NASA'S JOURNEY TO MARS

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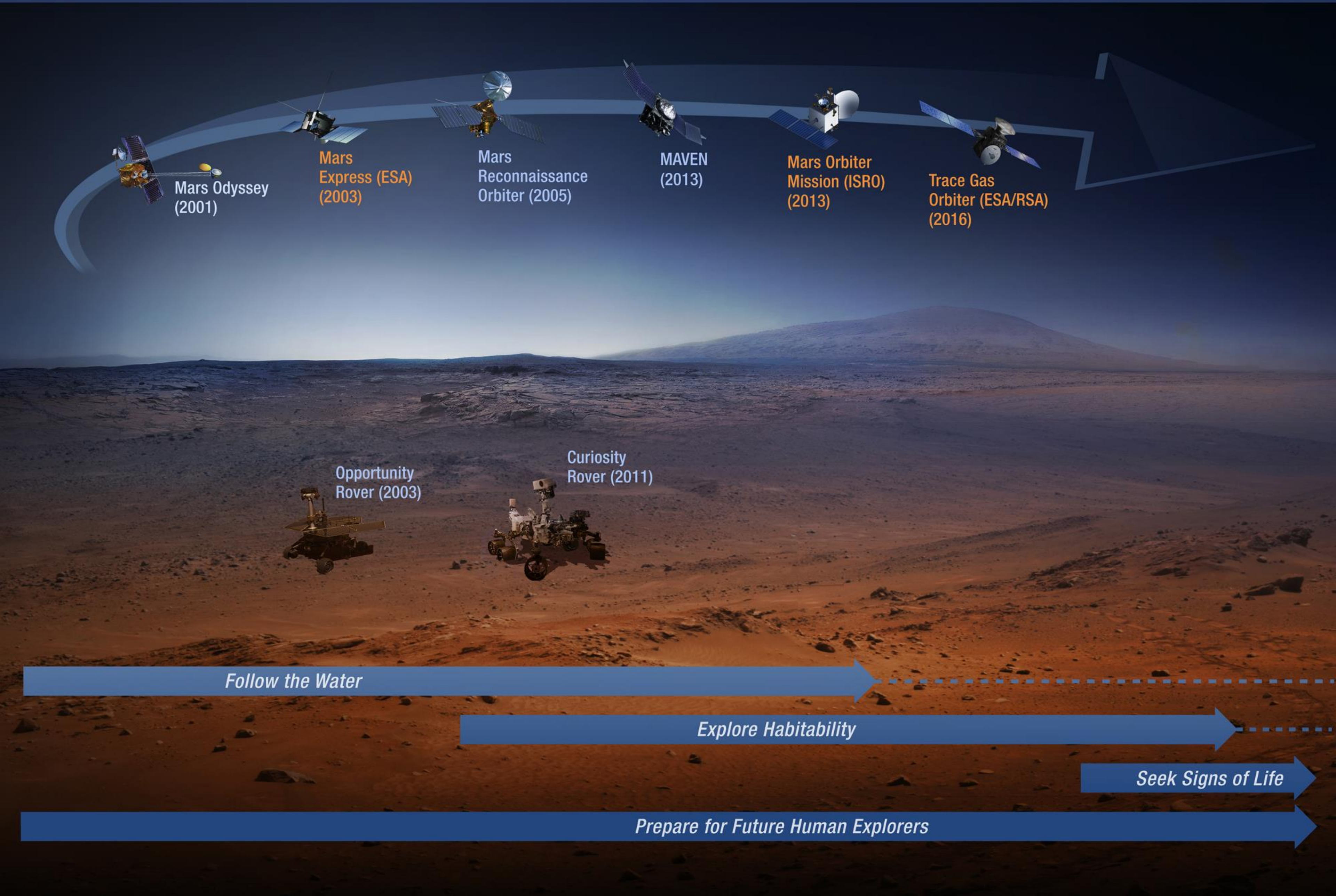
Presentation to the
Committee on the Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences
National Academy of Sciences

