# Exploration of Our Solar System and Beyond…

Sarath Gunapala

NASA - Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
USA

March 24, 2016

Jet Propulsion Laboratory
California Institute of Technology

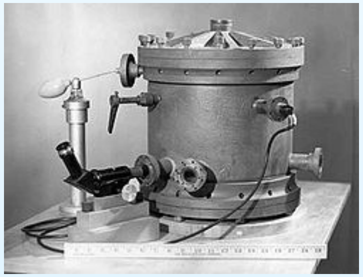
# Outline

- Introduction to the NASA Jet Propulsion Laboratory (JPL)
- Types of spacecrafts
- Voyager
- Phoenix
- Voyager
- Phoenix
- Cassini
- Curiosity
- Planet hunting

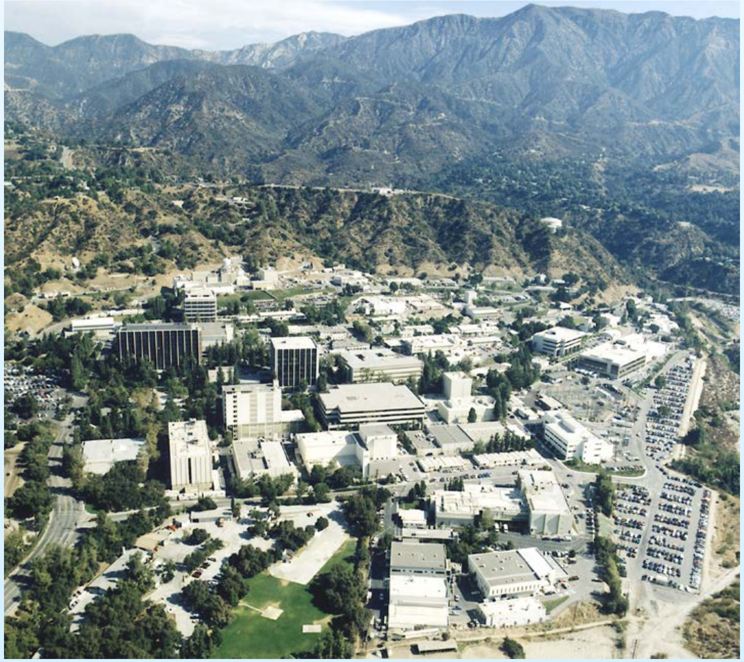
# JPL is an Operating Division of Caltech

- JPL is a child of Caltech:  founded in 1936 as a graduate student project under Professor Theodore von Kármán.
- JPL led the development of US rocket technology in WWII.
- Developed the first U.S. satellite, Explorer I.
- JPL was transferred to NASA upon its creation in 1958.
- JPL spacecraft have explored all the planets of the solar system except Pluto.

- Caltech was founded in 1891 as Throop University
  - The name was changed to Throop Polytechnic Institute (1893-1912) and then to Throop College of Technology (1913-1919)
  - Caltech became the California Institute of Technology on February 10, 1920.
- About JPL:
  - A Federally-Funded Research and Development Center (FFRDC) under NASA sponsorship; A NASA Center
  - A division of Caltech, staffed with ~ 5,000 employees



Millikan's Oil Drop Apparatus



# Mt. Wilson Observatory

**June 13, 1904:** George Ellery Hale **signs 99-year lease with Mount Wilson Toll Road Company.**

**1906: Hale orders glass for 100-inch mirror from Saint-Gobain glass works in France.**

**1907: Toll "road" widened to accommodate motorized vehicles.**

**May 28, 1907: First motor car to reach summit (1907 Franklin).**

**March 17, 1910: Andrew Carnegie visits Mount Wilson.**

**July 1, 1917: 100-inch mirror arrives at Mount Wilson.**

**November 2, 1917: "First light" for the** 100-inch telescope**. Read an article about building the** 100-inch telescope**.**

**October 5, 1923:** Edwin Hubble **finds Cepheid variable star in Andromeda Galaxy (M31).**

**January 1, 1925: Historic paper by** Edwin Hubble **shows distance to M31, proving that our Milky Way is only one of many galaxies.**

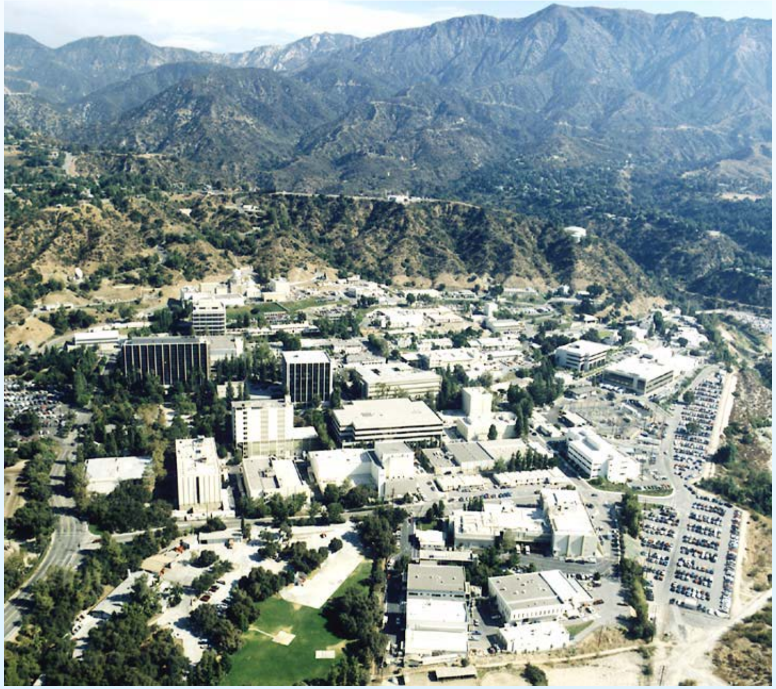
**1925-1929: Albert Michelson measures velocity of light by projecting a light beam from Mount Wilson to Lookout Mountain and timing its return.**

**March 15, 1929:** Edwin Hubble **correlates distance to galaxies with their recessional velocity, confirming the expansion of the Universe.**

**January 29, 1931: Albert Einstein visits Mount Wilson.**

# A little about JPL ……


1940

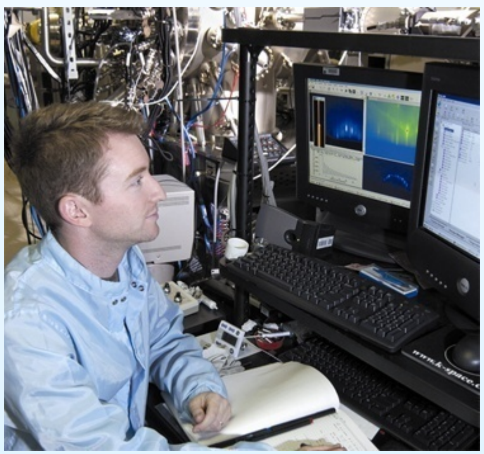


JPL Today

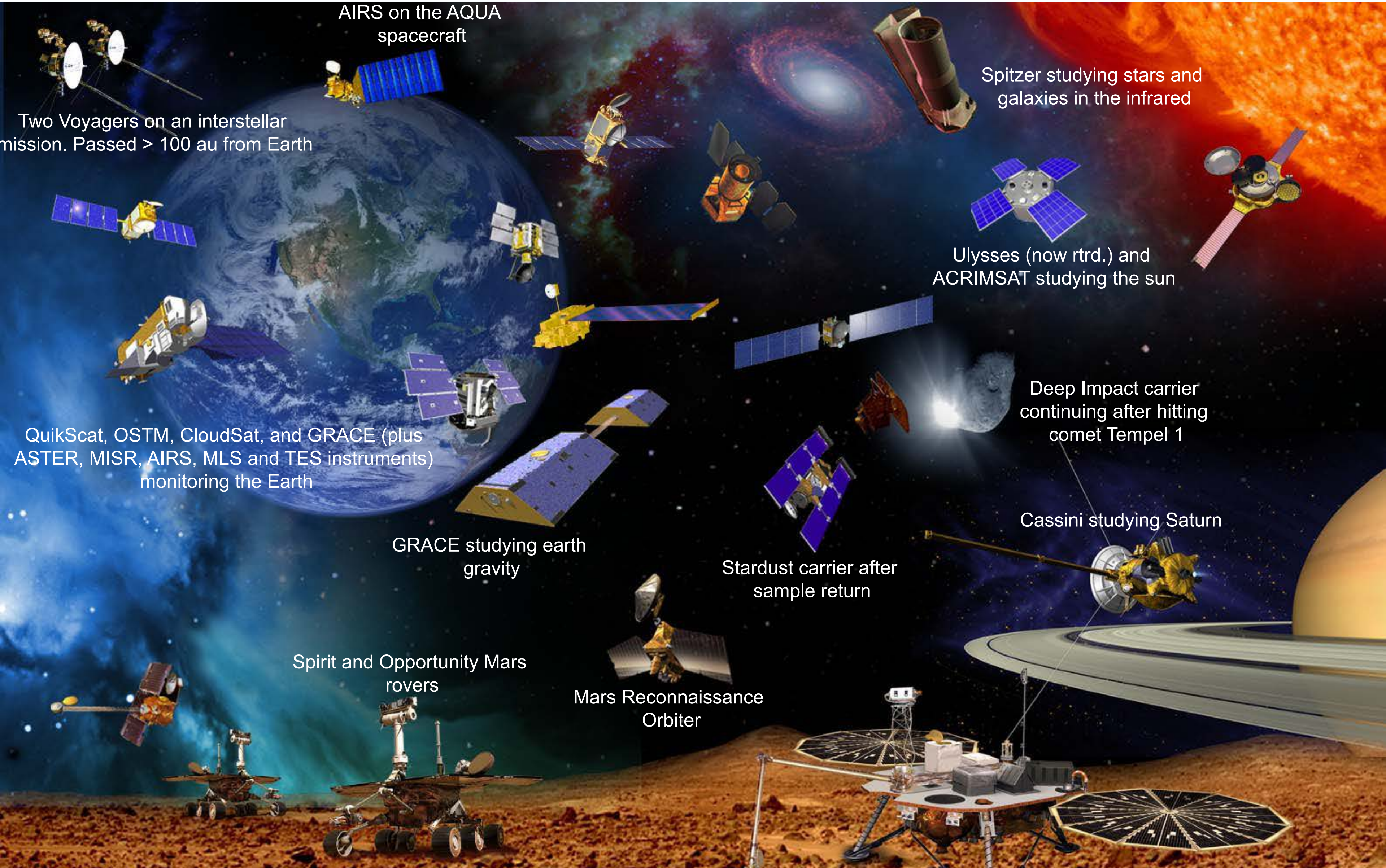

1950

# Microdevices Laboratory….

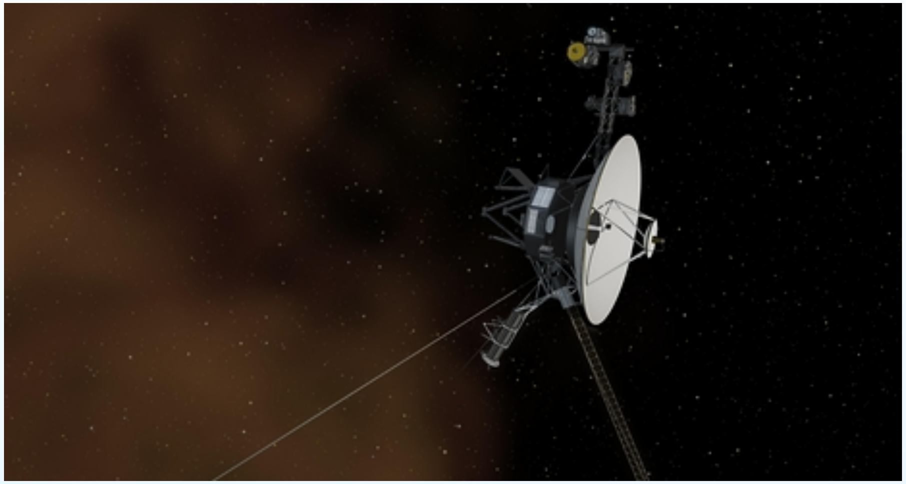
- Facility built in 1989 to provide end-to-end capabilities for advanced electronic materials, device fabrication and characterization. Architects have recently (2008) estimated that it would take over $ 50M to replicate the facility if done today.
- Class 10–1,000 cleanrooms with e-beam & optical lithography, materials growth & deposition, wet & dry etching, thermal processing, optical/structural/electronic characterization capabilities for III-V fabrication.
- Nom. $ 50M of equipment investments are housed within MDL. The III-V IR FPA thrust has access to over 84 major pieces of Central Processing Equipment (+ 16 wet benches).
- Chartered to support innovative NASA and DoD space missions.



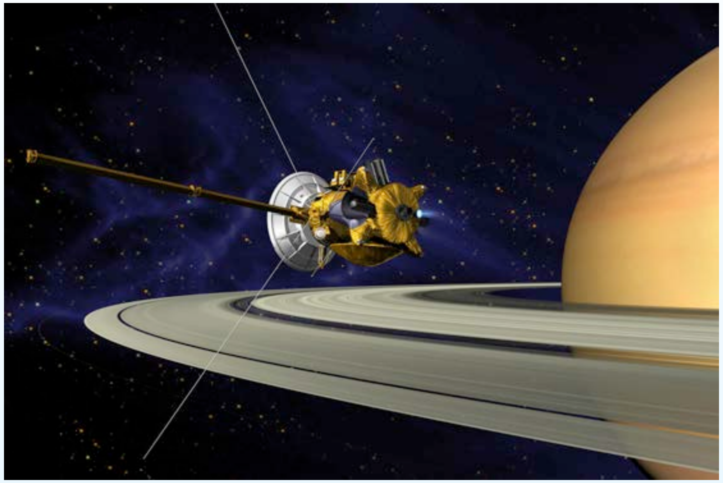

# 31 robotic spacecraft and 8 instruments across the solar system and beyond…….



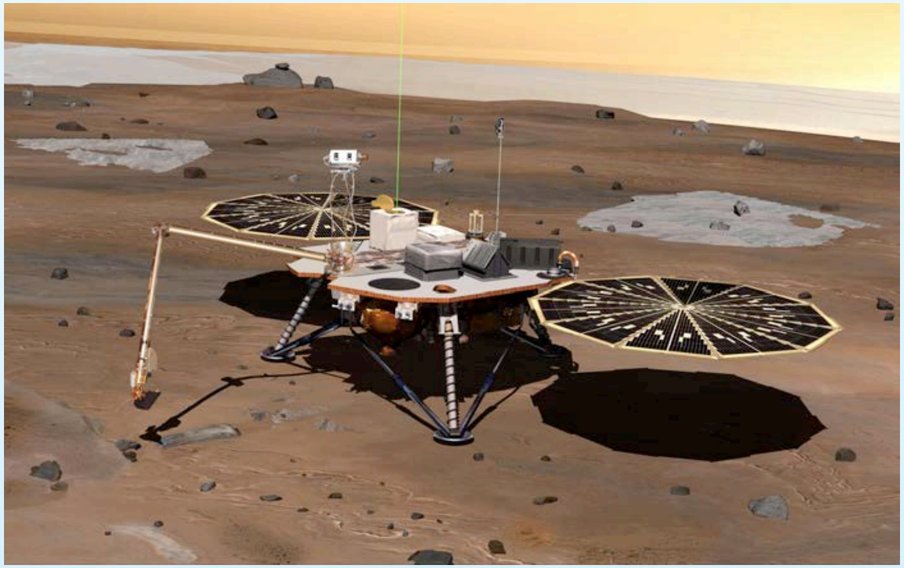
# Types of Planetary Spacecrafts



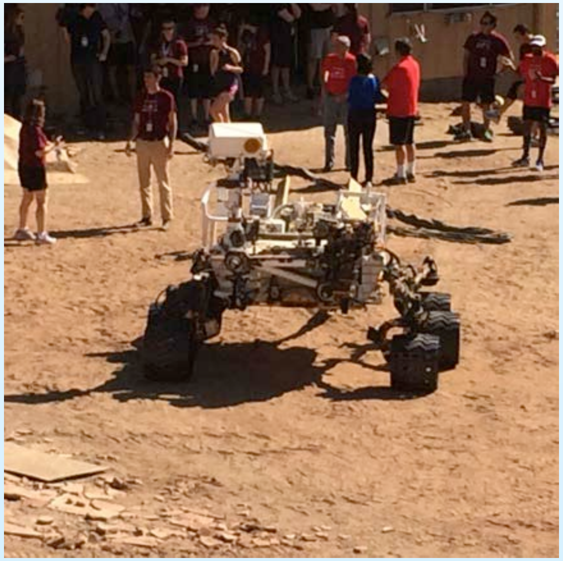
Flybys



Orbiters



Landers



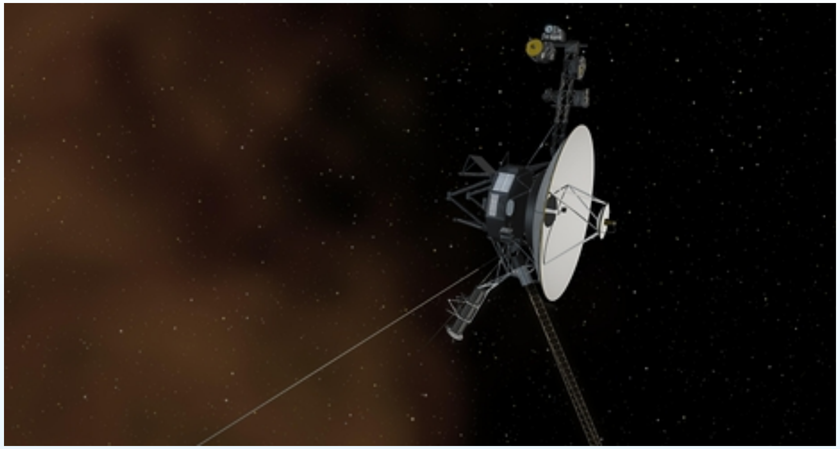
Rovers

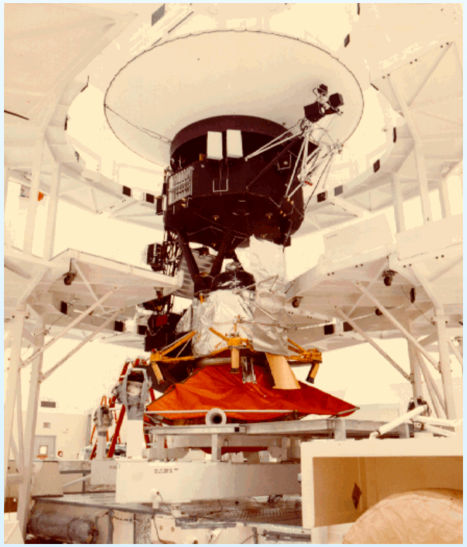
# Voyager Flyby Mission

Jet Propulsion Laboratory
California Institute of Technology

# Voyager Interstellar Mission

The twin Voyager 1 and 2 spacecraft are exploring where nothing from Earth has flown before. In August 2012, Voyager 1 made the historic entry into interstellar space. In 2012 Voyager 2 was in the “heliosheath" -- the outermost layer of the heliosphere where the solar wind is slowed by the pressure of interstellar. They are three-axis gyro stabilized spacecrafts to maintain pointing of the high-gain antennas toward Earth.





