MAVEN
InSIght
Perserverence Rover
Ingenuity Helicopter
Esca PADE
Legend
Fail preMars
Fail postMars
Flyby
Landing
Orbit
Rover
Helicopter
Japan
Nozomi Orbiter
ESA
Mars Express
Beagle 2 Lander
Trace Gas Orbiter
Schiaparelli Lander
Rosalind Frankl Rover
China
Yinghuo-1
Tianwen-1 Flyby
Tianwen-1 Orbiter
Tianwen-1 Lander
Tianwen-1 Rover
India
Mars Orbiter Mission / Mangalyaan
UAE
Emiratei Hope

US Mars Science Laboratory aka Curiosity

- $2.5 billion rover launched November 2011, landing August 2012
- Powered by 10 pounds of plutonium dioxide ($t_{½}$ = 88 years)
- Still operating

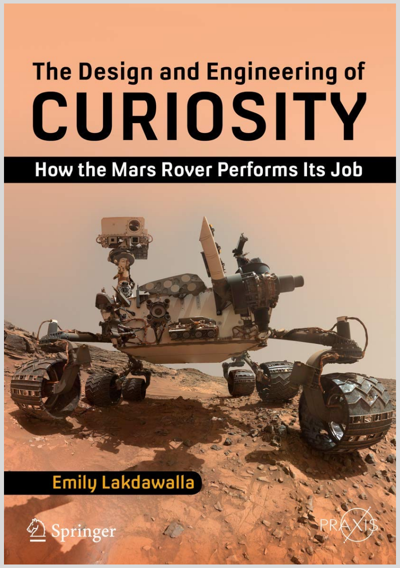


Curiosity Development

- April 2004: Announcement of Opportunity for scientists and engineers from around the world to propose instruments
  - Goals: quantitatively assess the habitability and environmental history of the landing site, characterize the geology, investigate planetary processes that influence habitability, and characterize surface radiation
  - 10 instruments chosen out of 48 proposed
- Size and weight of Vikings, but mobile
- Goal to reduce landing ellipse from MER's 90 x 12 miles to 4 x 2 miles (final design: 12 x 4 miles) achieved with steerable aeroshell
- Eventual workforce of 800 people
- Changed from Super Light Ablator (corkwood, epoxy and gas filled silica glass spheres) to tiled Phenolic Impregnated Carbon Ablator

Curiosity Instrumentation

- Mostly similar to Spirit and Opportunity
- Duplicate computers and navigation imaging
- ChemCam (0:30) for laser-induced breakdown spectroscopy



Explanation by Emily Lackdawalla, planetary geologist and space science journalist

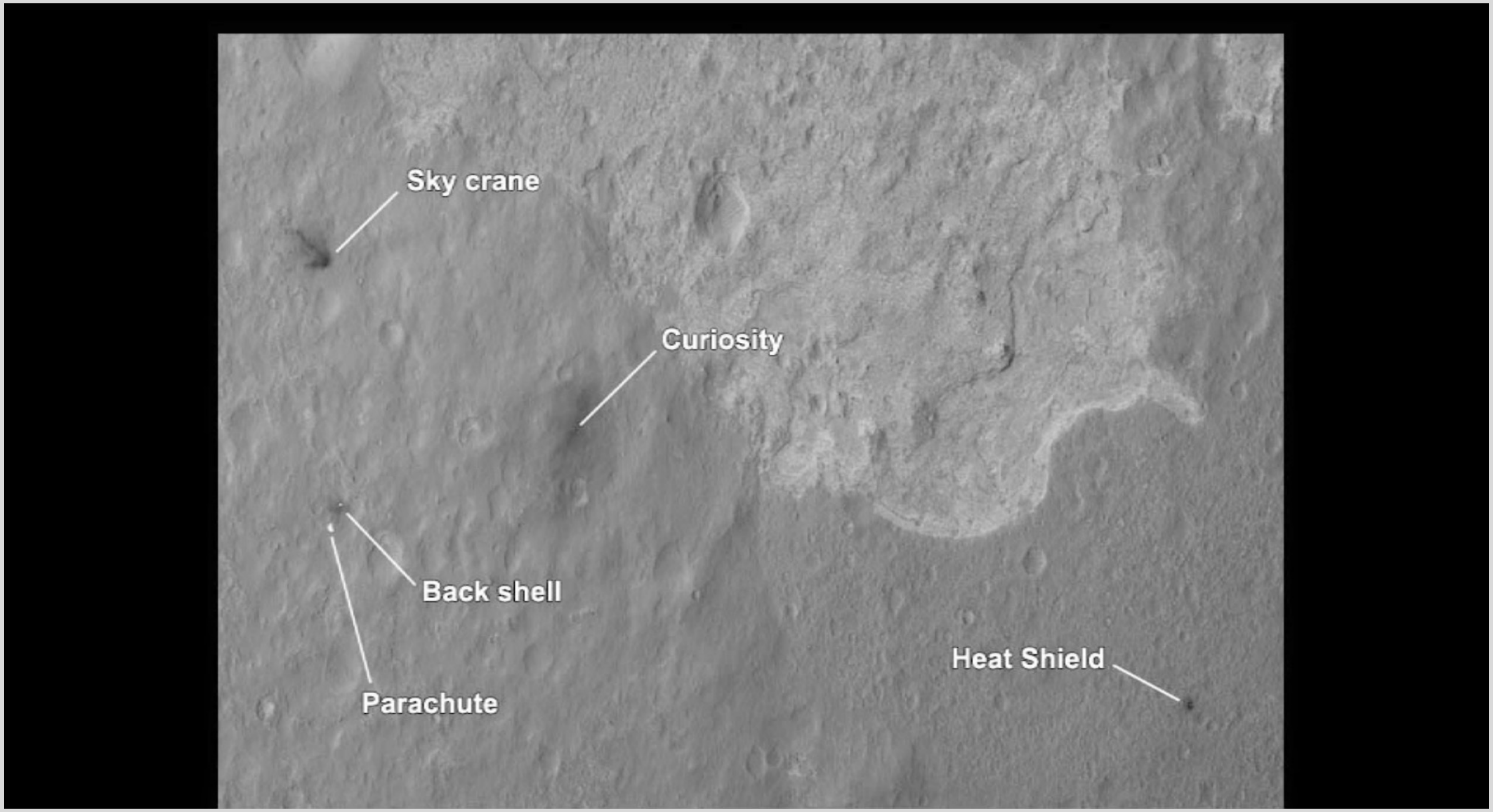
- CheMin for first direct mineralogy by x-ray diffraction and fluorescence