May 4, 2017

Mars Operational Missions 2001–2017



MARS SCIENCE

Decadal Survey
High-Priority Science Goals for Mars

- Determine if life ever arose on Mars — Does life exist, or did it exist, elsewhere in the universe?
  - Assess the past and present habitability of Mars
  - Assess whether life is or was present on Mars in its geochemical context, and
  - Characterize carbon cycling and prebiotic chemistry.
- Understand the processes and history of climate — Climate and atmospheric studies remain a major objective of Mars exploration.
  - Characterize Mars's atmosphere, present climate, and climate processes under both current and different orbital configurations; and
  - Characterize Mars's ancient climate and climate processes.
- Determine the evolution of the surface and interior — Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as to providing context for the history and processes of Earth.
  - Determine the nature and evolution of the geologic processes that have created and modified the martian crust over time; and
  - Characterize the structure, composition, dynamics, and evolution of Mars's interior.

MARS

Crosscutting Themes

Decadal Survey 2011

"All three of the committee's crosscutting themes for the exploration of the solar system include Mars, and studying Mars is vital to answering a number of the priority questions in each of them."

- The building new worlds theme:
  - What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?
- Mars is central to the planetary habitats theme:
  - What were the primordial sources of organic matter, and where does organic synthesis continue today? and,
  - Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?
- The workings of solar systems theme:
  - Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth

MARS

Progress in Mars Science

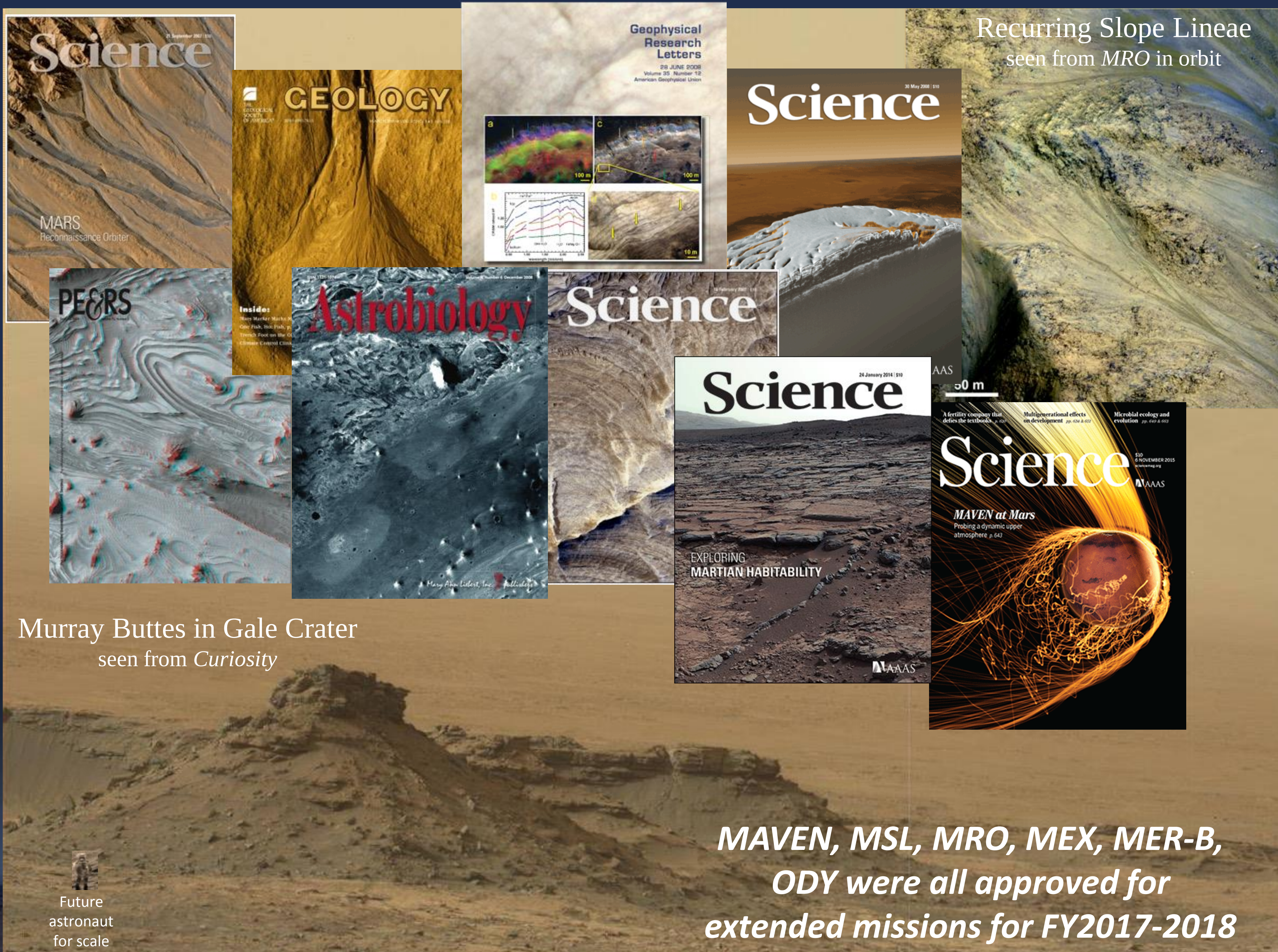
What have we learned? What remains to be discovered?