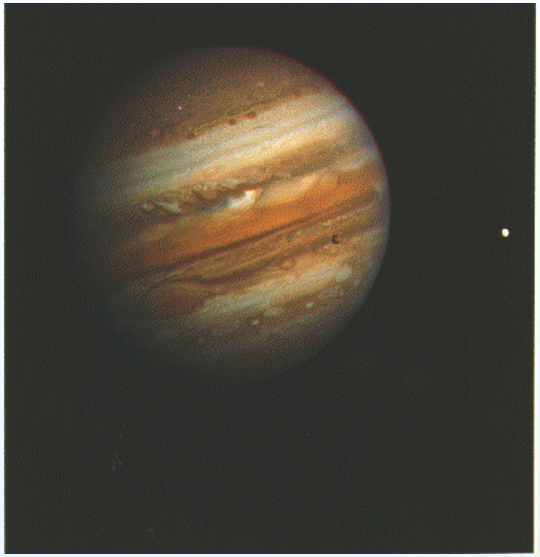
Voyager spacecraft being assembled in JPL high-bay

- Magnetometer
- Low-energy Charge Particle Detector
- Imaging system, slow scan vidicon, f/3, 8 filters
- Plasma instrument to measure particles in plasma
- UV spectrometer
- Infrared spectrometer
- Photopolarimeter
- Planetary Radio Astronomy instrument
- Plasma Wave Subsystem

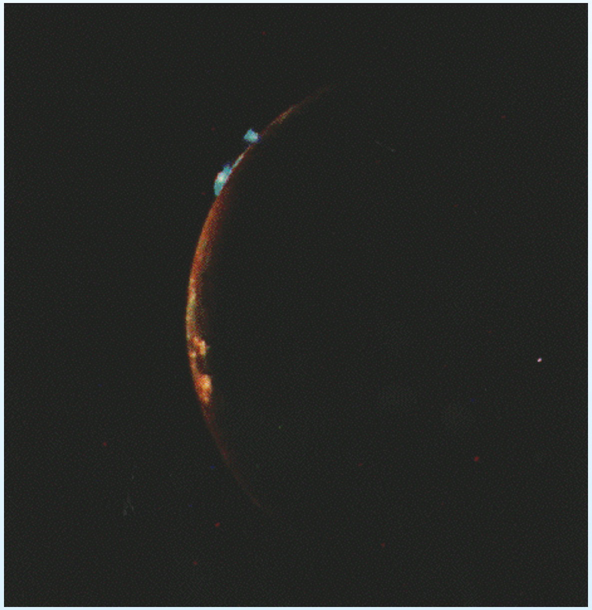
The mission objective of the Voyager Interstellar Mission is to extend the NASA exploration of the solar system beyond the neighborhood of the outer planets to the outer limits of the Sun's sphere of influence, and possibly beyond.

# Voyager's Encounter with Jupiter

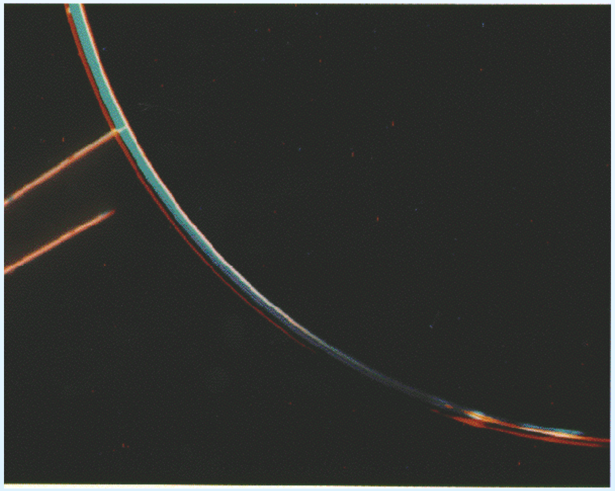
- Voyager 1's closest approach to Jupiter occurred March 5, 1979
- Voyager 2's closest approach was July 9, 1979
- Voyager 1 took 19,000 pictures and completed many scientific measurements
- Voyager 2 took 33,000 pictures
- Discovery of active volcanism on the satellite Io was probably the greatest surprise



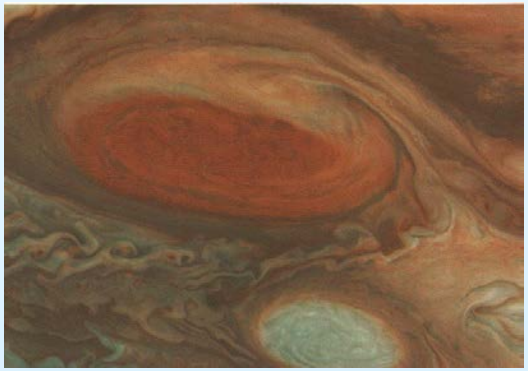
Jupiter



Io's volcanoes



Jupiter's rings



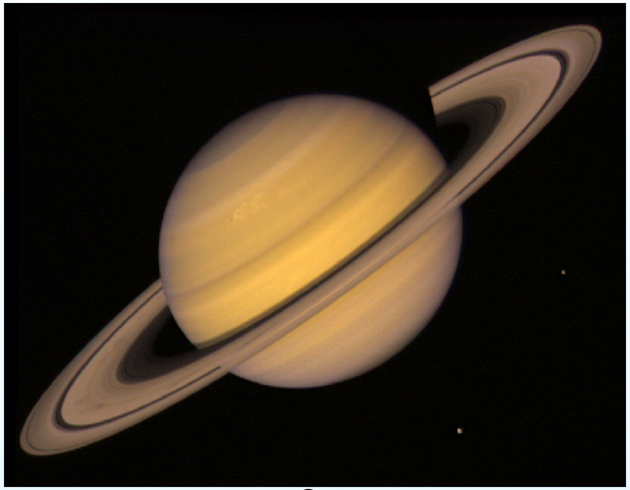
Jupiter's rings

It was the first time active volcanoes had been seen on another body in the solar system

Jet Propulsion Laboratory
California Institute of Technology

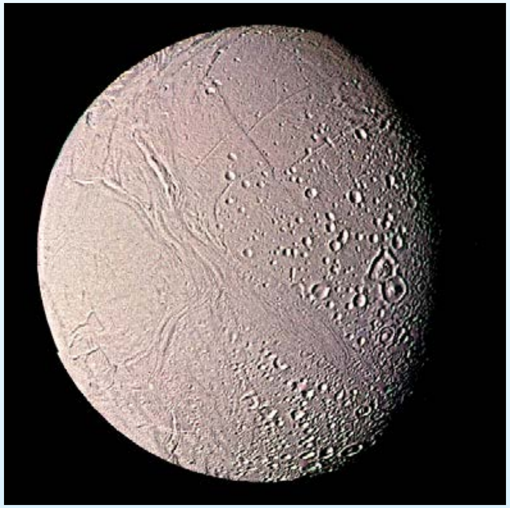
# Voyager's Encounter with Saturn

- The Voyager 1 and 2 Saturn encounters occurred nine months apart, in November 1980 and August 1981.
- Saturn's atmosphere is almost entirely hydrogen and helium
- Saturn is the only planet less dense than water
- The chemistry in Titan's atmosphere may be similar to what occurred in Earth's atmosphere several billion years ago.

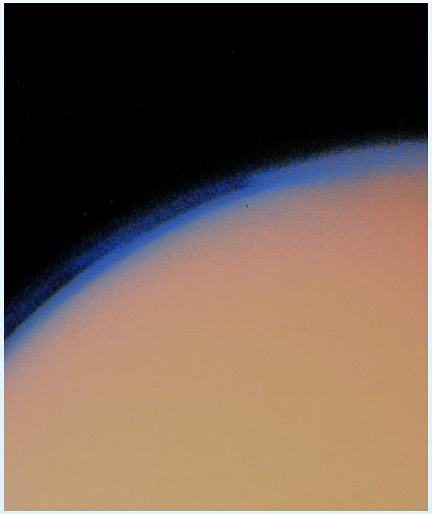


Saturn

Io's volcanoes



Enceladus



Hydrocarbon cloud in Titan's atmosphere

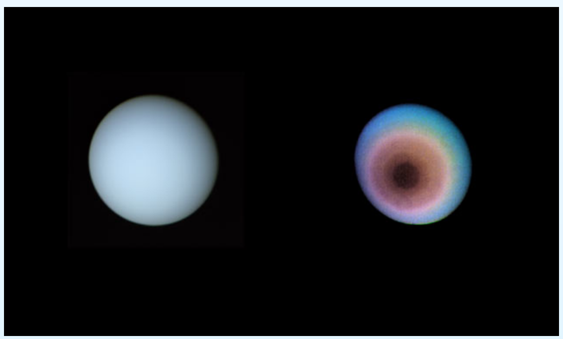
It was the first time active hydrocarbon cloud had been seen on another body in the solar system

Jet Propulsion Laboratory
California Institute of Technology

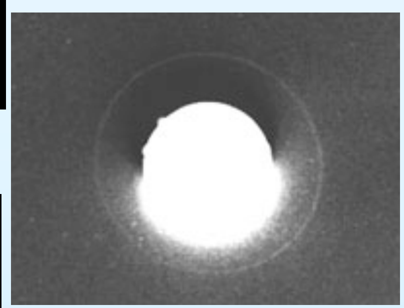
# Voyager's Encounter with Uranus and Neptune

- Voyager 2 spacecraft flew closely past distant Uranus in January 1986
- Closest approach was 50,600 miles of Uranus's cloudtops
- Voyager 2's images of the five largest moons around Uranus revealed complex surfaces indicative of varying geologic pasts.
- The cameras also detected 10 previously unseen moons.

- In the summer of 1989, NASA's Voyager 2 became the first spacecraft to observe the planet Neptune
- Closest approach was 3,000 miles above Neptune's north pole
- Five hours later, Voyager 2 passed about 25,000 miles from Neptune's largest moon, Triton, the last solid body the spacecraft has studied.

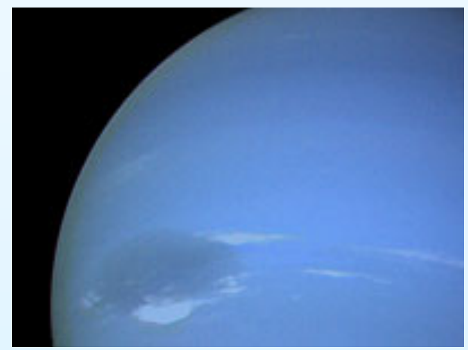


Uranus

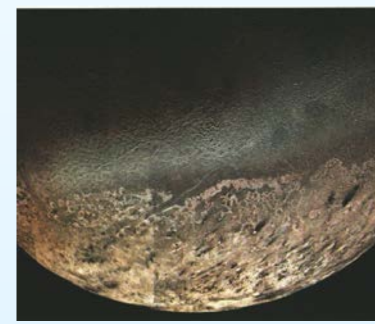


Uranus' outer ring

Uranus' Largest moon Titania

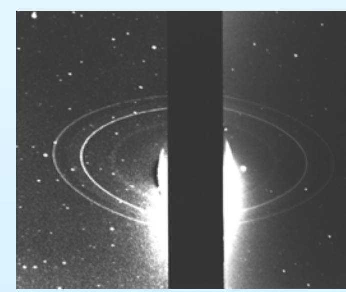


Neptune



Neptune's moon triton

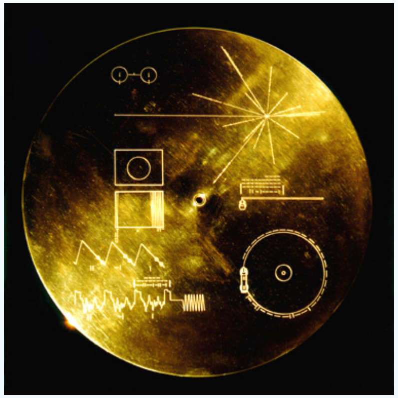
Neptune's Dark spot



Neptune's rings

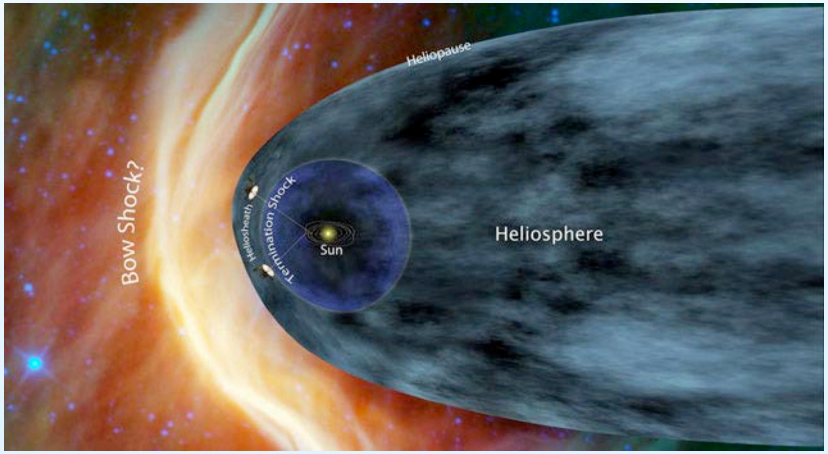
# Voyager’s tour beyond our solar system

- Voyager 1's closest approach to Jupiter occurred March 5, 1979
- Voyager 2's closest approach was July 9, 1979
- Voyager 1 took 19,000 pictures and completed many scientific measurements
- Voyager 2 took 33,000 pictures
- Discovery of active volcanism on the satellite Io was probably the greatest surprise

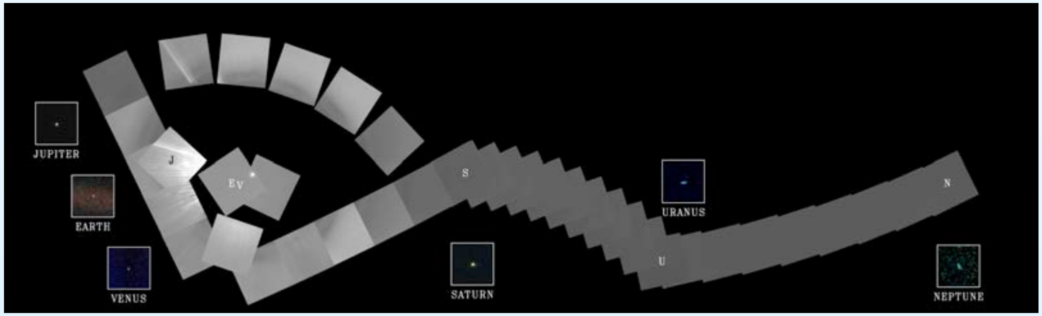


Golden record

- Greeting from 55world languages including “Ayubovan”
- 115 pictures
- Variety of natural sounds
- Printed messages from President Carter and U.N. Secretary General Waldheim
- 90 minutes of western and eastern classical music




Heliosphere and the interstellar medium




Portrait of our solar system taken from more than 4 billions miles from Earth

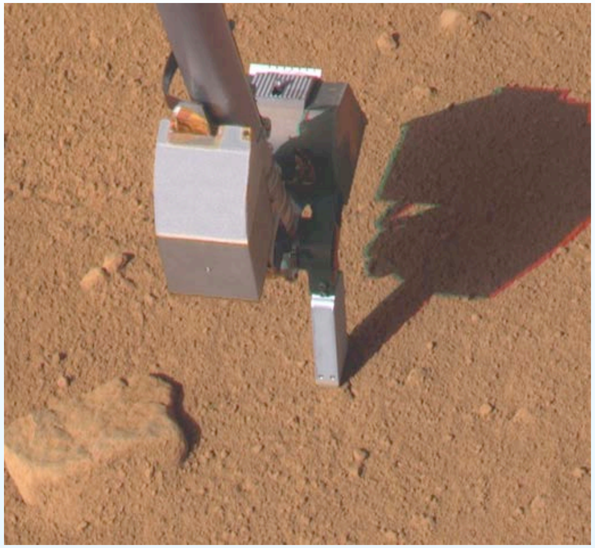
It will be forty thousand years before they make a close approach to any other planetary system. As Carl Sagan has noted, "The spacecraft will be encountered and the record played only if there are advanced spacefaring civilizations in interstellar space. But the launching of this bottle into the cosmic ocean says something very hopeful about life on this planet."

# Phoenix Lander Mission

# Phoenix Lander Mission

Jet Propulsion Laboratory
California Institute of Technology

Mars is a cold desert planet with no liquid water on its surface. But in the Martian arctic, water ice lurks just below ground level. Discoveries made by the Mars Odyssey Orbiter in 2002 show large amounts of subsurface water ice in the northern arctic plain. The Phoenix lander targets this circumpolar region using a robotic arm to dig through the protective top soil layer to the water ice below and ultimately, to bring both soil and water ice to the lander platform for sophisticated scientific analysis.



Lander's robotic arm is inserting its electrical and thermal conductivity experiment probe as seen by its camera

Self portrait of Phoenix lander on Mars

**Objective 1:** Study the history of water in all its phases

**Objective 2:** Search for evidence of habitable zone and assess the biological potential of the ice-soil boundary

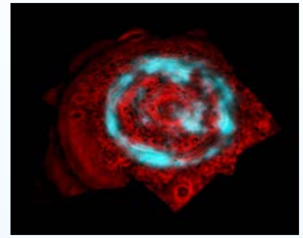
Experiments prompted by a 2008 surprise from NASA's Phoenix Mars Lander suggest that soil examined by NASA's Viking Mars landers in 1976 may have contained carbon-based chemical building blocks of life.

# Cassini Orbiter Mission

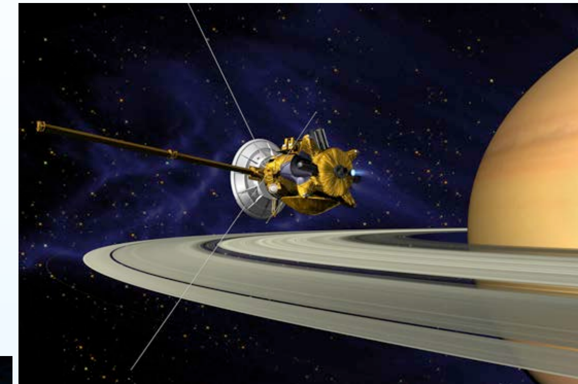
Jet Propulsion Laboratory
California Institute of Technology

# Cassini Orbiter Mission

On October 15, 1997, the Cassini spacecraft rocketed into space, beginning a seven-year journey to Saturn. On board was the Huygens probe and an array of powerful instruments. On July 1, 2004, Cassini began orbiting the ringed planet
The Huygens probe separated from Cassini in December 2004 and coasted a million miles to Saturn's largest moon, Titan. In January 2005 it descended through Titan's smoggy atmosphere, and landed on the moon's surface.