Curiosity EDL

- Added steering capability to the aeroshell to reduced the size of the landing ellipse
- Goal to land directly on the rover wheels
- Sky crane is straightforward: as soon as the descent phase detects slack in the tether, it can cut the tether and fly away from the landing site
- Curiosity EDL (3:41) August 5, 2012
- Real Movie of Curiosity Descent (0:55) at 2.5 times normal speed

Curiosity Cruise and Landing

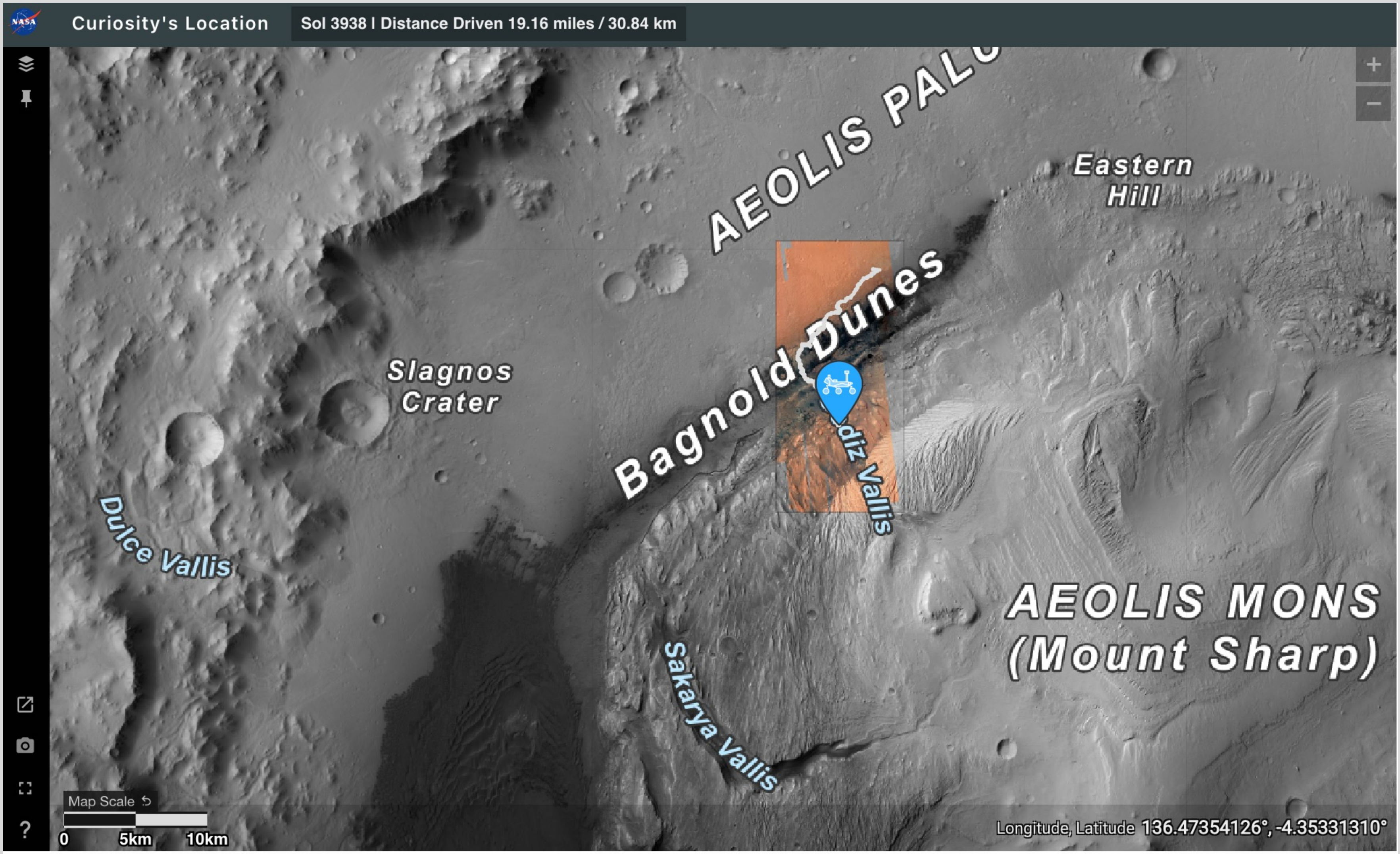
- During cruise phase measured radiation from galactic cosmic rays and solar coronal mass ejections: one round trip is more than NASA allowable lifetime dose of radiation
- Landing Site Gale Crater
    - An impact crater 90 miles in diameter and 3 miles deep
    - Later filled with sediment (wind and/or water)
    - Later eroded around the edges to form central Mount Sharp in the middle
    - Alluvial fan in the lowlands