Fundamental Questions Remain

- Consistent with V&V2011, MEP and the community have defined high-priority objectives that should be pursued in the next decade of Mars exploration
  - Did Mars ever have life? Is it still there?
    - We are on the threshold of some answers with Mars 2020 and Sample Return
  - The great transition from a much wetter environment to the cold, dry planet of today – How, when, and how often did that happen?
    - Much will be accomplished with MSL and MAVEN
  - What is the nature of accessible water/ice on Mars? How did it vary through time? Can it be used? Does it/did it harbor life? What are the hazards?
    - Map polar/mid-latitude ice and hydrated minerals for science characterization and potential resource utilization
  - What is the significance of the new discoveries of a dynamic Mars?
    - Recurring Slope Lineae – seasonal flows, wet or dry?
    - Methane – What is the source (biological or geochemical)? The sink?

MARS

OPERATING MISSIONS



Science
MARS
Reconnaissance Orbiter
GEOLOGY
Geophysical Research Letters
Science
Recurring Slope Lineae
seen from *MRO* in orbit
PE&RS
Astrobiology
Science
Science
EXPLORING MARTIAN HABITABILITY
AAAS
Science
MAVEN at Mars
Probing a dynamic upper atmosphere
AAAS
Murray Buttes in Gale Crater
seen from *Curiosity*
Future astronaut for scale
MAVEN, MSL, MRO, MEX, MER-B, ODY were all approved for extended missions for FY2017-2018

Status of Orbital Missions: Odyssey

- Science
  - Continues to operate after 15+ years in Mars orbit
  - Observing Mars systematically in its new near-terminator orbit (~ 6 a.m., 6 p.m.)
    - Observing atmospheric clouds and surface frosts at different times of day
  - Completing polar coverage of visual imaging using spacecraft rolls
  - Continuing to add to climate records of atmospheric dust and temperature

- Programmatic: Relay & Reconnaissance
  - Primary relay for MER-B (*Opportunity*)
  - Two contacts for day for MSL (*Curiosity*), providing a third of its data return

- Risk to long life being mitigated
  - All-thruster control mode mitigates loss of a second reaction wheel (mission would run out of fuel in about 1 year if that loss occurs)
  - Migration to serve as backup relay for Mars 2020 EDL would exhaust remaining fuel