Saturn's north pole Aurora

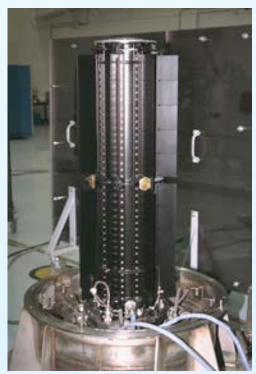


Saturn's sourth pole Aurora

Saturn's electrical storm

Cassini spacecraft being assembled in JPL high-bay

Plutonium dioxide pellet inside RTG



Radioisotop thermoelectric generator

- Composite IR spectrometer
- Imaging science subsystem
- Ultraviolet imaging spectrograph
- Visible and IR mapping spectrometer
- Cassini plasma spectrometer
- Cosmic dust analyzer
- Ion and neutral mass spectrometer
- Magnetometer
- Magnetospheric imaging instrument
- Radio and plasma wave science
- Radar
- Radio science subsystem

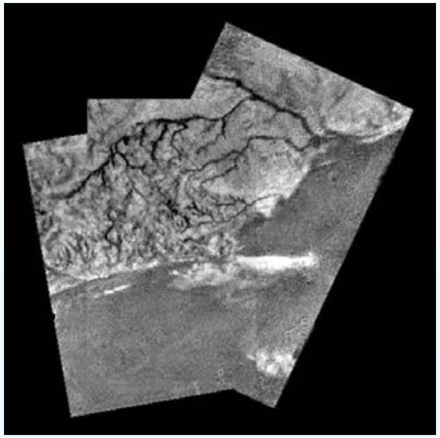
Because of Saturn's distance from the Sun, solar arrays were not feasible as power sources for this space probe. The Cassini orbiter is powered by three radioisotope thermoelectric generators (RTGs), which use heat from the natural decay of about 33 kg (73 lb) of plutonium dioxide to generate direct current electricity via thermoelectrics.

# Titan

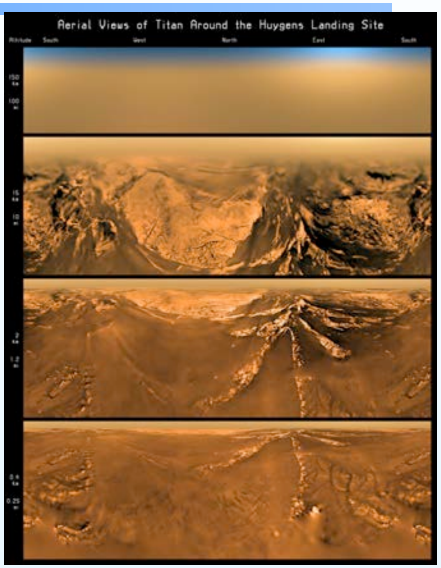
Jet Propulsion Laboratory
California Institute of Technology

In many respects, Saturn's largest moon, Titan, is one of the most Earth-like worlds we have found to date. With its thick atmosphere and organic-rich chemistry, Titan resembles a frozen version of Earth, before life began pumping oxygen into our atmosphere.

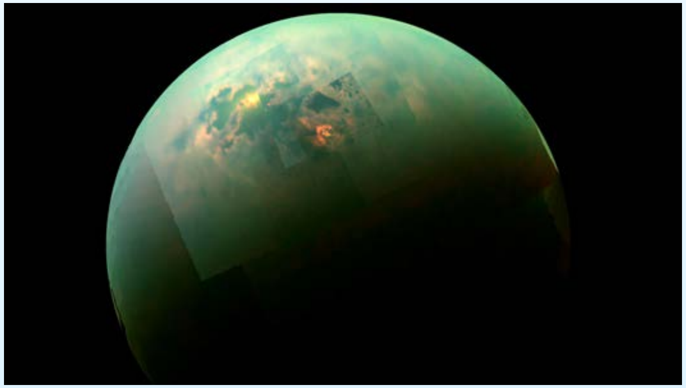
Titan is of great interest to scientists because it has a substantial, active atmosphere and complex, Earth-like processes that shape its surface. The moon is enveloped by an orange haze of naturally produced photochemical smog.



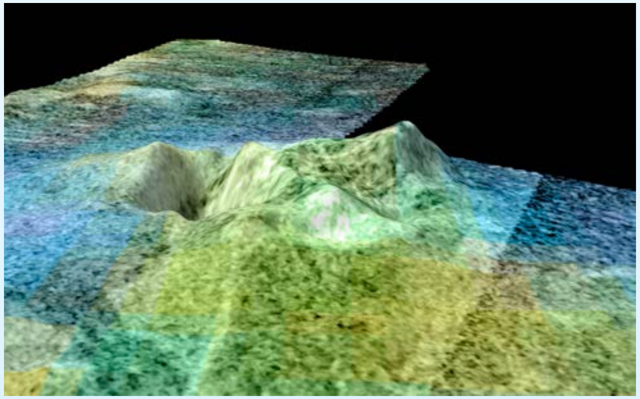
Titan's rivers



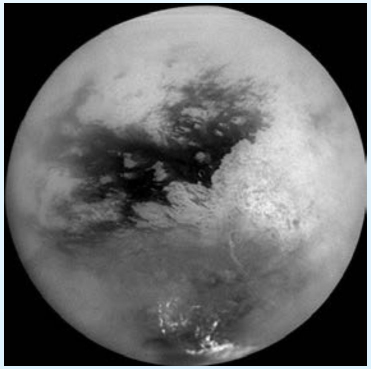

Ariel view of Titan's surface



Sun reflecting from the Titan's ocean



Titans ice volcanoe



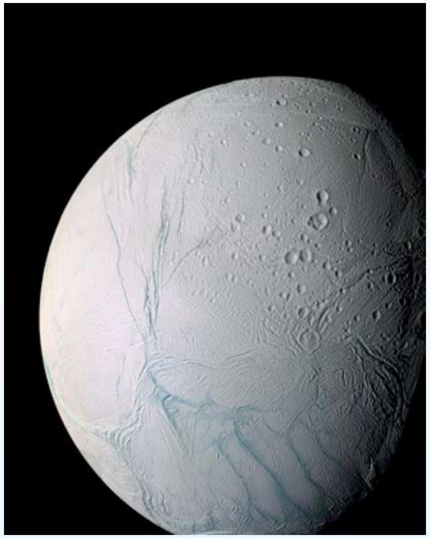
Titan's clouds

Cassini has revealed that Titan's surface is shaped by rivers and lakes of liquid ethane and methane (the main component of natural gas), which forms clouds and occasionally rains from the sky as water does on Earth. Winds shape vast regions of dark, hydrocarbon-rich dunes that girdle the moon's equator and low latitudes. Volcanism may occur as well, but with liquid water as the lava.

# Enceladus

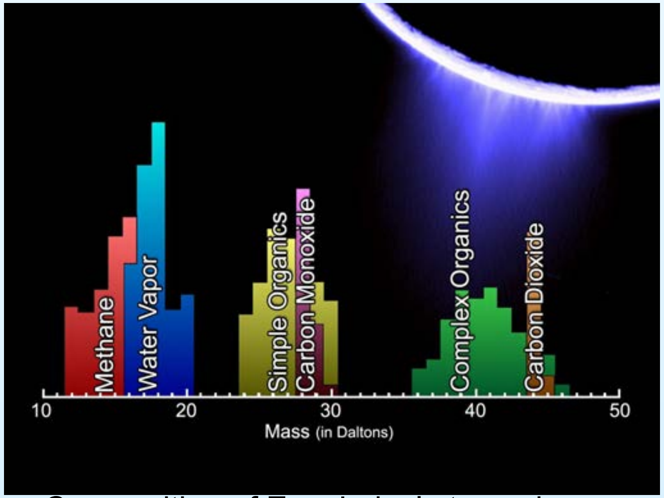
Enceladus is one of the brightest objects in our solar system. Covered in water ice that reflects sunlight like freshly fallen snow, Enceladus reflects almost 100 percent of the sunlight that strikes it. Because Enceladus reflects so much sunlight, the surface temperature is extremely cold, about -201° C (-330° F).

Enceladus has 5 different types of terrain. It has craters no larger than 22 miles in diameter. Other areas show regions with no craters indicating major resurfacing events in the geologically recent past.



Enceladus

Ice and water jets of Enceladus




Composition of Enceladus' atmosphere

Cassini's magnetometer has found an atmosphere on Enceladus. This is the first time an atmosphere has been detected on a moon of Saturn other than Titan.

Unlike Titan, which is 3,200 miles across, Enceladus' diameter is approximately 310 miles. This means the amount of gravity present on the moon is not enough to hold an atmosphere for very long. Moons and planets need a lot of gravity to support an atmosphere. Therefore, a strong source must be present on the moon to "feed" Enceladus's atmosphere.

Scientists currently hypothesize that volcanic eruptions or geysers might provide the necessary material.

# CURIOSITY


# Results from the Mars Science Laboratory

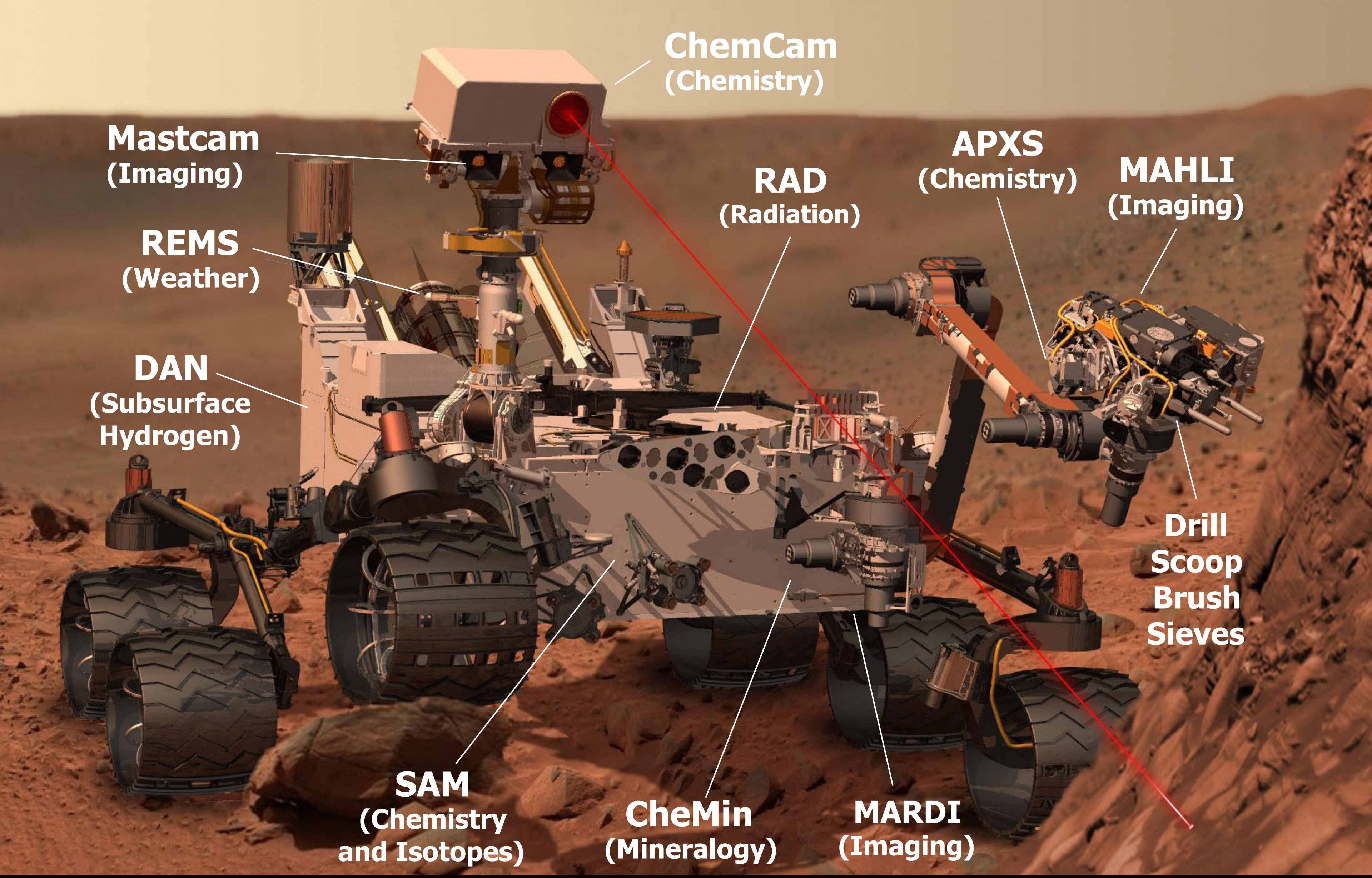
MSL Science Team

# Curiosity's primary scientific goal is to explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present

- Biological potential
- Geology and geochemistry
- Water, weather, and climate
- Radiation levels and hazards