Curiosity First Year

- Rogue “pilot” computer
- Unexpected wheel damage
- Rocks with sand grains too large to be transported by wind is good evidence of flowing water (billions of years ago)
- Sample Analysis at Mars (SAM) tunable laser spectrometer (TLS) found no methane in the atmosphere (less than 1 ppb)
- TLS measured atmospheric composition much more accurately than ever before: 96.0 % CO_2, 1.9 % Ar, 1.9 % N_2, 0.1 % O_2, 0.06 % CO
- SAM found much higher deuterium to hydrogen ratios than on Earth, suggesting preferential loss of lighter elements, which supports the idea that the atmosphere was lost via the solar wind
- Combined evidence of habitability (2:37)

Curiosity As of September 2023



Curiosity Rover's Location: This interactive map shows the route driven by NASA's Curiosity rover since landing in Gale Crater on Aug. 5, 2012.

China’s Yinghuo-1 Orbiter and Russia’s Phobos-Grunt Phobos Sample Return Mission

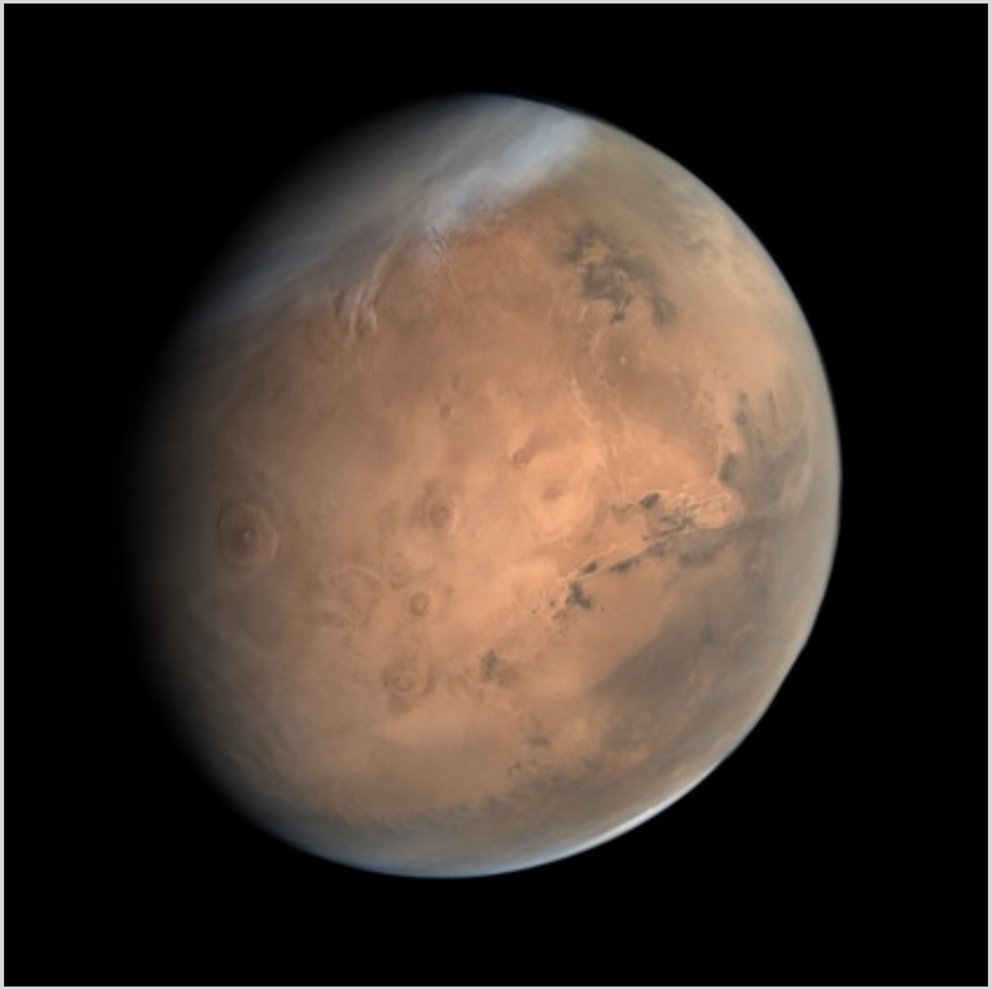
- Part of a cooperative space agreement between Russia and China
- Launched together from Baikonur November 2011
- Failed to initiate burn to leave Earth orbit
- Disintegrated over the Pacific Ocean in January 2012