MARS

Status of Orbital Missions: Mars Reconnaissance Orbiter

- Continuing to characterize changes on a dynamic Mars
  - Diversity of possibly habitable environments on early Mars
  - Polar ice cap internal layering and mid-latitude subsurface ice distribution; large south polar deposits of buried CO_2 ice
  - Active changes today: New impacts, Recurring Slope Lineae, subliming CO_2 as an erosive agent, dust storm tracks and seasonal patterns
- Programmatic: Relay & Reconnaissance
  - MSL: ~227 Mbits per pass twice a day
  - Preparing for critical event coverage (i.e., EDL telecom) of InSight in Nov 2018 and relay during its commissioning phase
  - Landing site characterization/certification for InSight lander, 2020 NASA and ExoMars rovers, Human Exploration Zones
- Risks to long life being mitigated; lifetime goal ≥ 2023
  - Eclipse power management being implemented to extend battery life
  - Development of all-stellar mode to complement inertial (IMU) control
  - Remarkably, *all* instrument modes are available 11 years after launch, including measured use of CRISM IR spectrometer cooler
  - 200 kg of fuel still available for use

MARS

Status of Orbital Missions: MAVEN

- Continuing to characterize atmospheric loss processes
  - Observations in 2nd Mars year to characterize interannual variability
  - Observing different parts (approaching minimum) of the solar cycle
  - Characterizing effects of new solar events (e.g., CMEs)
  - High-resolution mapping of cold-ion outflow
  - High-resolution mapping of ion outflow near remanent magnetic fields
  - Directly measure neutral winds in the upper atmosphere
  - New radio occultations to map ionosphere electron density peak
- Programmatic: Relay
  - Demonstrated relay capability with MER and MSL
  - Ongoing assessment of aerobraking options:
    - Can enable move to a more relay-friendly orbit, but will impact MAVEN science
- Risks to long life being being mitigated
  - No degradation observed in spacecraft capabilities
  - Looking for ways to conserve fuel to extend life for 2020 missions
    - e.g., Gravity-gradient attitude may reduce fuel needed for momentum management

Status of Orbital Missions: ESA Mars Express and Trace Gas Orbiter

- Mars Express
  - Continues to operate after 13+ years in Mars orbit
  - Science instruments continue to operate except during periods of long eclipse when they are powered off to conserve battery
  - Mars observations, including NASA-ASI radar observations of the polar caps, continue; NASA supporting US co-investigators
  - New Phobos observation campaign with close approaches
  - Coordinated observations with MAVEN (ASPERA, MARSIS instruments)
  - Back-up relay periodically tested for use with Curiosity
  - Amount of remaining fuel uncertain; unlikely to be available after 2020

- Trace Gas Orbiter
  - Began aerobraking March 15; will pause for Solar Conjunction
  - Final science orbit will be achieved by March 2018
  - Carries dual Electra relay units, which have been tested with Curiosity
    - Prime for 2020 ExoMars rover
    - Can work with 2020 NASA rover and other NASA assets