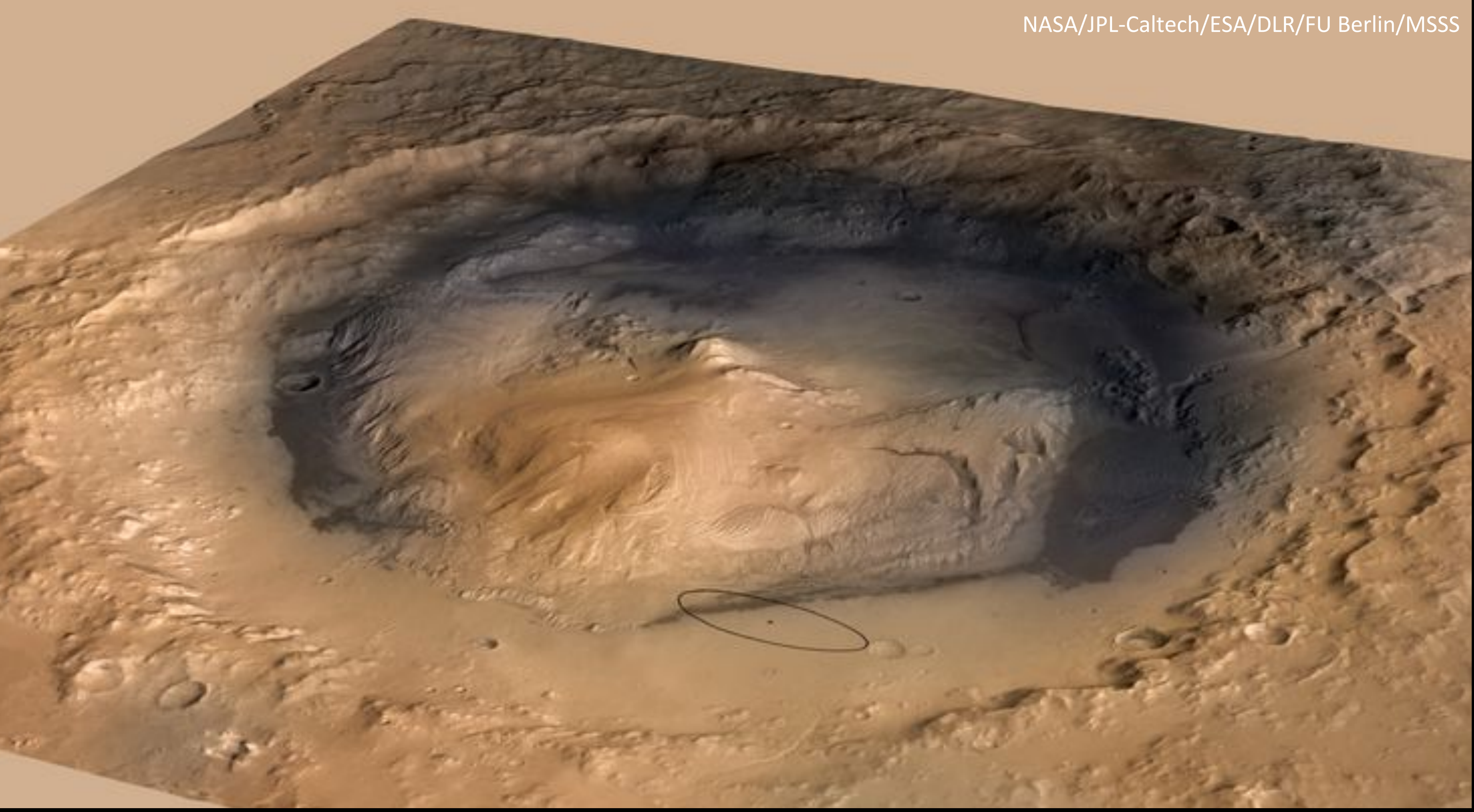


NASA/JPL-Caltech



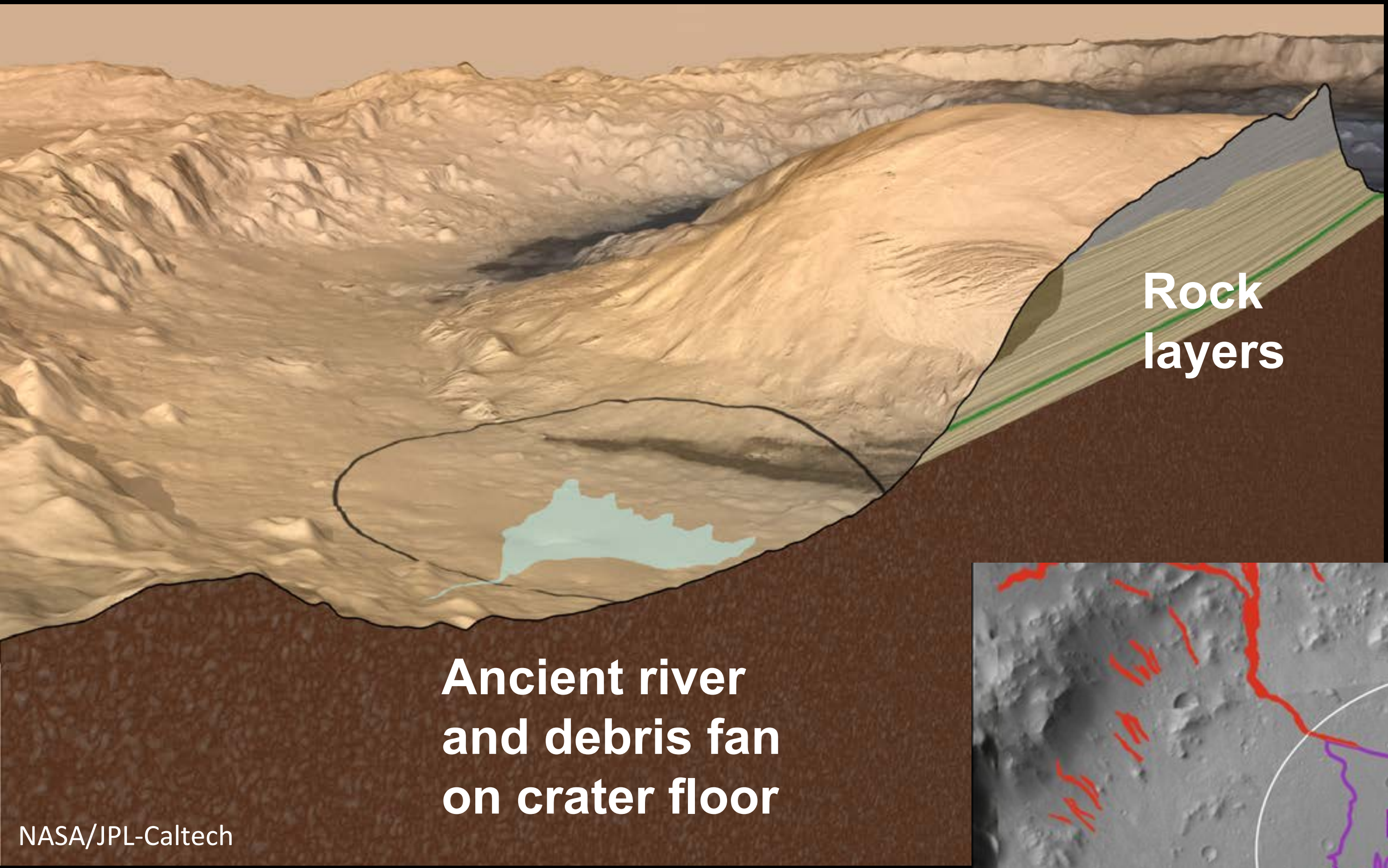

CURIOSITY

# Curiosity's Science Payload

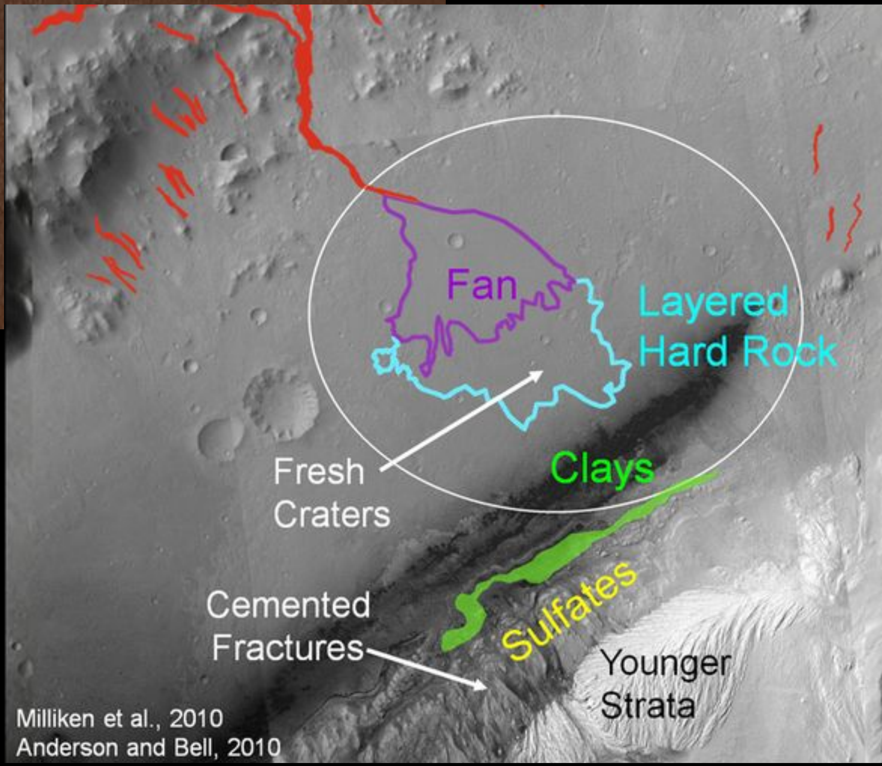



**150-km Gale Crater contains a 5-km high mound of stratified rock. Strata in the lower section of the mound vary in mineralogy and texture, suggesting that they may have recorded environmental changes over time.**

CURIOSITY



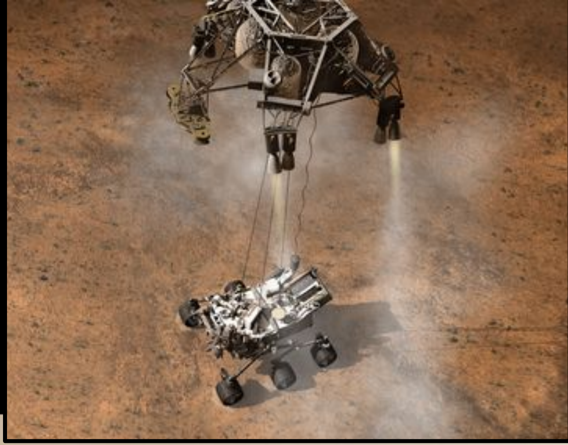

# Water-Related Geology and Minerals around Mount Sharp




# Heat shield separation captured by Curiosity's Mars Descent Imager


# Kicking up dust just prior to landing

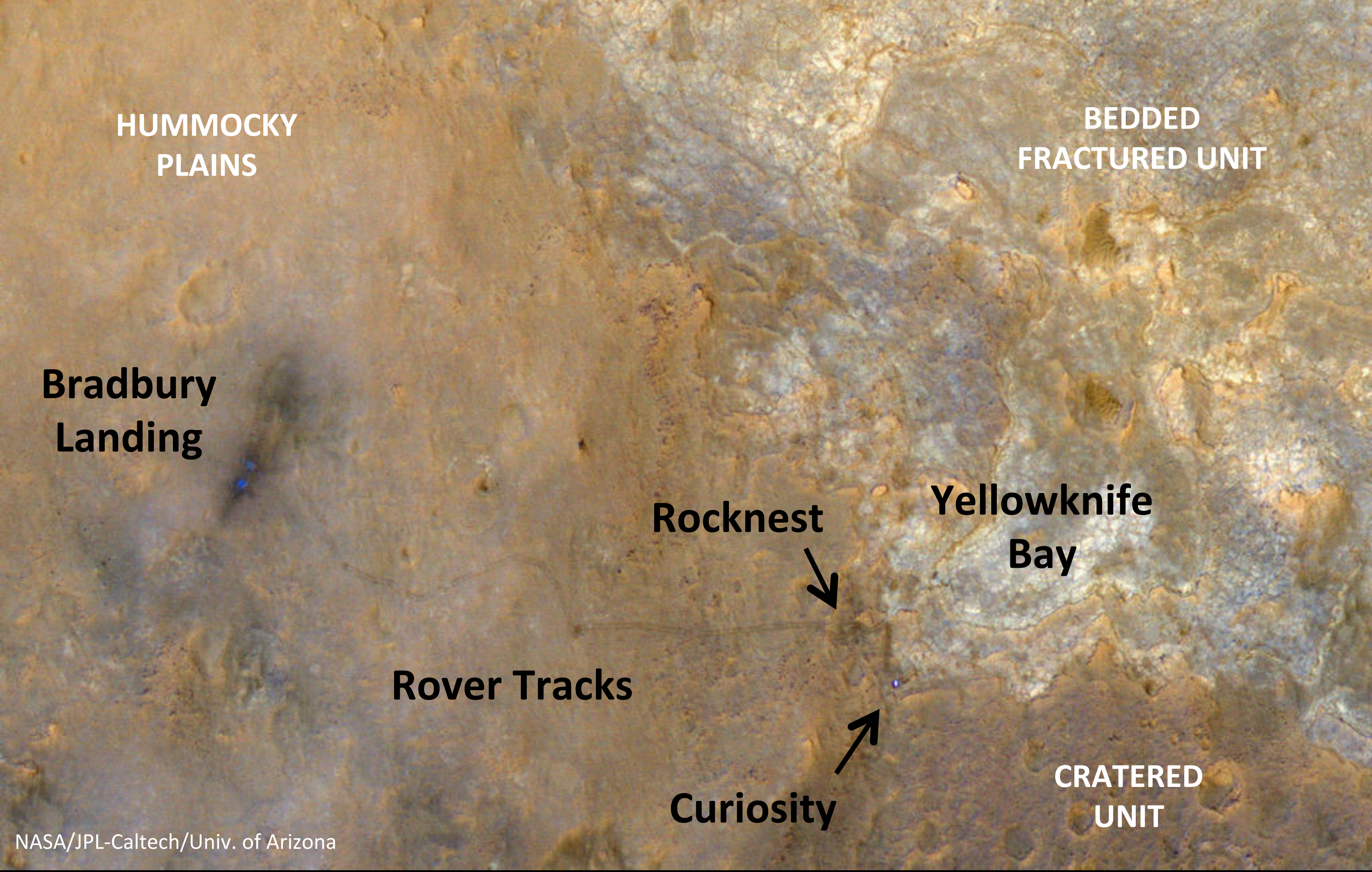

August 5, 2012: “Touchdown confirmed.”
“Let’s see where Curiosity will take us.”



NASA/JPL-Caltech/MSSS

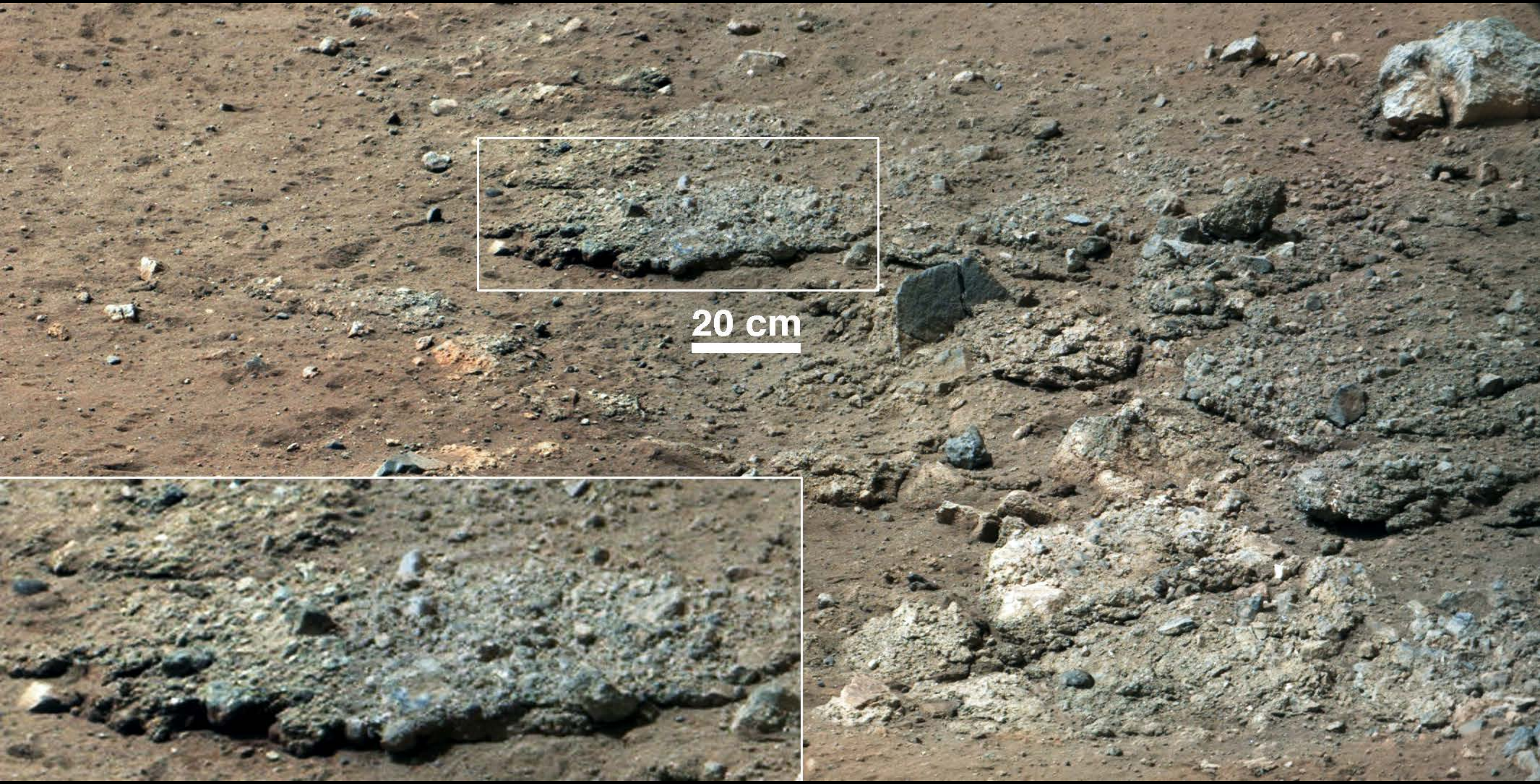
# Mastcam mosaic of Mount Sharp, descent rocket scours, and rover shadow