US MAVEN

- Mars Atmosphere and Volatile Evolution
- $582 million
- Launched November 2013, orbited September 2014
- Showed how water in the atmosphere is split to H_2 and O by solar radiation, H_2 rises and is stripped away by the solar wind

India’s Mars Orbiter Mission (Mangalyaan)

- Built and operated by the Indian Space Research Organization (ISRO)
- $73 million
- Launched November 2013 from Satish Dhawan Space Center
- Entered orbit around Mars in September 2014
- Operated until April 2022
- Instrumentation
  - Visible and infrared cameras
    Lyman-alpha Photometer measured H and D in the atmosphere
  - Methane sensor (fatal flaw in how data was returned to Earth)
  - Mass-spectrometer measured altitude profiles of CO_2, CO, N_2 and O_2



US InSight Lander

- Interior exploration using Seismic Investigations, Geodesy and Heat Transport
- $830 million mission to place a seismometer and measure heat transfer with a deep probe
- Launched May 2018, landed November 2018
- Recorded 1,313 marsquakes, including one in May 2022 estimated at magnitude 5
- Concluded that the core is partially molten, and the crust is thinner than expected and may have two or three sub-layers
- The heat transfer probe was to be hammered 16 feet in with a percussive drill, which underperformed resulting in it going only about one foot deep rendering the science useless

Emirati Hope

- $200 million United Arab Emirates Mars orbiter
- 200 Emirati scientists and engineers design, developed, and operated the spacecraft under the Mohammed bin Rashid Space Centre
- Assembled at the University of Colorado in cooperation with US engineers
- Launched from Japan on July 2020 with orbit insertion in February 2021

- Contains an imager and infrared and ultraviolet spectrometers
- Imaged auroras, returned data on atmosphere, climate and dust storms

A view of Elysium Planitia as seen by the UAE's Hope Mars orbiter on March 15, 2021. (Image credit: Emirates Mars Mission/EXI)

China Tianwen-1

- Launched from the Wenchang Spacecraft Launch Site on the island of Hainan in July of 2020 on a Long March 5 heavy-lift launch vehicle, and entered Martian orbit in February of 2021
- After studying landing sites, the lander touched down 25^{o} north in Utopia Planitia in May 2021 using an aeroshell, supersonic parachute and retrorockets
- Ten days later the Zhurong rover was deployed and explored for the planned 90 days, and continued out to one Earth year, then went into hibernation for the Martian winter
- The orbiter has the usual array of instruments and continues to operate well as of Summer 2023