Status of Landed Missions: MER

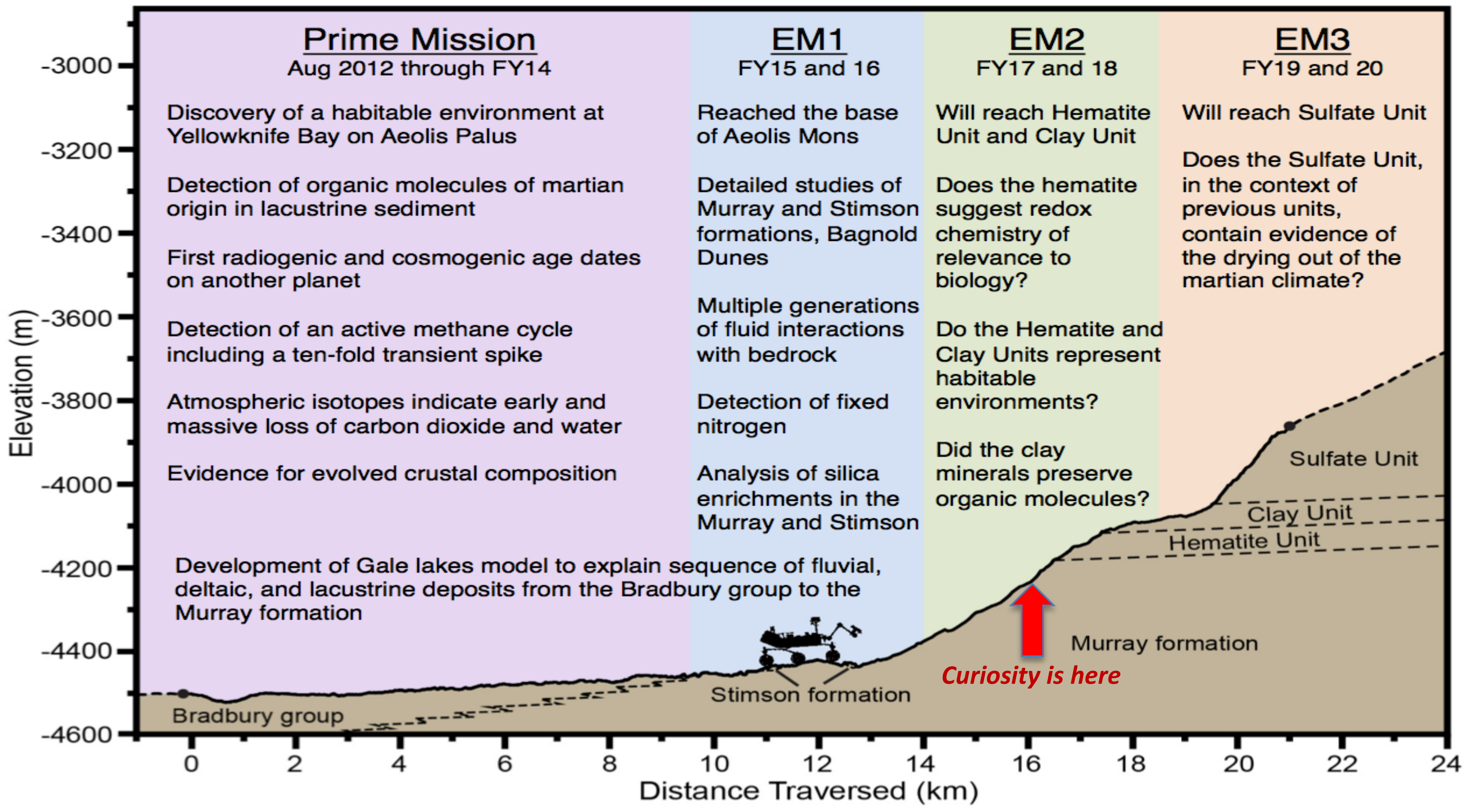
- MER-B (*Opportunity*); 13 years and 44 kilometers of roving
  - Continuing to characterize Noachian-age environments in Endeavour Crater
    - Will drive down Perseverance Valley (an ancient gulley-like feature) to determine if it formed via debris flow or fluvial processes
    - Characterization of rocks during transit into the crater will provide cross section of crater rim and its sedimentary strata
      - Also provides ground truth for orbital measurements (by ODY THEMIS, MRO CRISM and MEX OMEGA)
  - Risks to long life being mitigated
    - Solar power still adequate thanks to episodic dust removal by winds
      - MRO MARCI monitors regional weather and provides dust storm alerts
    - Successful work-arounds for overnight memory loss
      - e.g., additional MRO passes during winter when rover cannot stay up for an ODY pass

Status of Landed Missions: MSL (*Curiosity*)