# Bradbury Landing to Rocknest




CURIOSITY

# Curiosity and its tracks captured by HiRISE on the Mars Reconnaissance Orbiter

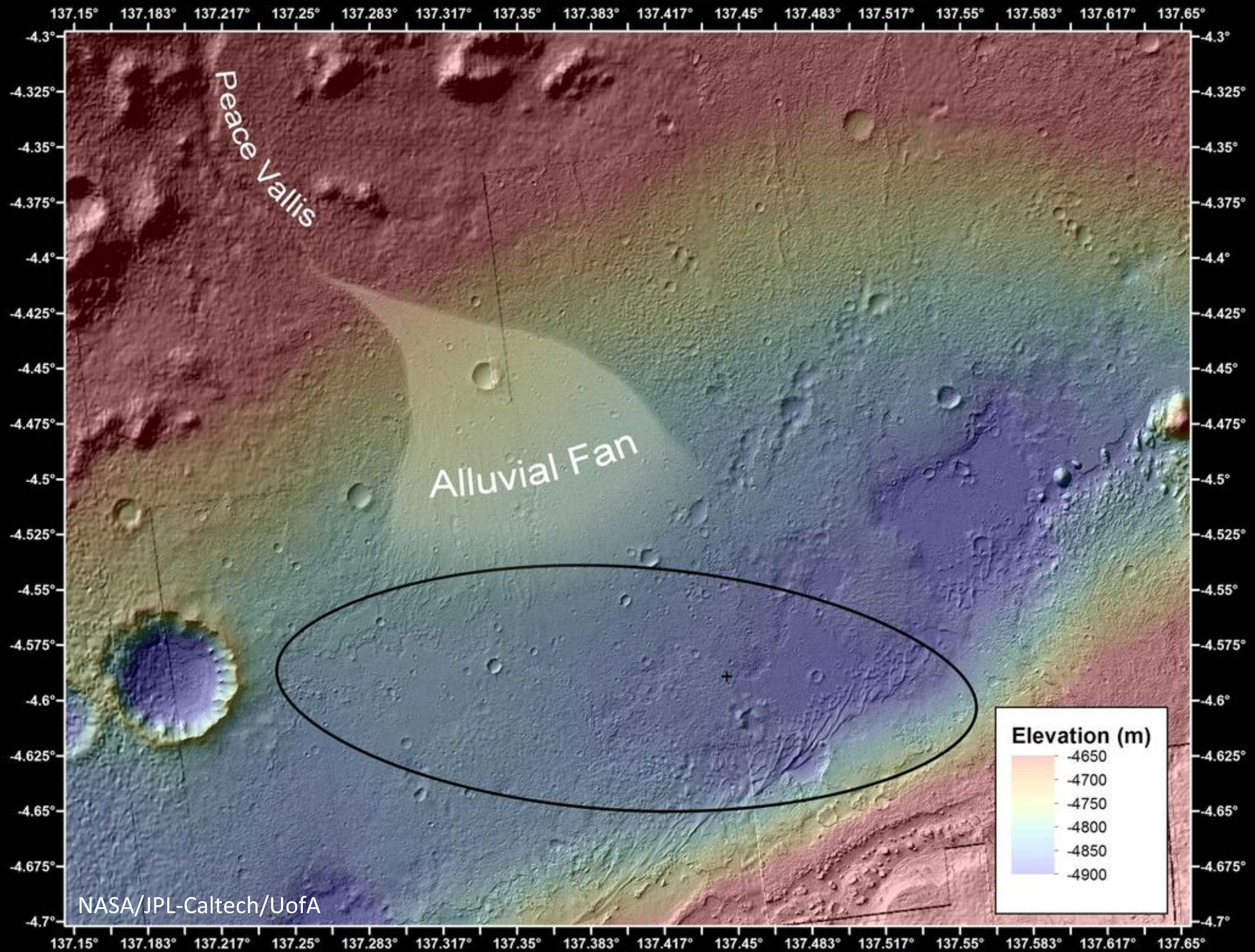


NASA/JPL-Caltech/MSSS

CURIOSITY

# Goulburn, scoured by Curiosity's descent rockets, first revealed bedrock


**Rounded pebbles and sand in the conglomerate "Link" indicate water flowed ankle to hip deep**

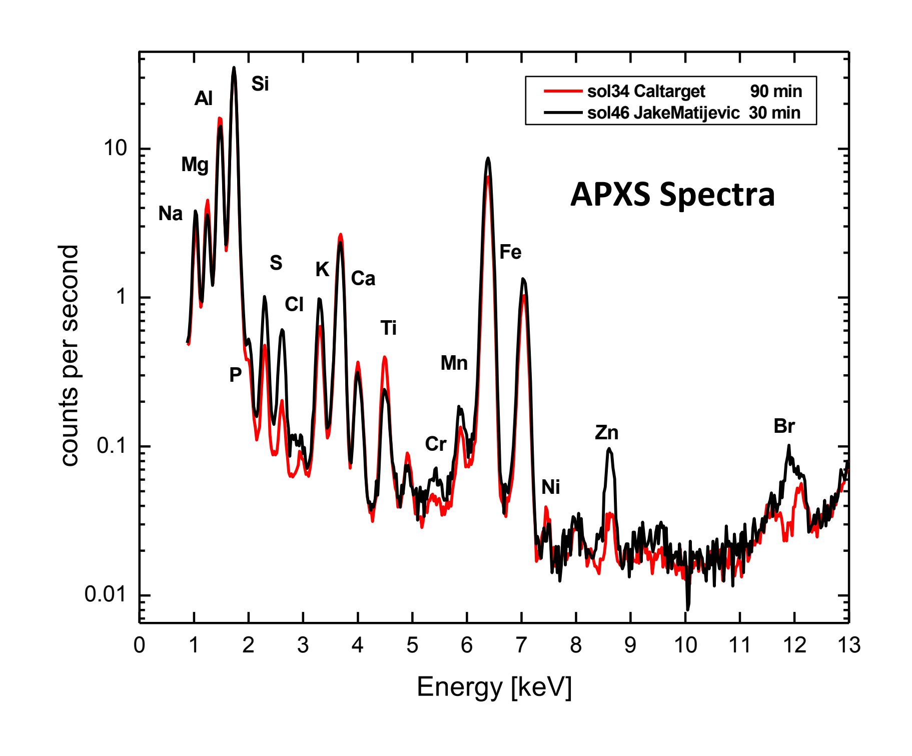



CURIOSITY

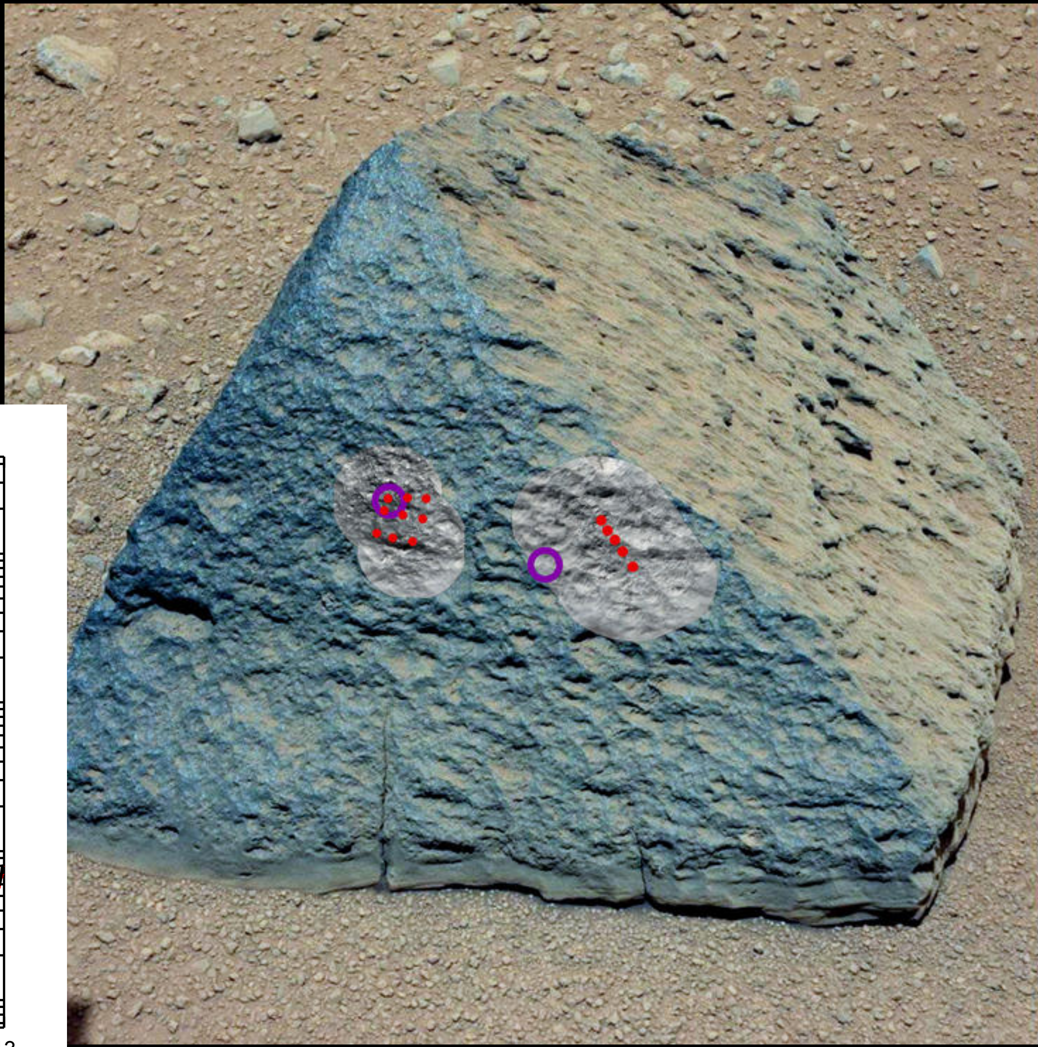
# The conglomerate reveals an ancient streambed, likely originating at the northern crater rim

# Jake Matijevic studied by Mastcam (image), APXS, and ChemCam

Composition is similar to alkaline basalts on Earth produced by partial melting of the mantle



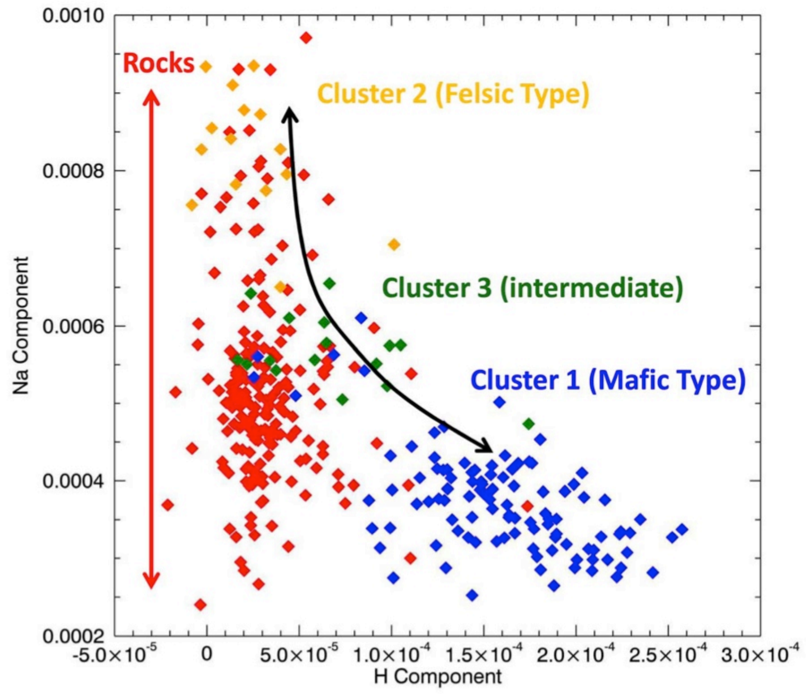

NASA/JPL-Caltech/U. Guelph



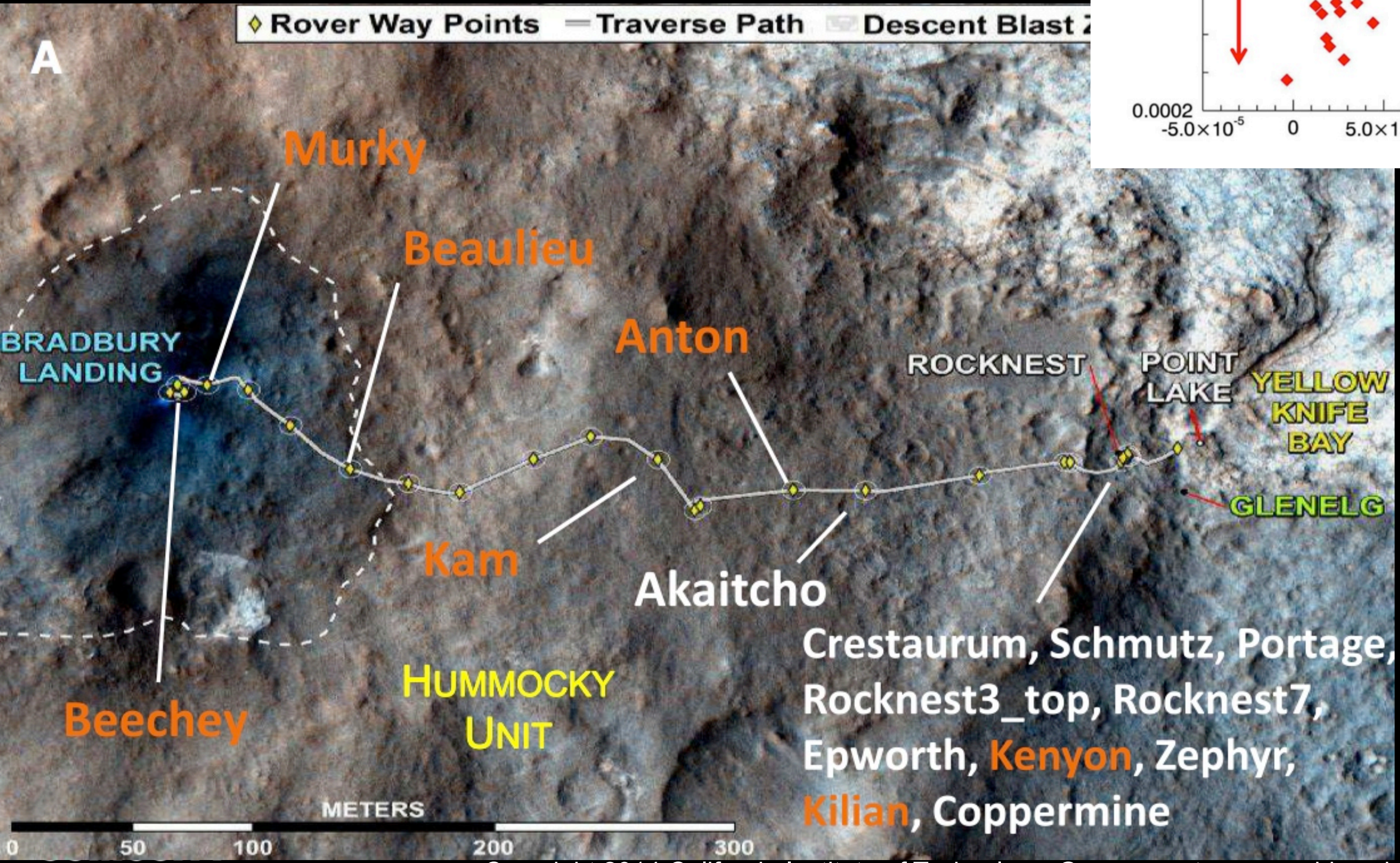
NASA/JPL-Caltech/MSSS
LAN L/IRAP/CNES/IAS/LPGN

**ChemCam identified two principal soil types along the traverse to Yellowknife Bay: a fine-grained, mafic type similar to other soils, and a locally derived, coarse-grained felsic type.**

**The mafic soil component has a hydration signature, corresponding to the X-ray amorphous component sampled by CheMin and SAM, and to the orbital detections of hydrogen in Mars' soils.**




Meslin et al. [2013]




**Mafic**

**Felsic**


NASA/JPL-Caltech/LANL/CNES/IRAP/LPGNantes/CNRS/IAS/MSSS

CURIOSITY

# Large feldspar-rich crystals (phenocrysts) in an igneous clast

# Rocknest Scooping Campaign

NASA/JPL-Caltech/MSSS

CURIOSITY

# Windblown “sand shadow” at the Rocknest site

Wheel scuff to confirm depth of sand, for safe scooping

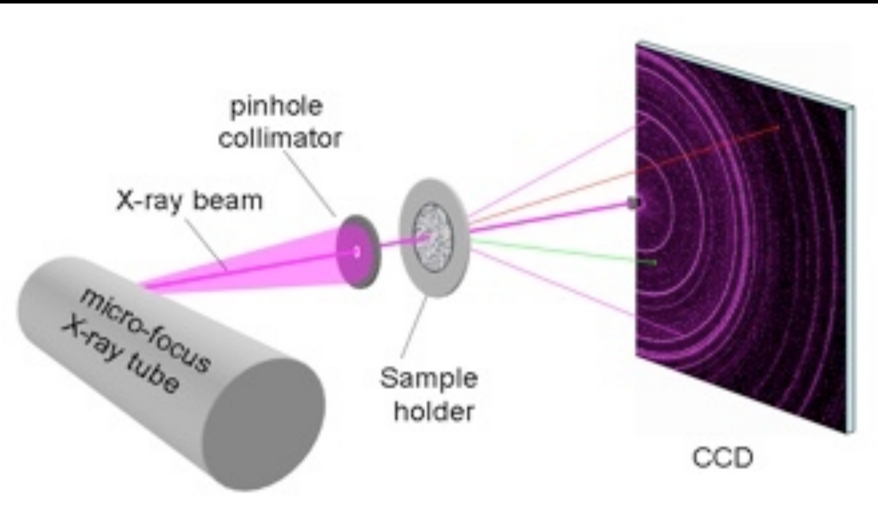


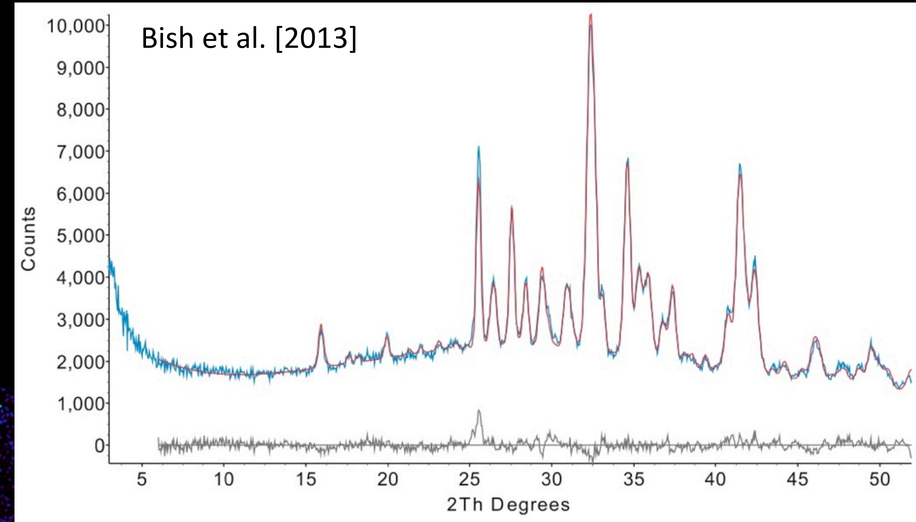
NASA/JPL-Caltech

NASA/JPL-Caltech/MSSS

CURIOSITY

**MAHLI view of coarse (0.5 to 1.5 mm) sand from the ripple's surface, and fine (< 0.25 mm) sand on wall and floor of trench**

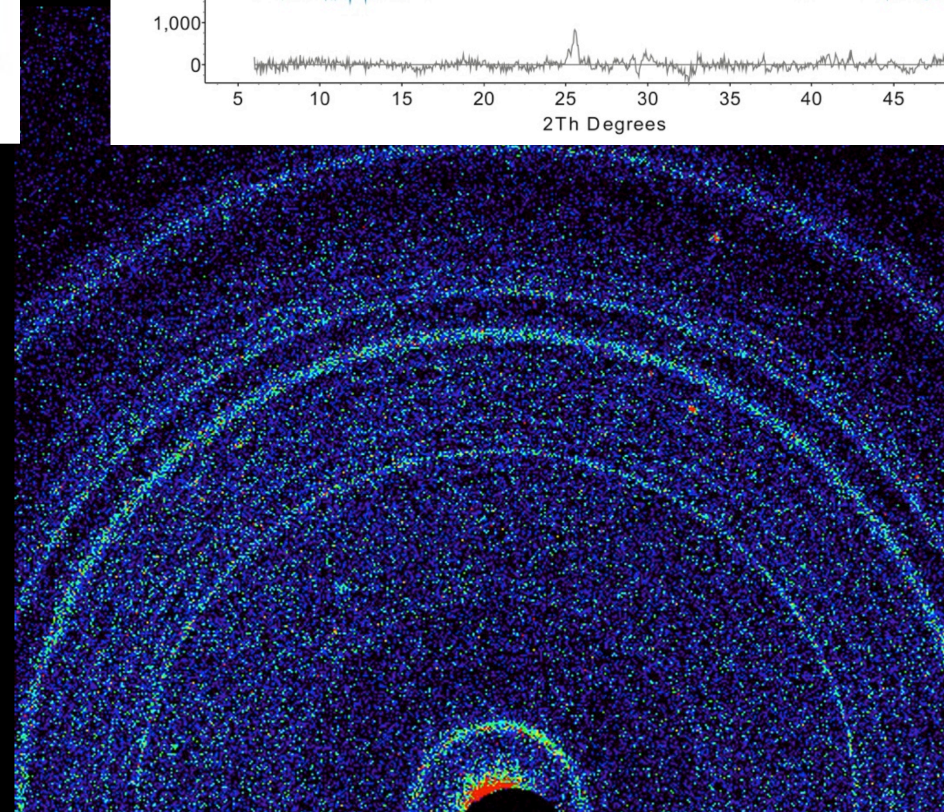



# CheMin uses X-rays to identify minerals

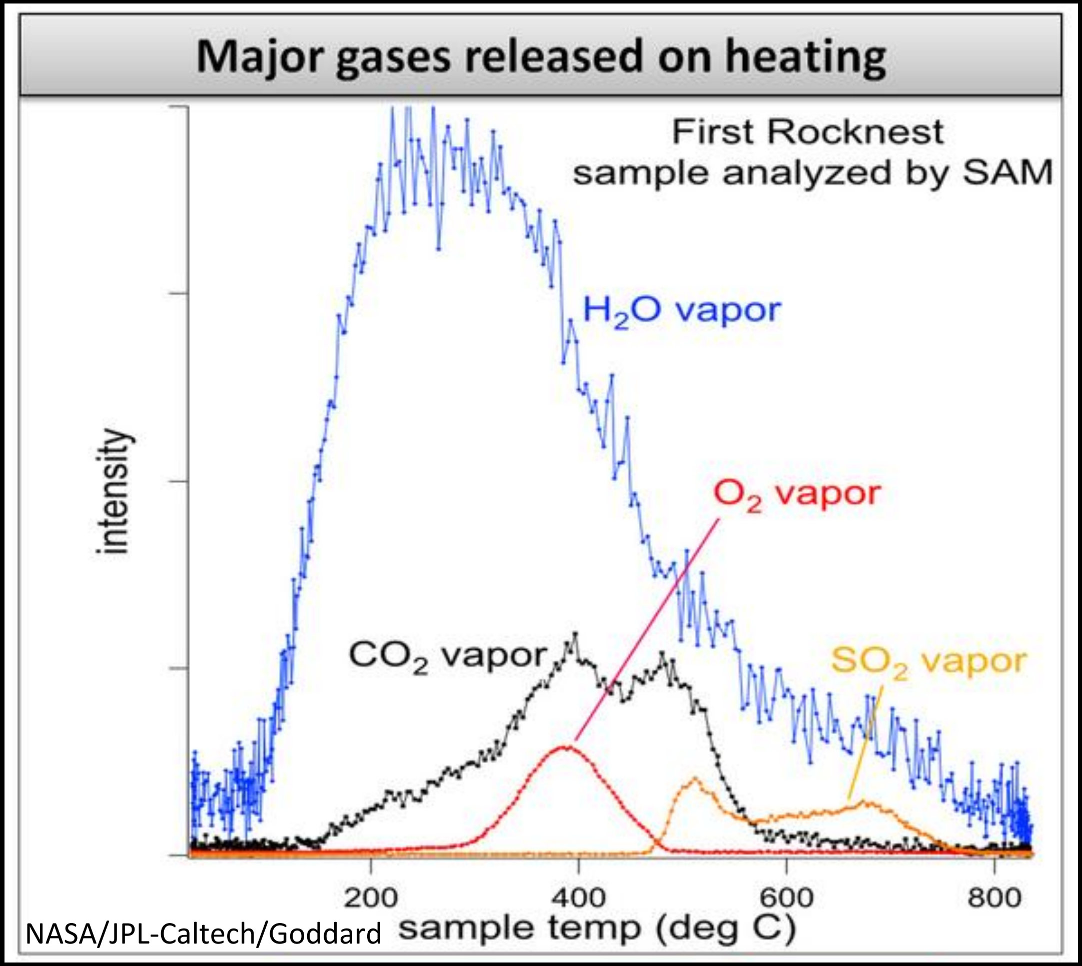
**Rocknest sand is composed of unaltered basaltic minerals, typical of rocks and soils on Mars**