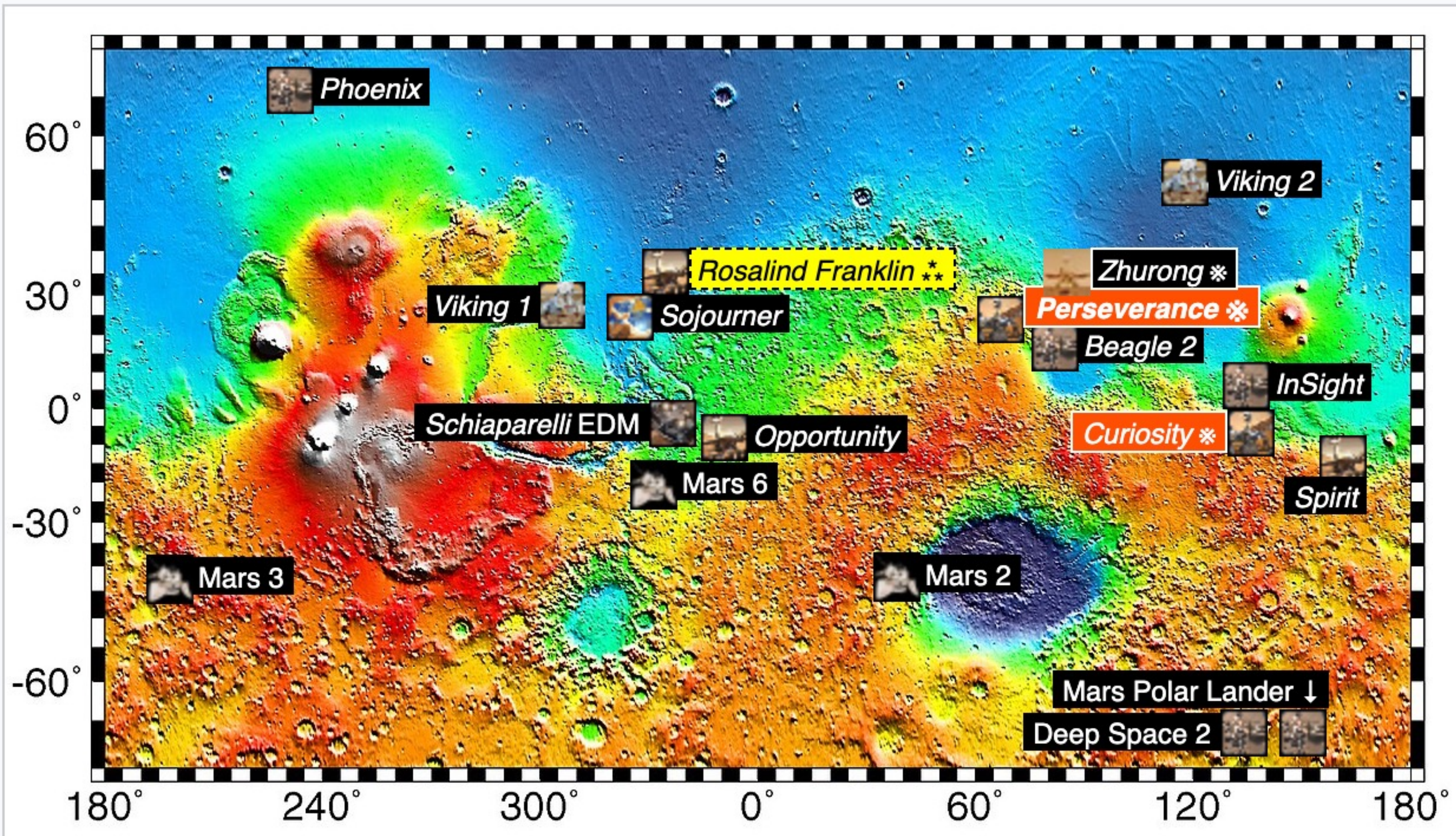
US Perseverance Rover

- Similar to Curiosity and designed to explore Jezero Crater, the $2.2 billion spacecraft launched July 2020 and landed February 2021
- EDL like Curiosity, but live streamed (3:05) for the first time and using cameras to control the landing site for the first time
- Has an engraved caduceus in honor of Covid healthcare workers
- Similar instrumentation to Curiosity with the addition of two microphones (3:15)
- Cached samples for future Sample Return Mission
- Added a helicopter named Ingenuity
- Some findings
  - Detected organic molecules in 2022: Raman and fluorescence spectroscopy found single-ring aromatics and polycyclic aromatic hydrocarbons
  - Jezero Crater is made of igneous rocks containing olivine and pyroxene which are usually found in thick magma bodies, but these were changed by water since carbonate and sulfate minerals were also found
  - On a typical Martian day at least four dust devils pass Perseverance peaking just after noon

Ingenuity Helicopter

- Design and construction (3:27)
- First flight (1:15) April 19, 2021
- Designed to perform five flights and last 30 days
- Still operating, including as a scout
- As of September 2023, flew 55 times for a total of one hour and 40 minutes over a distance of 8 miles

Summary of Mars Exploration



Interactive image map of the global topography of Mars, overlaid with the position of Martian rovers and landers. Coloring of the base map indicates relative elevations of Martian surface.