- Continuing to characterize environments in Gale Crater
  - Diverse habitable environments with fluctuating water activity
  - Investigated active dunes, revealing new phenomena
  - Exiting Murray Formation and approaching higher elevation hematite, clay and sulfate strata (see diagram)
    - Murray Formation has revealed a complex and evolving environment
    - Contains clays & hematite minerals more widespread than detected from orbit
- Risk to long-lived science objectives being mitigated
  - RTG power will enable full science capability for the current and following two-year extended missions
    - Subsequent power limitations will still permit significant science activity, but mobility will be increasingly limited
  - Present difficulties with the drill are being explored. This remains a challenge for the team.
    - Samples can be scooped for CHEMIN & SAM (will be done as drill is being investigated)
    - Other instruments are expected to continue with current capabilities: MastCam, ChemCam, APXS, REMS (not winds), MAHLI, DAN

MARS

MSL: Next 4 Years



DEVELOPMENT MISSIONS

InSight – A Discovery Mission

Interior Exploration using Seismic Investigations, Geodesy and Heat Transport – Objective is to understand the evolutionary formation of rocky planets by investigating the interior structure and processes of Mars. Also, the dynamics of Martian tectonic activity and meteorite impacts

- Seismic Experiment for Interior Structure (SEIS), and
- Heat Flow and Physical Properties Package (HP^3),
- Rotation and Interior Structure Experiment (RISE)

- On pace to launch in 2018 and arrive November 2018
- MEP orbital assets will be prepared to support EDL & relay

MARS

Mars 2020 Mission Overview

LAUNCH

- Atlas V 541 vehicle
- Launch Readiness Date: July 2020
- Launch window: July/August 2020

CRUISE/APPROACH

- ~7 month cruise
- Arrive Feb 2021

ENTRY, DESCENT & LANDING

- MSL EDL system + Range Trigger and Terrain Relative Navigation, guided entry and powered descent/Sky Crane
- 16 x 14 km landing ellipse
- Three sites under assessment
  - Jezero Crater
  - NE Syrtis
  - Columbia Hills
- Curiosity-class Rover

SURFACE MISSION

- 20 km traverse distance capability
- Enhanced surface productivity/efficiency
- Qualified to 1.5 Martian year lifetime
- Seeking signs of past life
- Returnable cache of samples
- Prepare for human exploration of Mars