**Samples also contained 30-45% non-crystalline material, containing volatiles, sulfur, calcium, and perhaps nanophase ferric oxide.**



CURIOSITY

## Rocknest sand has a typical Mars basalt composition, but also 1.5-3% bound water




Water

Oxygen

Sulfate

Hot → Hotter

**SAM found evidence for water, sulfate minerals, Fe/Mg carbonates, and chlorate/perchlorate compounds**

CURIOSITY

# Gases released during SAM experiments

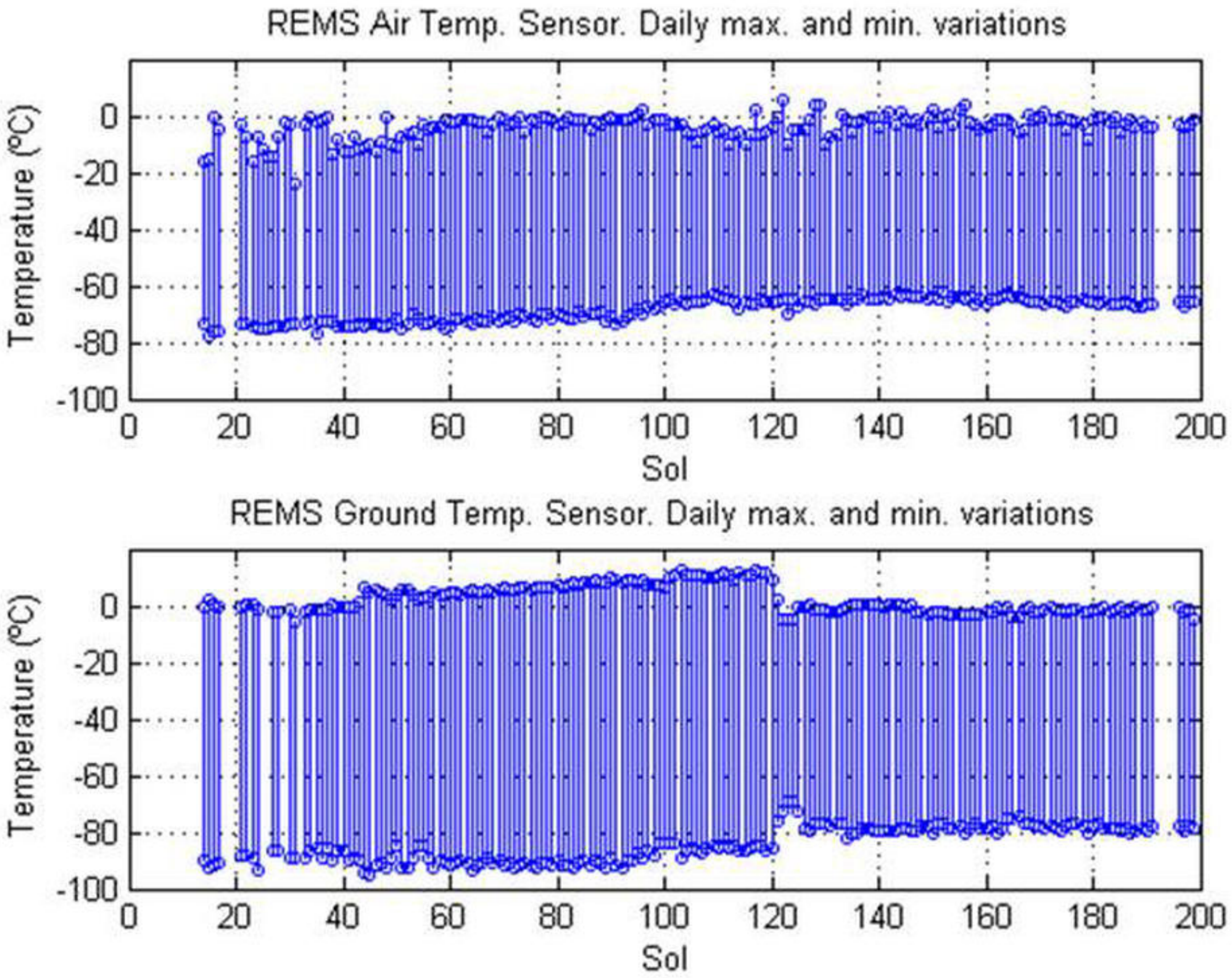
Curiosity self-portrait at Rocknest

Assembled from 55 MAHLI images

Shows four scoop trenches and wheel scuff

CURIOSITY

# Measurements of Mars' Atmosphere and Environment



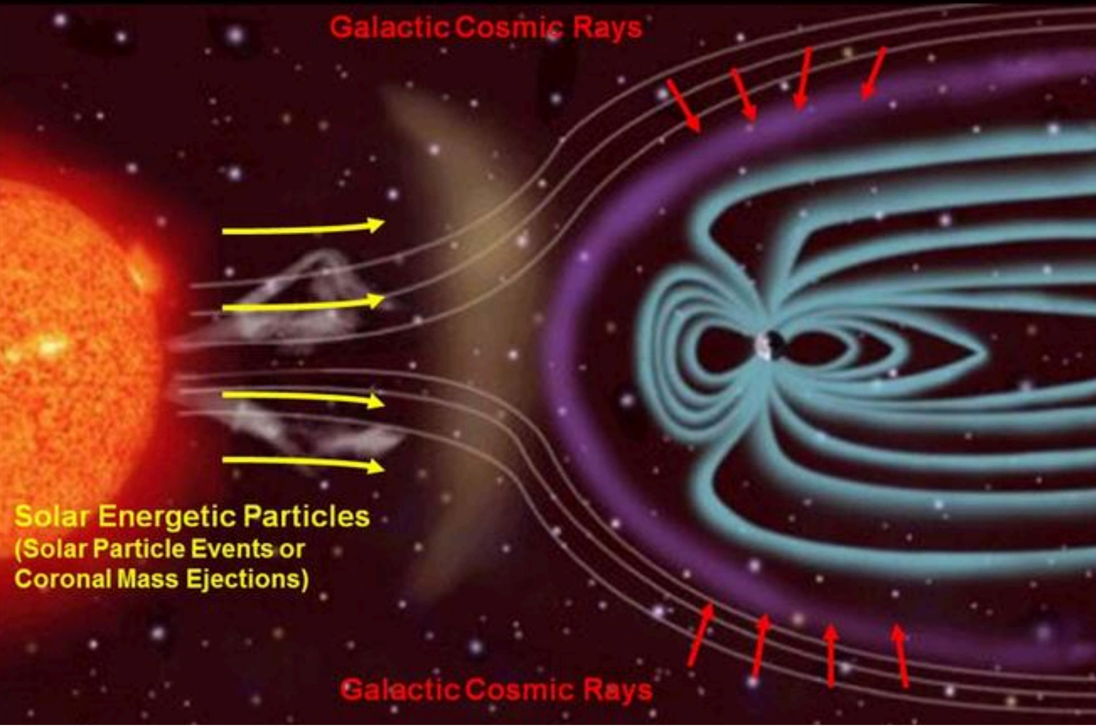

NASA/JPL-Caltech/CAB(CSIC-INTA)

**The air and ground temperature sensors are located on small booms on the rover's mast**

**The ground temperature changes by 90°C (170 degrees Fahrenheit) between day and night**

**Around Sol 120, the rover drove from gravel onto bedrock, resulting in a smaller temperature swing each sol**

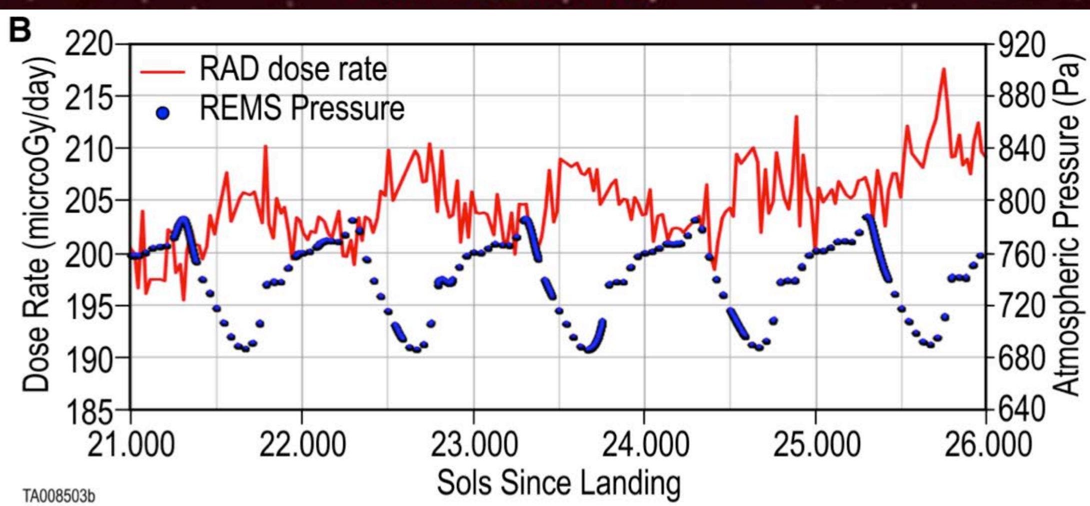
# Curiosity's Rover Environmental Monitoring Station is taking weather readings 24 × 7



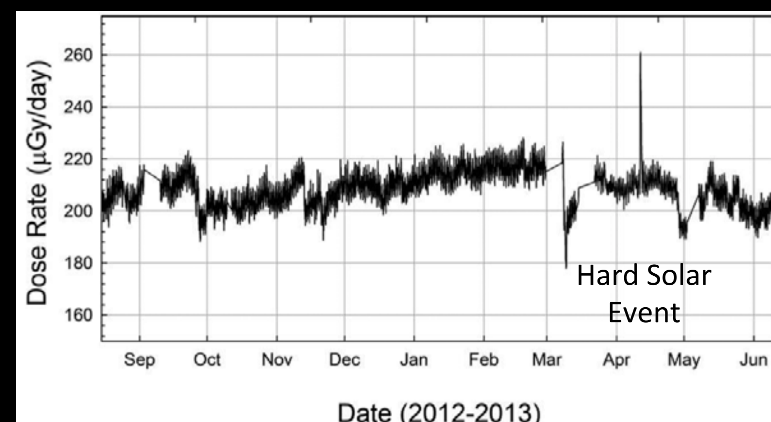

The RAD instrument measured the radiation flux from both galactic cosmic rays and solar energetic particles, in cruise and at Mars' surface

The surface dose rate is about half that measured in cruise

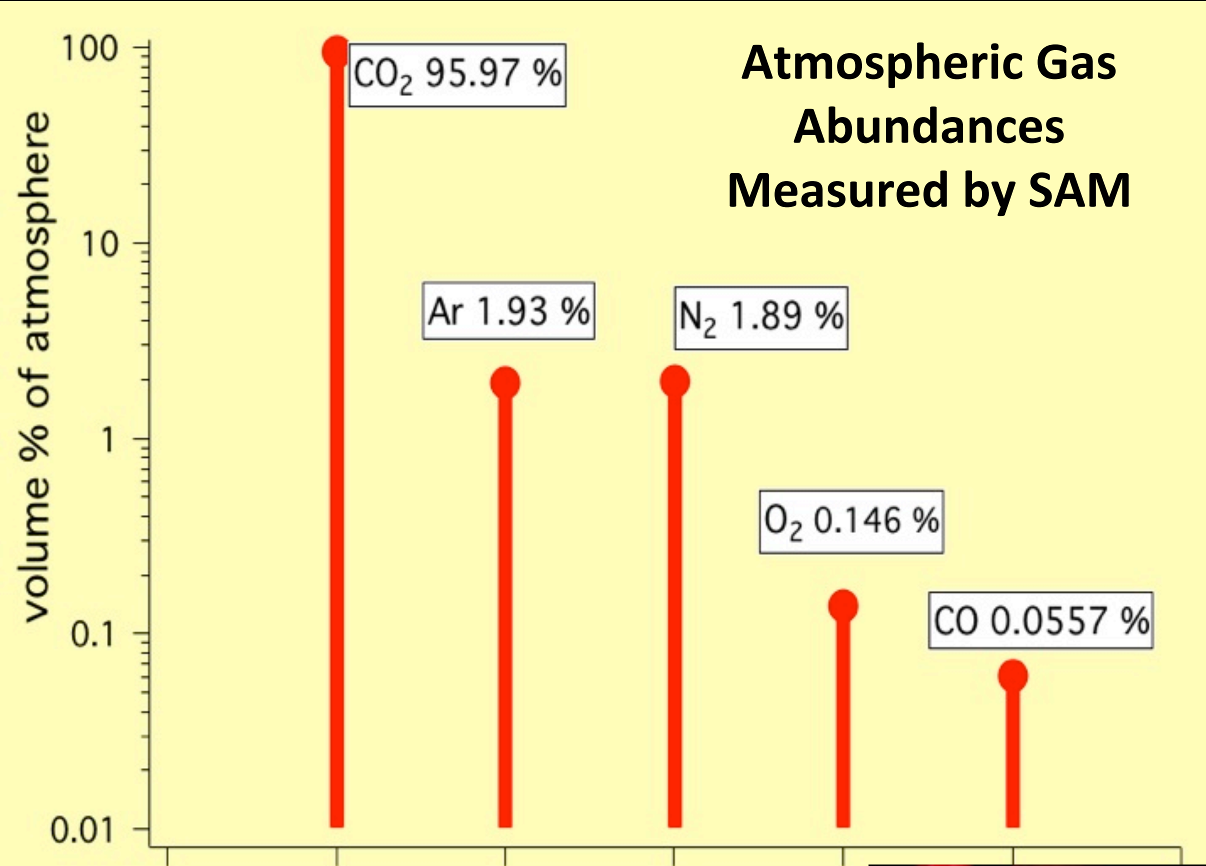
A crewed mission would receive ~1 Sievert of exposure in a trip to Mars with 500 sols on the surface




[Hassler et al., 2014]




# Curiosity's Radiation Assessment Detector measures high-energy radiation



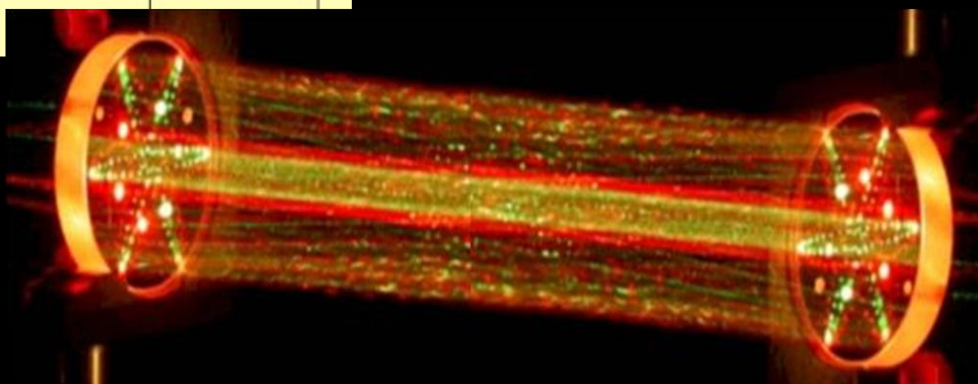

SAM found that argon, rather than nitrogen is the second most abundant gas

SAM also found that Mars' atmosphere is enriched in the heavy versions of isotopes, indicating massive atmospheric loss to space

$\delta^{13}C = 46 \pm 4$ per mil

$\delta D = 4950 \pm 1080$ per mil

$^{40}Ar/^{36}Ar = 1900 \pm 300$



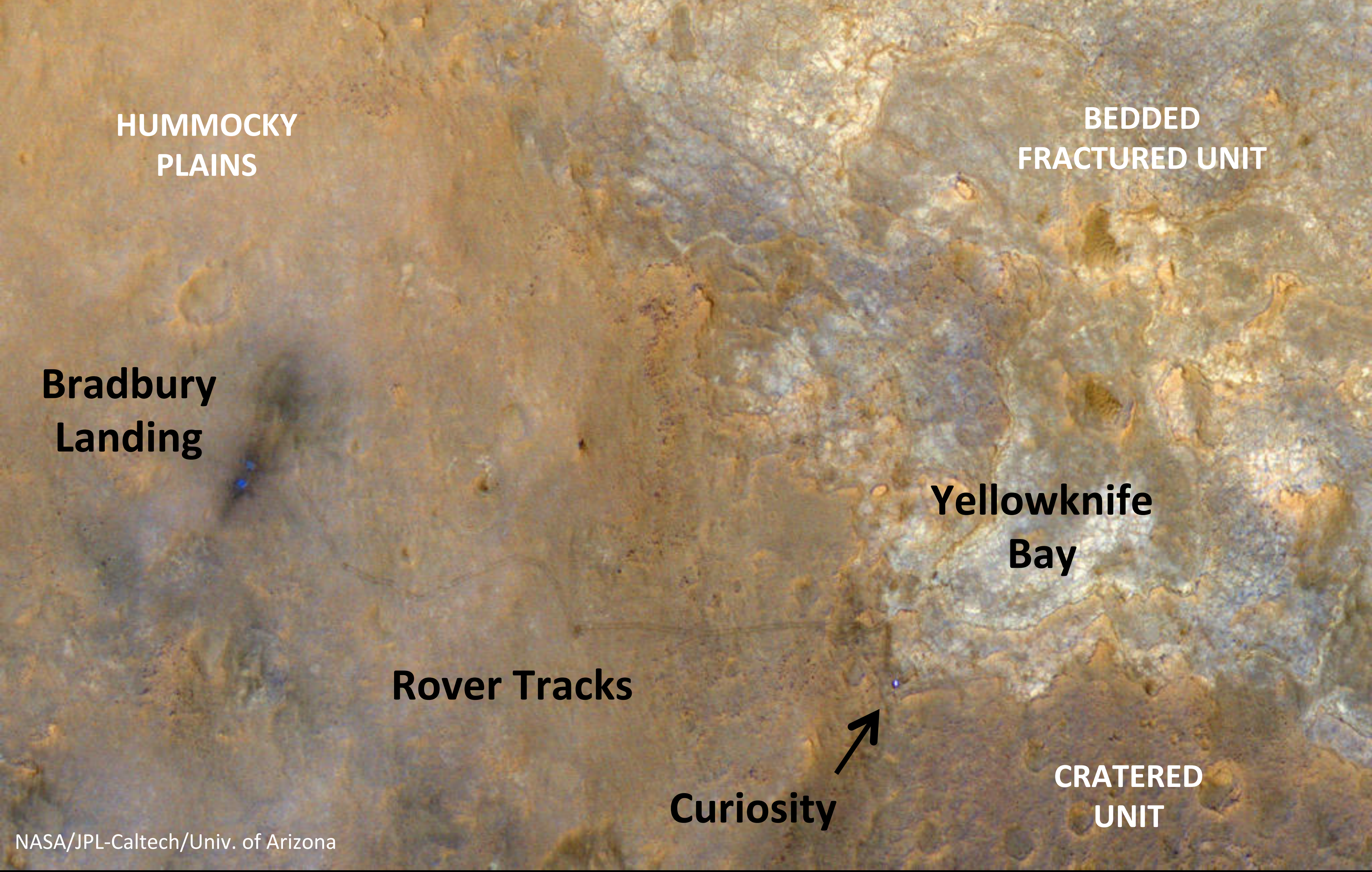
Methane has not been definitively detected