Clickable image: *Clicking on the labels will open a new article.*

Legend: Active (white lined, ⋇) • Inactive • Planned (dash lined, ⁂) (view • discuss)

- 7 working orbiters, 3 working landers
- 2 working rovers, 1 working helicopter

Missions in Preparation

- ESA Exo-Mars
  - Part 1 was an orbiter launched in 2016 to study trace gasses and the Schiaparelli lander which crashed
  - Part 2 is a Roscosmos lander designed to deliver the Rosalind Franklin rover, but in the Winter of 2022 the partnership was put on permanent hold due to sanctions against Russia for its invasion of Ukraine
- US EscaPade
  - To demonstrate low-cost planetary exploration ($79 million)
  - Twin craft to investigate the magnetosphere and solar wind
  - Planned for August 2024

Aspirational Mission: Sample Return

- Main idea: Earth based laboratories have much greater capabilities than anything than can be flown to Mars
- Perseverance has cached 22 samples for future return, including an atmospheric sample
- Stored at on-board and at a backup site
- Proposed sample retrieval mission (2026 or 2028)
  - Sample Retrieval Lander + Sample Transfer arm + 2 Ingenuity class helicopters + Mars ascent vehicle
  - Airbus Earth Return Orbiter from Mars orbit to Earth landing
  - Simulation (1:24)
- In June 2023, the cost of development doubled from $4.5 billion to $9 billion
- China, Japan, France and Russia have all floated similar plans

Science Summary: Planet formation

- Our solar system formed about 4.5 billion years ago from gravitational collapse of molecular gasses, about 98% from big bang hydrogen and helium and 2% from earlier stars which created heavier elements at the ends of their lives
- Accretion from the disk-shaped cloud of gas and dust left over from solar formation formed “planetesimals” about 1/20th of Earth size containing iron, nickel, aluminum and silicates in the region near the Sun
- The planetesimals collided and merged to form Mercury, Venus, Earth and Mars, but could not form planets in the asteroid belt region due to the effects of Jupiter’s gravity
- From about 4 to 3.8 billion years ago many asteroids migrated inward producing the Late Heavy Bombardment, producing many craters on the rocky planets

Science Summary: Mars vs. Earth Internal Heat

- Earth’s core is hot because of residual heat of formation and radioactive decay
- The heat spreads from the core to the mantle, and a warm mantle has convection at the top, causing plate tectonics
- Mars has about half of Earth’s diameter, and so has less internal heat
- We were unable to ”take Mars temperature” because InSight’s heat transfer experiment failed.
- Mars had plate tectonics and active volcanoes from about 4 billion years ago until about 3 billion years ago
- Small, intermittent volcanic flows appear to have occurred as recent as a few tens of thousands of years ago, so future flows are possible
- Frequent small to medium sized Marsquakes, mostly coming from Cerberus Fossae, also indicate that magma still flows in Mars mantle
- On Earth plate tectonics recycles the water locked in minerals
- (Venus has the most active volcanoes in the solar system but no plate tectonics and no magnetic field)

Science Summary: Mars vs. Earth Magnetic Field

- On Earth convection of the liquid outer core creates the magnetosphere which protects the Earth from the solar wind
- One theory says that multiple large asteroid strikes on Mars warmed the mantle, disrupting the convection of the core, and destroying the magnetosphere about 4 billion years ago
- In the absence of a magnetosphere, the solar wind from removes gases from the atmosphere, especially water vapor
- The loss of water vapor by the solar wind resulted in higher levels of heavy hydrogen (deuterium) on Mars compared to Earth
- It is thought that Mars is dry because of a combination of loss of water from the atmosphere and lack of tectonic recycling of water
- It appears that residual magnetism in rocks created during Mars' prior period of a magnetic field cause ultraviolet auroras

Science Summary: Geologic Periods on Mars

- Pre-Noachian (4.5 to 4.1 billion years ago)
  - Formation of the “Martian dichotomy” (northern hemisphere is about 2 km lower than southern, and its crust is thinner) by impacts or plate tectonics
  - Formation of Hellas basin, but most other effects lost to erosion and impacts
- Noachian (4.1 to 3.7 billion years ago)
  - Many impact craters
  - Ocean(s), rivers, and erosion by water
- Hesperian (3.7 to 3.1 billion years ago)
  - Olympus Mons volcano
  - Formation of extensive lava plains (and lava tubes and caves)
  - Ephemeral lakes or seas in the northern lowlands
- Amazonian (~3.1 billion years ago to present)
  - Fewer impacts
  - Lava flows, periods of glacial activity, small liquid water flows