MARS

Mars 2020 is delivering 35% more payload by mass than MSL

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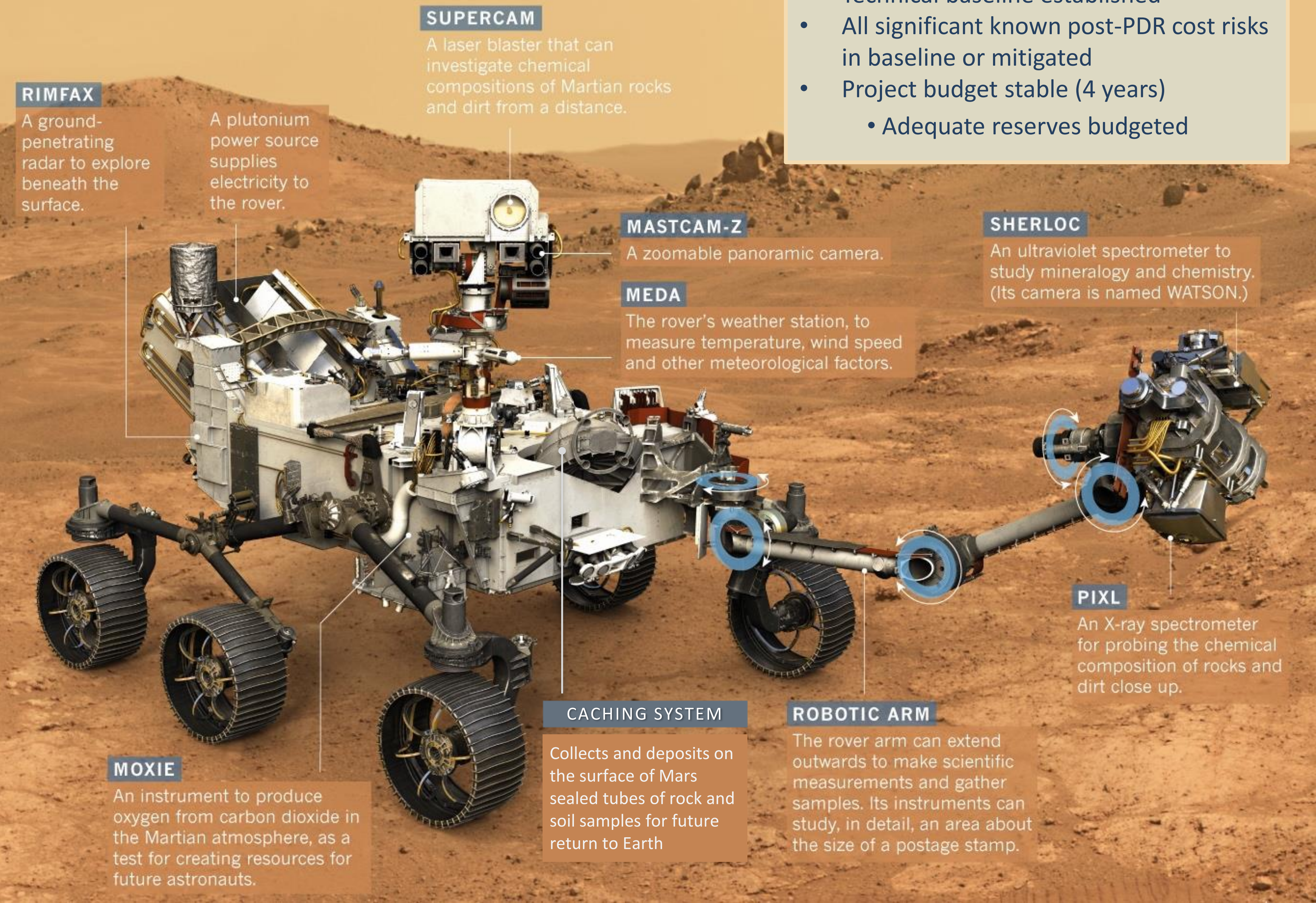
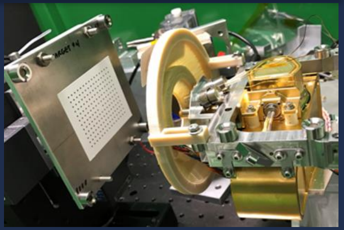
Mars 2020 Programmatic Summary

✓ Completed CDR

- Technical baseline established
- All significant known post-PDR cost risks in baseline or mitigated
- Project budget stable (4 years)
  - Adequate reserves budgeted



Mars 2020 Project Status – Key Areas



- Instruments
  - Substantial progress on all fronts
  - PIXL x-ray tube challenges resolved, awaiting test results on new configuration
  - SHERLOC Laser alignment and mirror changes in-work. Power supply corona testing underway – alternate implementation approach for electronics being pursued
- Sampling System and Actuators
  - Major contracts in place. Completed PDRs and most DDRs/CDRs
  - Return sample cleanliness budgets look good. Approach appears stable and sufficient. Added (MSL) T-zero purge for robustness.
- Parachute
  - Sounding rocket test program added. Key technical challenge and concern
  - Test definition and logistics proceeding. Anticipate ~3 tests in calendar 2017
  - Dual (heritage, strengthened) parachute flight builds underway
- Heritage Systems
  - MSL residual risks have been largely retired
  - Heritage elements beginning integration

MARS

Mars Organic Molecule Analyzer (MOMA) on the 2020 ExoMars Rover

MOMA combines two complementary techniques (GCMS, LDMS) to characterize organic compounds in drill samples

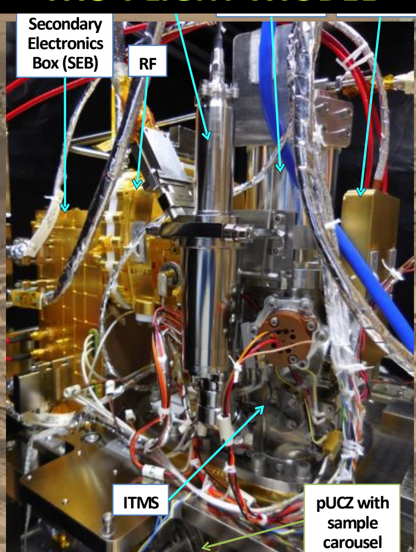
- ➢ Primary astrobiology payload
- ➢ Processes sample from 2m drill