Upper limit = 1.3 ppb

CURIOSITY

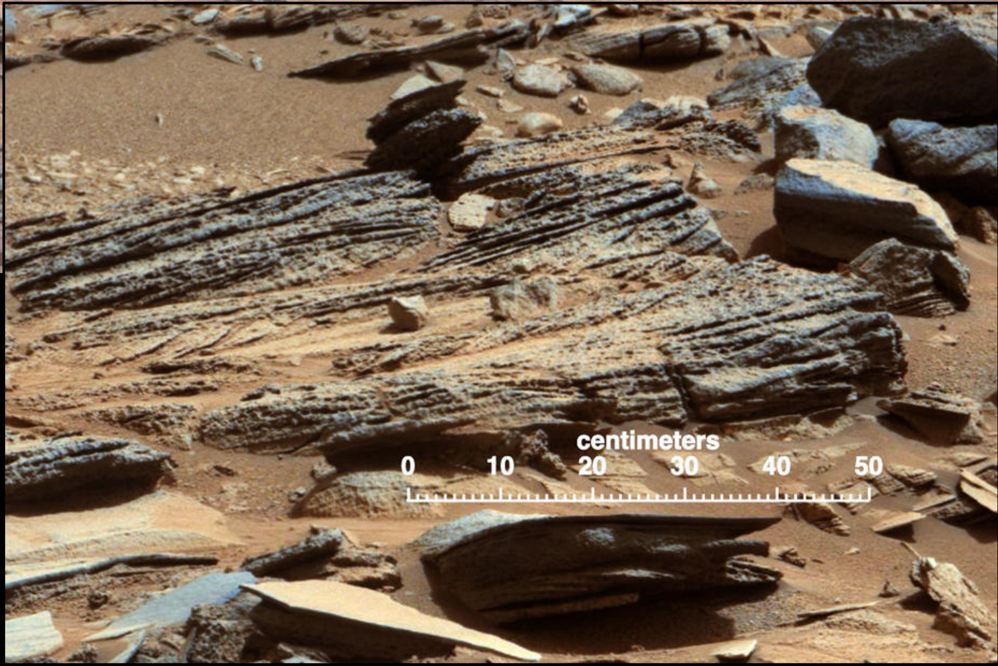
# The SAM Tunable Laser Spectrometer and Mass Spectrometer measure atmospheric composition

# Exploration of Yellowknife Bay




CURIOSITY

# Curiosity and its tracks captured by HiRISE on the Mars Reconnaissance Orbiter




NASA/JPL-Caltech/MSSS

# "Shaler" rocks just outside Yellowknife Bay show inclined, fine layers that indicate sediment transport

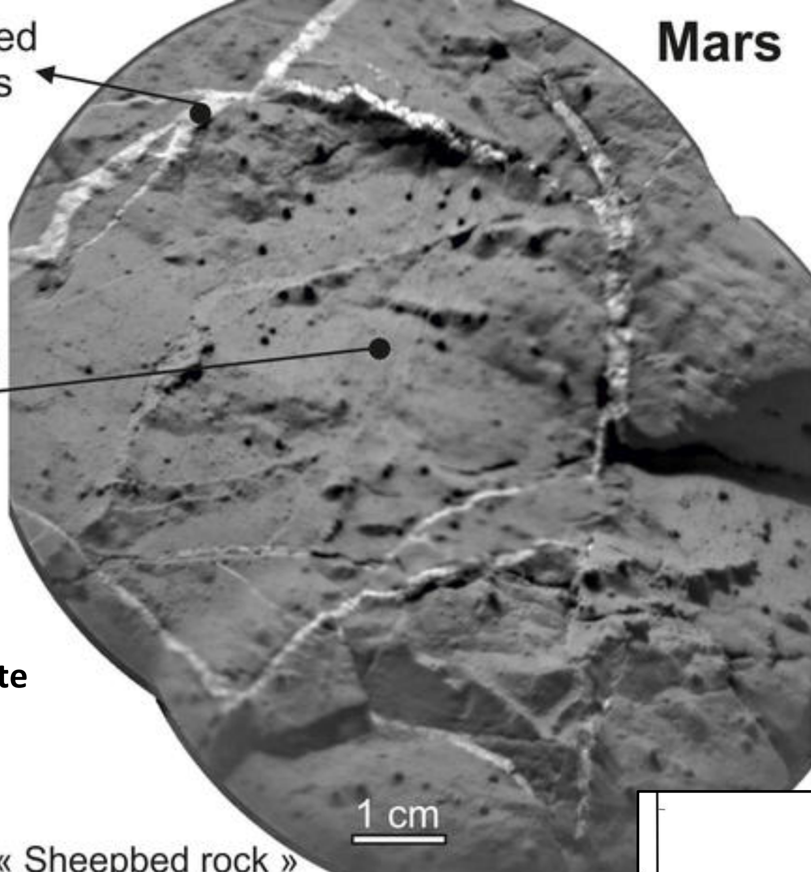
NASA/JPL-Caltech/MSSS

# Heading into Yellowknife Bay


# Yellowknife Bay shows a diversity of rock types, fractures, and veins

CURIOSITY

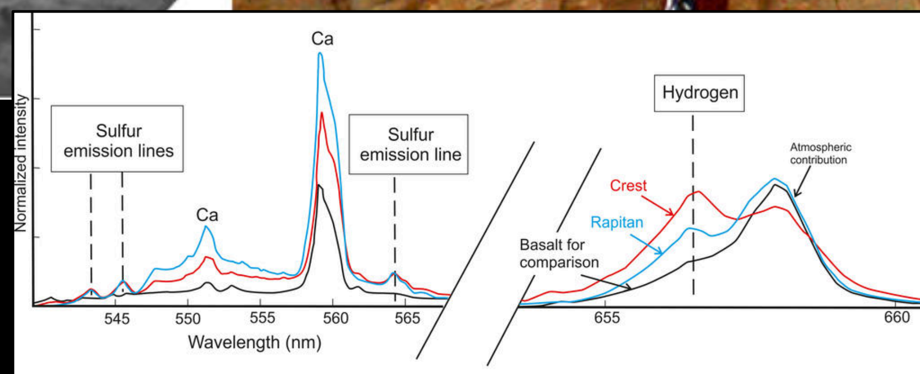
Mars




**ChemCam Remote Micro-Imager**

Earth

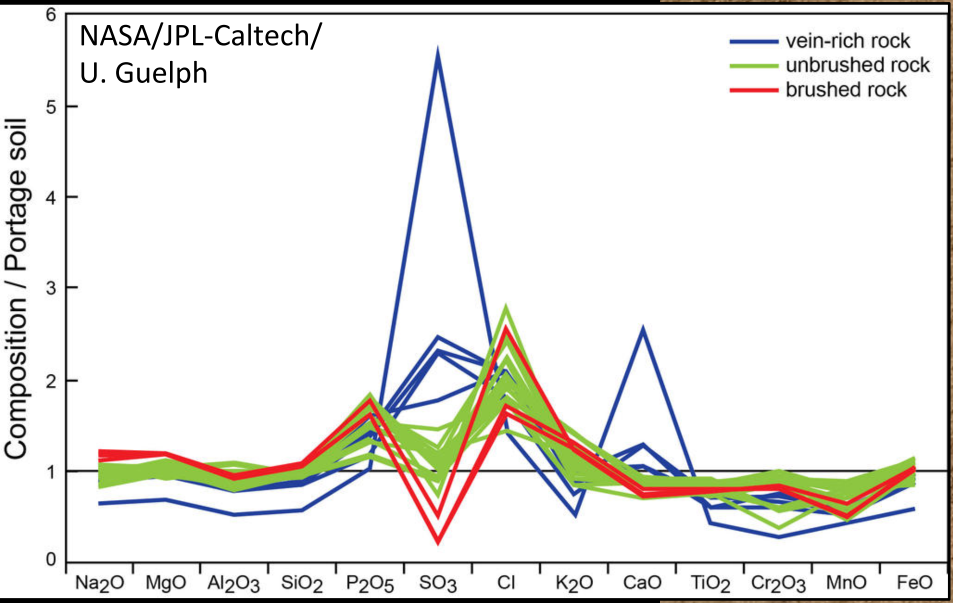
NASA/JPL-Caltech/LANL/CNES/IRAP/IAS/
LPGN/CNRS/LGLyon/Planet-Terre

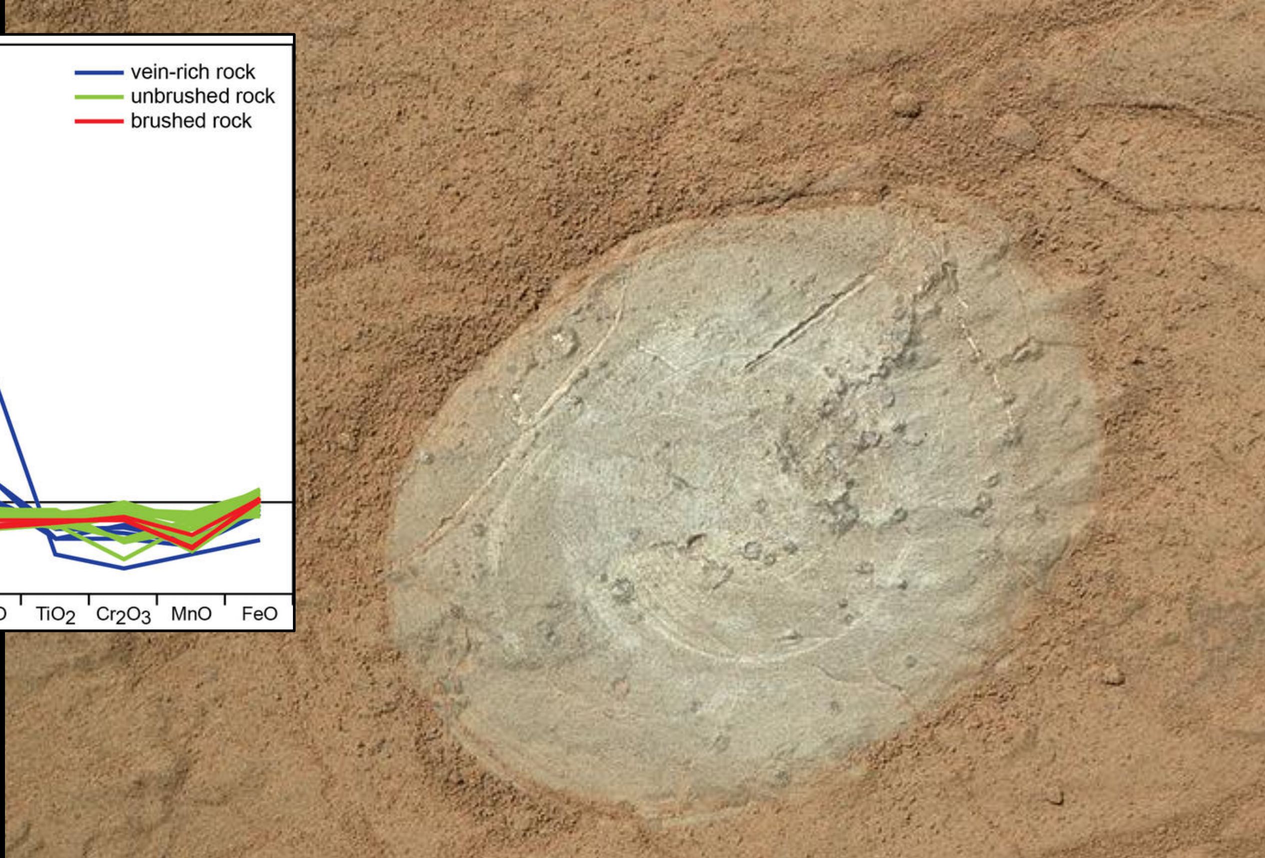



ChemCam spectra from sol 125 “Crest” and 135 “Rapitan”

# Sheepbed rocks contain 1 to 5-mm fractures filled with calcium sulfate minerals that precipitated from fluids at low to moderate temperatures