Science Summary: Water and methane

- Both ice caps are largely water ice, enough to cover the planet 36 feet deep
- During winter, about 25% of the atmospheric CO_2 freezes as a cover over the water ice, then sublimes back to gas in the summer
- The caps have spiral troughs due to Coriolis effect winds
- Subsurface water ice is also present at high latitudes beyond the caps
- Liquid water did flow in past and create landforms present today including dendritic networks, gullies, deltas, and alluvial fans
- Sedimental and mineralogic evidence for past crater lakes is strong
- Methane detection has been quite variable, but clearly methane is being formed now on Mars, because it decomposes to CO_2, H_2 and H_2O in a few hundred years due to UV radiation
- It is unclear if methane production is geochemical or biological

Science Summary: Dust storms

- Dust devils form often as sunlight heats rocks causing air close to the surface to rise into a column which is spun by horizontal winds
- Dust storms can carry dust over large areas at up to 60 mph, especially in the summer
- About every 3 Martian years these form into global dust storms
- Due to the low atmospheric pressure this does not blow over equipment, people, etc., though it does significantly reduce the amount of sunlight
- The dust is sticky and electrostatic so it can coat machinery and solar panels
- Sometimes the wind blows dust off of equipment and solar panels

Science Summary: Radiation

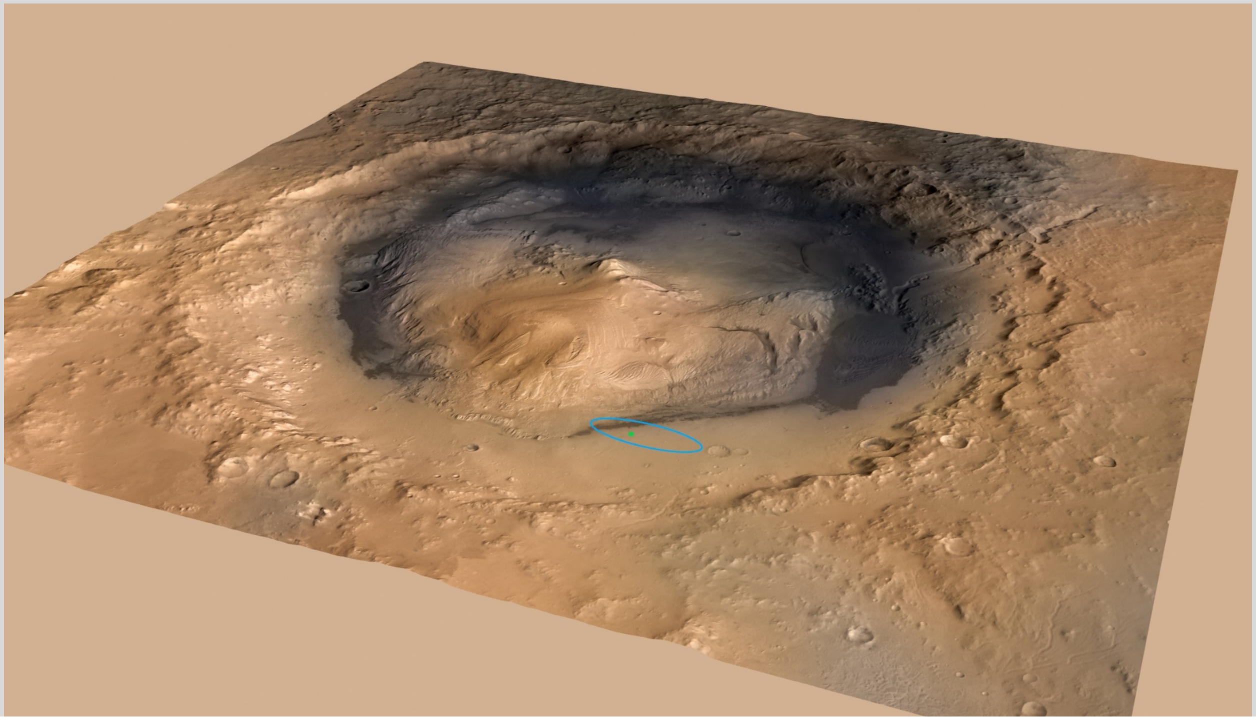
- The sievert is the unit of biological effect of ionizing radiation on tissue, often measured in thousandths (mSv)
- The average yearly radiation dose for people is

  2.0 mSv by inhalation (radon)
  + 0.3 mSv by cosmic rays
  + 0.3 mSv by ingestion (food and water; 4 Brazil nuts per day)
  + 0.2 mSv from radioactivity in rocks around us
  2.8 mSv total

- One chest x-ray is 0.1 mSv, one CT is 1.0 to 15.0 mSv
- NASA allows a lifetime exposure of 1000 mSv (~4 times normal)
- Low Earth orbit is 0.5 mSv per day (183 mSv per year)
- Interplanetary space between Earth and Mars is 1.84 mSv per day or 750 mSv for a 14-month round trip
- Average Mars surface radiation is 0.64 mSv/day or 83 times Earth radiation (one-way trip + 3 years = 1000 mSv)
- Radiation is estimated to be one tenth as much in a lava tube
- Radiation levels double after a solar storm (coronal mass ejection)