CURIOSITY



NASA/JPL-Caltech/MSSS

**APXS sees sulfur and calcium in vein-rich rock**

**Removing the dust results in slightly lower sulfur**

CURIOSITY

# APXS and the dust-removing brush


NASA/JPL-Caltech/MSSS

CURIOSITY

**Sheepbed rocks also contain many spherules suggesting that water percolated though pores**

NASA/JPL-Caltech/MSSS

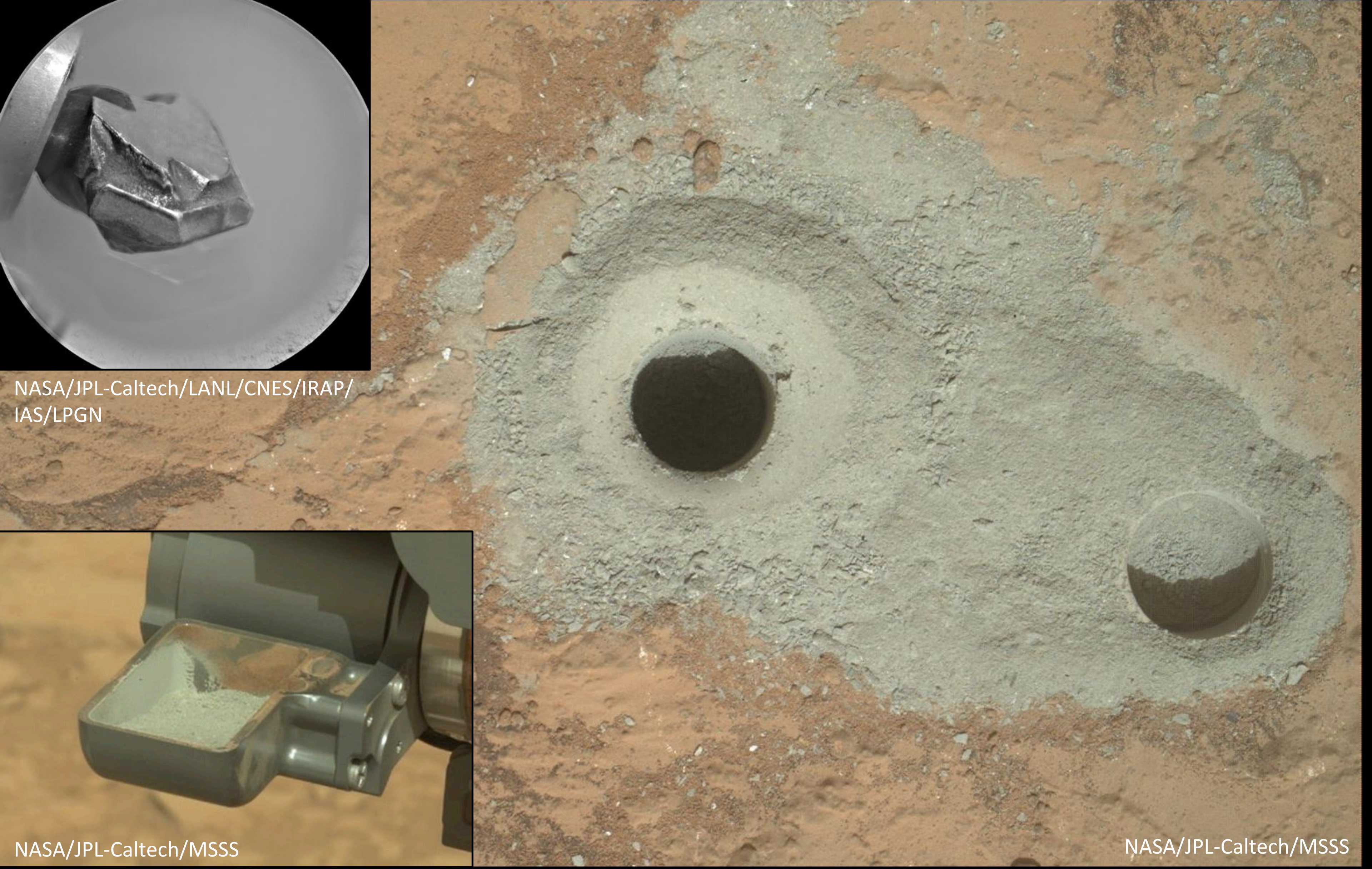
CURIOSITY

# John Klein drill site showing fractured bedrock and ridge-forming veins

NASA/JPL-Caltech/D. Bouic

# Arm deployed at John Klein

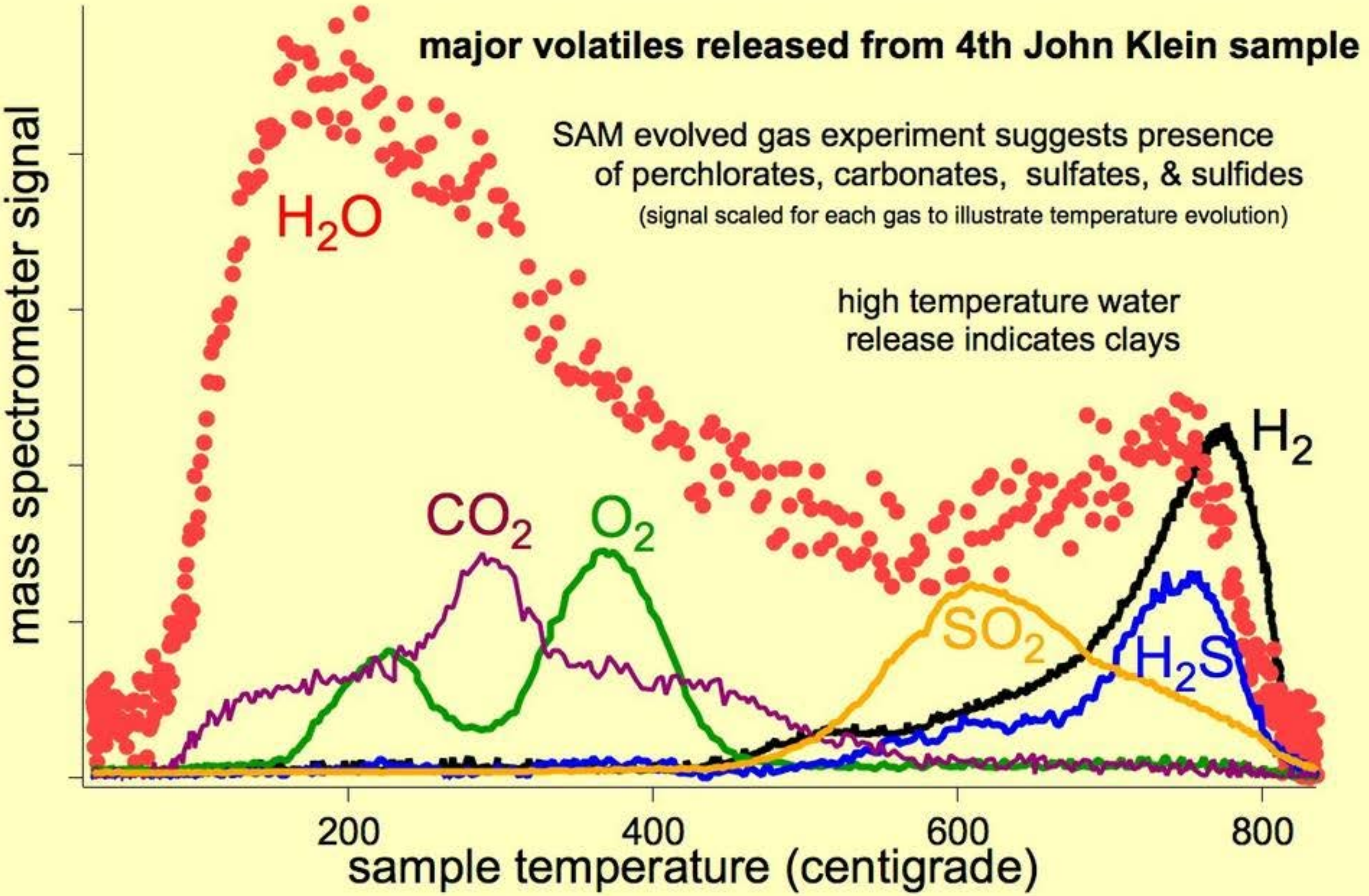
CURIOSITY




# Curiosity's 1.6-cm drill bit, drill and test holes, and scoop full of acquired sample


NASA/JPL-Caltech/MSSS

# John Klein dime-sized drill hole with light-toned veins and ChemCam profile




# Major gases released from John Klein sample and analyzed by SAM

CURIOSITY

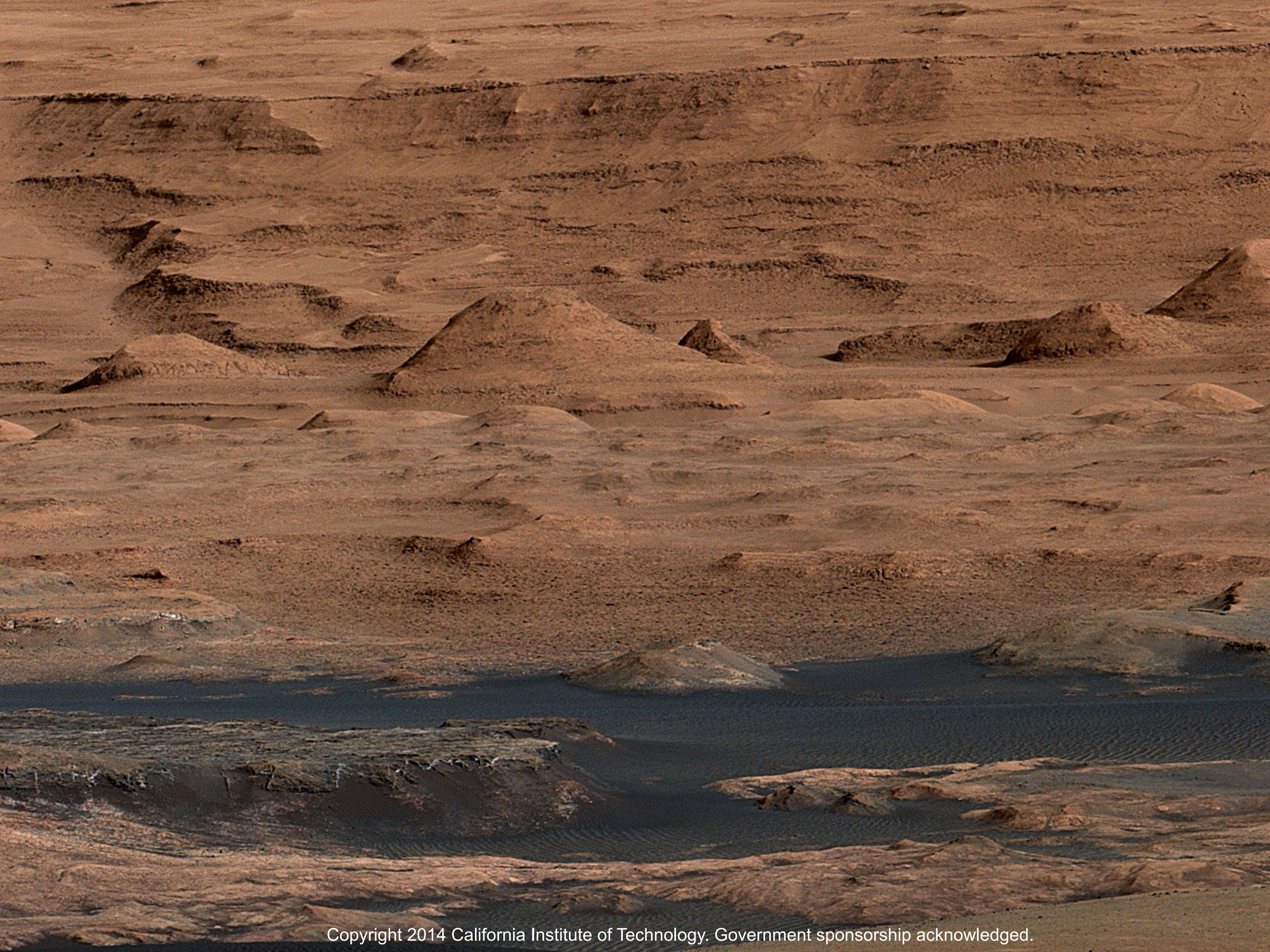
# An Ancient Habitable Environment at Yellowknife Bay

- **The regional geology and fine-grained rock suggest that the John Klein site was at the end of an ancient river system or within an intermittently wet lake bed**

- **The mineralogy indicates sustained interaction with liquid water that was not too acidic or alkaline, and low salinity. Furthermore, conditions were not strongly oxidizing.**

- **Key chemical ingredients for life are present, such as carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur**

- **The presence of minerals in various states of oxidation would provide a source of energy for primitive organisms**



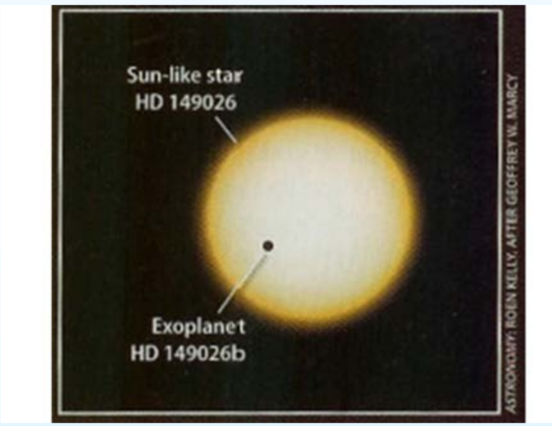
Jet Propulsion Laboratory
California Institute of Technology

# Search for Exoplanets…….

If there is a planet orbiting our nearest star Alpha Centauri, it' d be 7000 times more distant than Pluto

It is extremely difficult to see extrasolar planets,

1. They don' t produce light
2. They' re an enormous distance from us
3. They' re lost in the blinding glare of their parent star



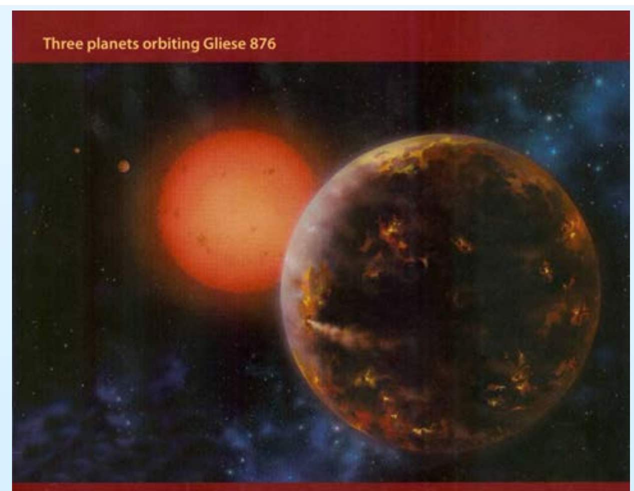

This exoplant HD 149026b orbit sun like star in 3 days. Size and mass of this exoplanet is similar to Saturn.

Multiple ways to track elusive planets

1. Doppler shift (frequency)
2. Transit method (brightness)
3. Gravitational microlensing (brightness)
4. Astrometric measurement (displacement)

There are clear evidence for substantial number of exoplantes in following categories,

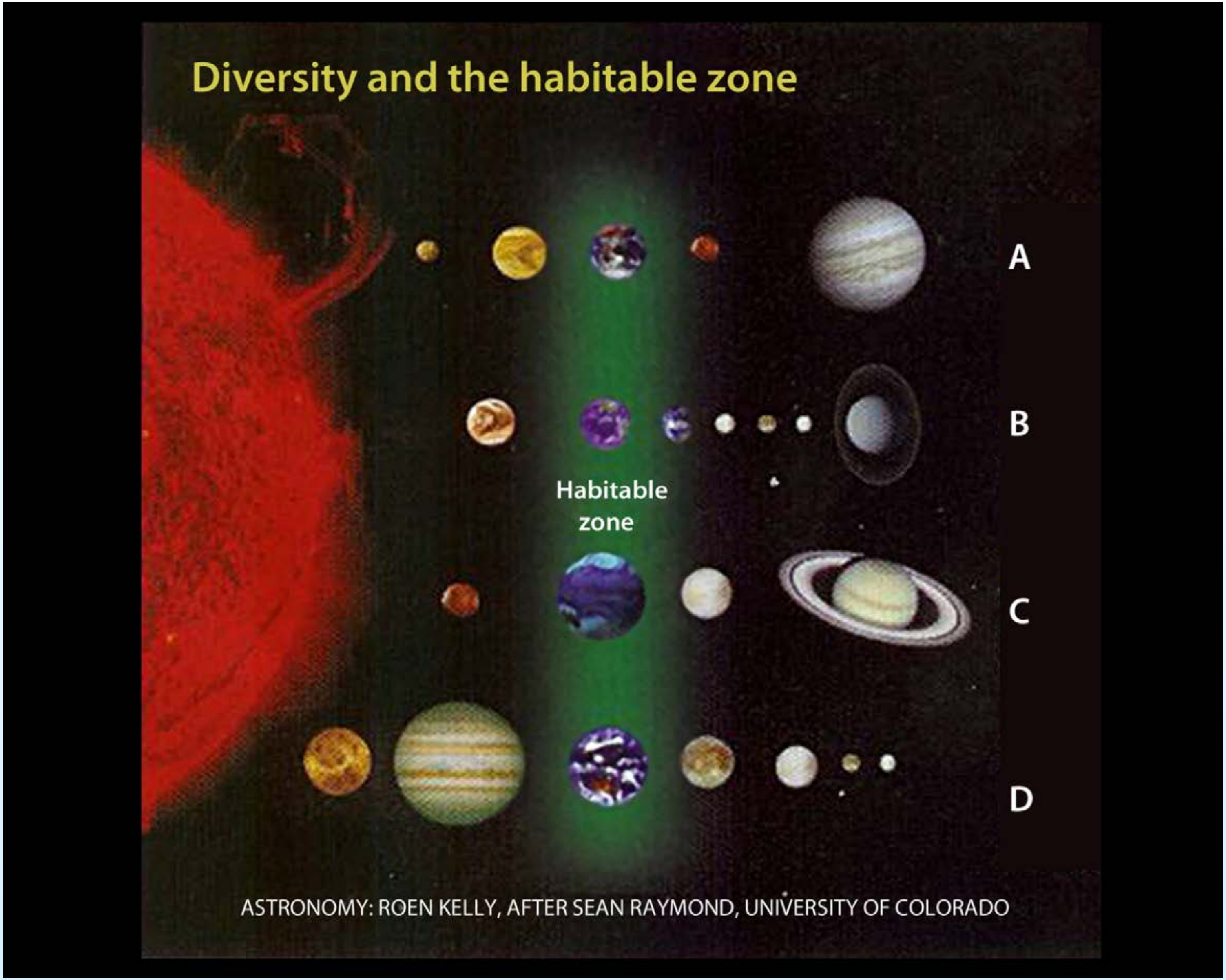
1. Gas giants
2. Hot-super Earths with short period orbits
3. Ice giants




Gliese 876 is depicted with three orbiting exoplanets, smallest is 7.5 Earth masses, the lowest mass of any extrasolar planet around a near by star.

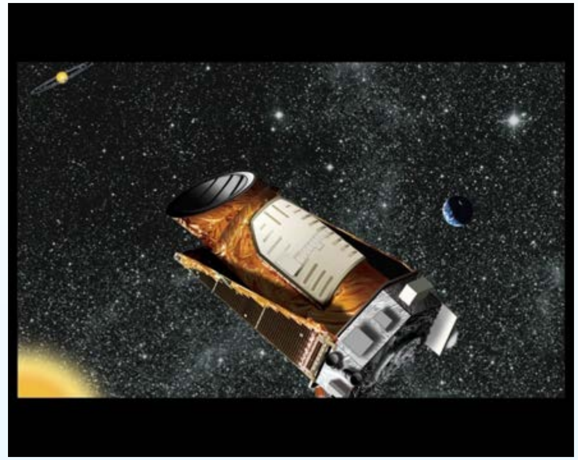
*This is like standing in Boston and trying to observe a moth near a spotlight in San Diego*

# Habitable Zones



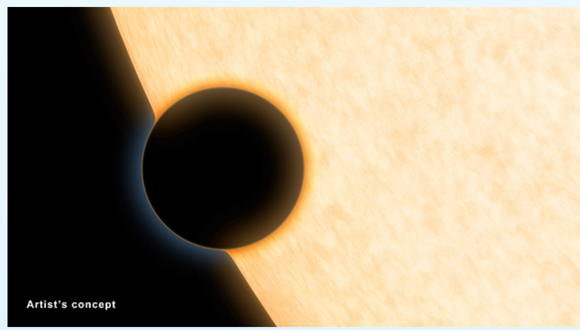
# Kepler mission looking for Earth like planets ....

Kepler mission specifically designed to survey our region of the Milky Way galaxy to discover hundreds of Earth-size and smaller planets in or near habitable zone and determine how many billions of stars in our galaxy have such planets.



95 Mega pixel Kepler detector array mosaic


The photometer's field of view in the constellations Cygnus, Lyra, and Draco.

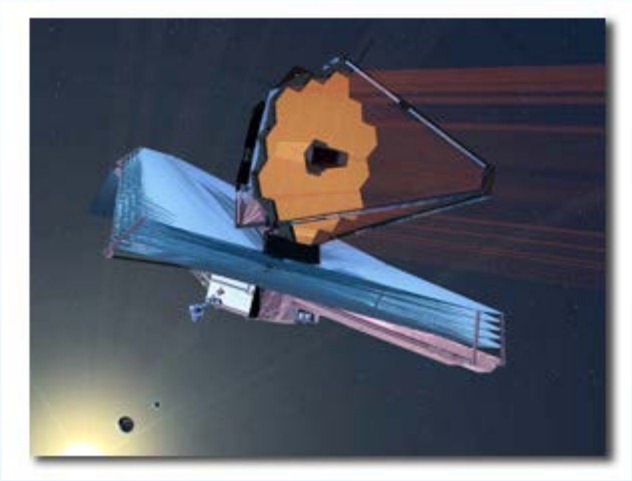



- Mirror – 1.4 meter
- Detectors – 95 Mega pixels
- Life of mission – 3.5 years
- Expected to find 50 Earth like planets with 1 AU
- Substantially higher number of planets with all orbits & all sizes

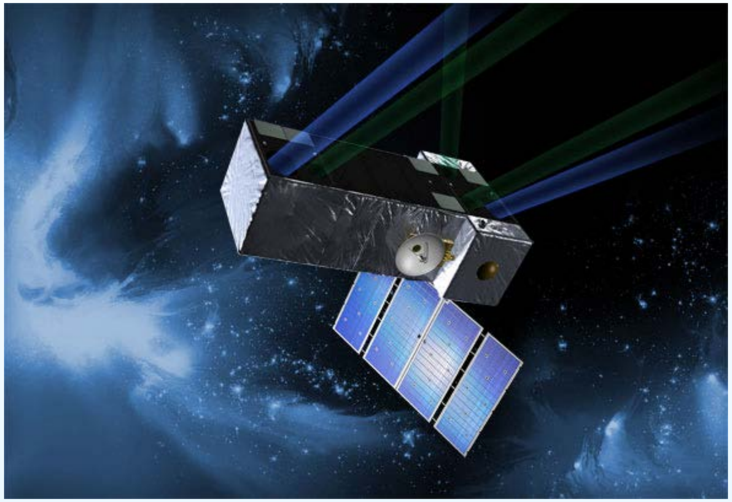
Astronomers using data from three of NASA's space telescopes -- Hubble, Spitzer and Kepler -- have discovered clear skies and steamy water vapor on a gaseous planet outside our solar system. The planet is about the size of Neptune, making it the smallest planet from which molecules of any kind have been detected.

**The centuries-old quest for other worlds like our Earth has been rejuvenated by the intense excitement and popular interest surrounding the discovery of thousands of planets orbiting other stars**

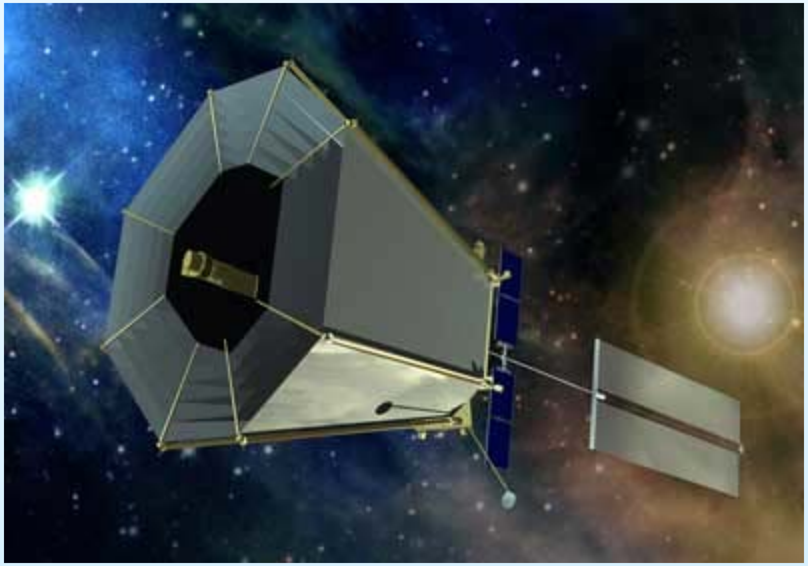
# Other planned instruments for exoplanet hunting…



James Webb Space Telescope



SIM Light



Terrestrial Planet Finder - Coronagraph


Terrestrial Planet Finder - Interferometer