Science Example: Gale Crater

- Site of Curiosity rover
- Asteroid or comet impact 3.5 to 3.8 bya
- Lowest layer is interstratified clay and sulfates
- Conglomerates, cross-bedded sandstones, mudstones and a sandstone delta indicate an early period as a lake
- Central mountain appears to be 2 billion years of lake sediment



Humans to Mars: Plans

- NASA plans are vague and target the 2030's using the Orion Multi-Purpose Crew Vehicle
- NASA psychology tests started in 2009, current one is Mars Dune Alpha
- The first launch of Elon Musk's Mars-capable Space-X Starship ended in "unscheduled disassembly", and the second launch is scheduled for September or October of 2023
- Elon Musk plans for Mars: Elon Musk 2022 video (6:50)
- Terraforming Mars
  - Methods include adding greenhouse gasses, oxygen factories, and spreading dark absorbent dust from Phobos
  - Additionally, some method to restart the magnetosphere would be need to prevent atmospheric losses
  - Might only take 100,000 years

Humans to Mars: Concerns

- Cumulative radiation exposure would be huge; effects include cancer and damage to the nervous system including altered cognition and behavior
- Can humans live peaceably under crowded, uncomfortable conditions?
- What will the Mars economy look like?
- Will separate colonies compete or cooperate?
- There will be no real-time communication with loved ones on Earth
- The effects of long-term Mars gravity are unknown
- Will opportunities to go to and work on Mars be equitable?
- Will Earth continue to support Mars colonists indefinitely?
- How long will it take to develop critical support technologies?
- Do you want to live without being able to go outside, travel, etc.?
- Does this divert attention and money from maintaining a healthy Earth?
- What other concerns do you have?

Course Summary

- Mars is difficult to get to and operate on, but incremental advances have resulted in moderately high success rates
- Mars has a huge variety of landforms to explore
- Several specific areas have been well explored, and subject to a wide variety of scientific testing
- Astronauts on Mars seems reasonable in the next few decades
- Elon Musk would like to have cities on Mars in that same time frame, but that seems unlikely

Curiosity Development

- April 2004: Announcement of Opportunity for scientists and engineers from around the world to propose instruments
  - Goals: quantitatively assess the habitability and environmental history of the landing site, characterize the geology, investigate planetary processes that influence habitability, and characterize surface radiation
  - Components: cruise stage, aeroshell, descent stage with a sky crane, rover lasting at least one Martian year carrying a 128 pound science package split between an arm, a mast, and the rover body
  - Excluding pre-specified Spanish meteorology package and Russian neutron spectrometer
  - Robotic arm does sample acquisition, processing and handling (SA/SPaH)
  - Radiothermal generator provides heat and electricity
  - 10 instruments chosen out of 48 proposed
- Goal to reduce landing ellipse from MER's 90 x 12 miles to 4 x 2 miles (final design: 12 x 4 miles) achieved with steerable aeroshell
- Eventual workforce of 800 people
- Changed from rock corer to percussive ”drill” to powder rocks
- Changed from dry lubricant to old wet lubricant (requiring heat)
- Changed from Super Light Ablator (corkwood, epoxy and gas filled silica glass spheres) to tiled Phenolic Impregnated Carbon Ablator

Curiosity Instrumentation

Explanations by Emily Lackdawalla, planetary geologist and space science journalist

[Exploring Curiosity Part 1 (3:12)]

[Exploring Curiosity Part 2 (5:18)]

Curiosity Subsequent Findings

- Intermittently found up to 7 ppb of methane indicating a current source
- SAM detected organic chemicals in drilled rocks, but specifics are complicated by the destructive effects of perchlorates
- Examination of the Martian atmosphere confirmed that some meteorites that have dropped to Earth really are from the Red Planet
- Rippled rocks represent waves in an ancient shoreline
- Ahead is a debris field which will allow sampling of rocks from areas too high to climb

US MAVEN

- Mars Atmosphere and Volatile Evolution
- $582 million
- Launched November 2013, orbited September 2014
- Two-year mission (then extended) to measure the rate with which the atmosphere is currently escaping to space
- Showed how water in the atmosphere is split to H_2 and O by solar radiation, H_2 rises and is stripped away by the solar wind
- Showed a 10-fold variation in H_2 loss depending on distance from the sun
- Detected a doubling of radiation during a solar storm

US InSight Lander

- Interior exploration using Seismic Investigations, Geodesy and Heat Transport
- $830 million mission to place a seismometer and measure heat transfer with a deep probe
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- Took three months to deploy and commission the instruments
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