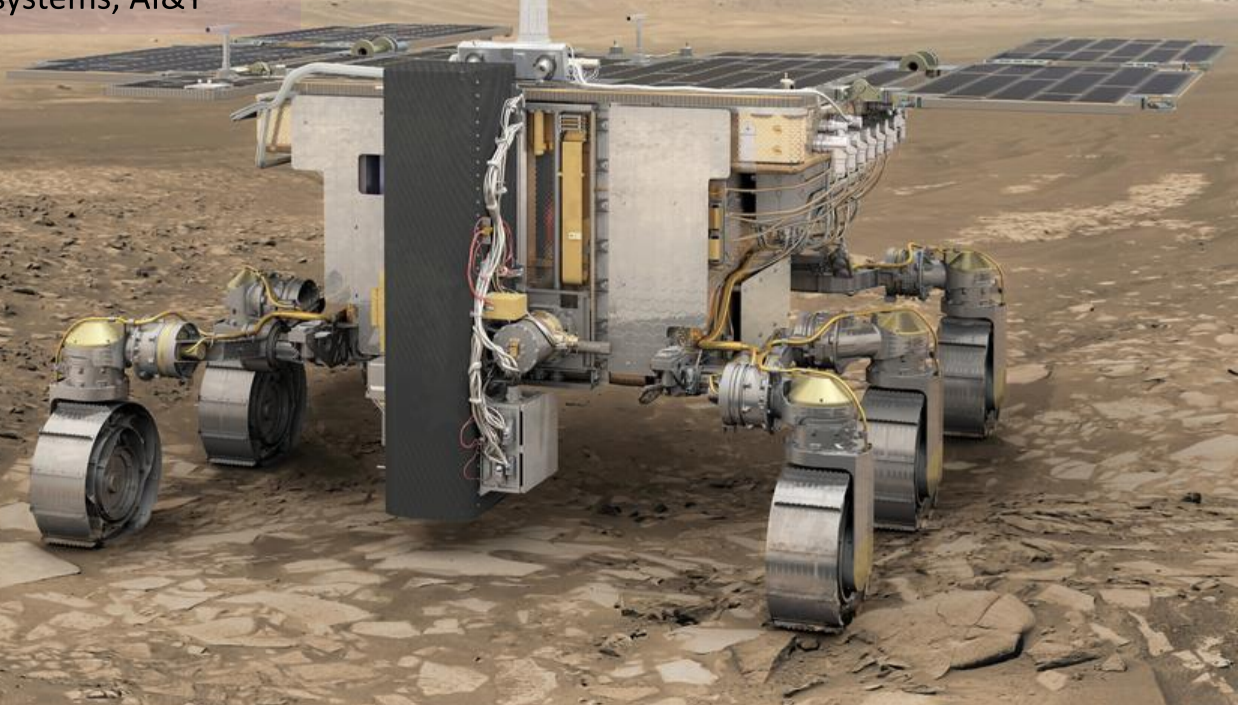
- DLR/Max Planck Institute, Germany: PI
  - Laser and Pyrolysis systems
- CNES/University of Paris, France: Co-PI
  - Gas Chromatograph (GC) system
- NASA/GSFC, USA: Project Scientist
  - Mass Spectrometer, electronics systems, AI&T

Status:

- ESA CDR complete
- MS and GCC integrated and under test with ETU laser
  - Performance/ calibration completed, meets all specs
  - 3 significant anomalies, all resolved
- Anticipate laser (late) delivery from DLR – June, 2017
- Delivery to ESA - March, 2018

MS FLIGHT MODEL

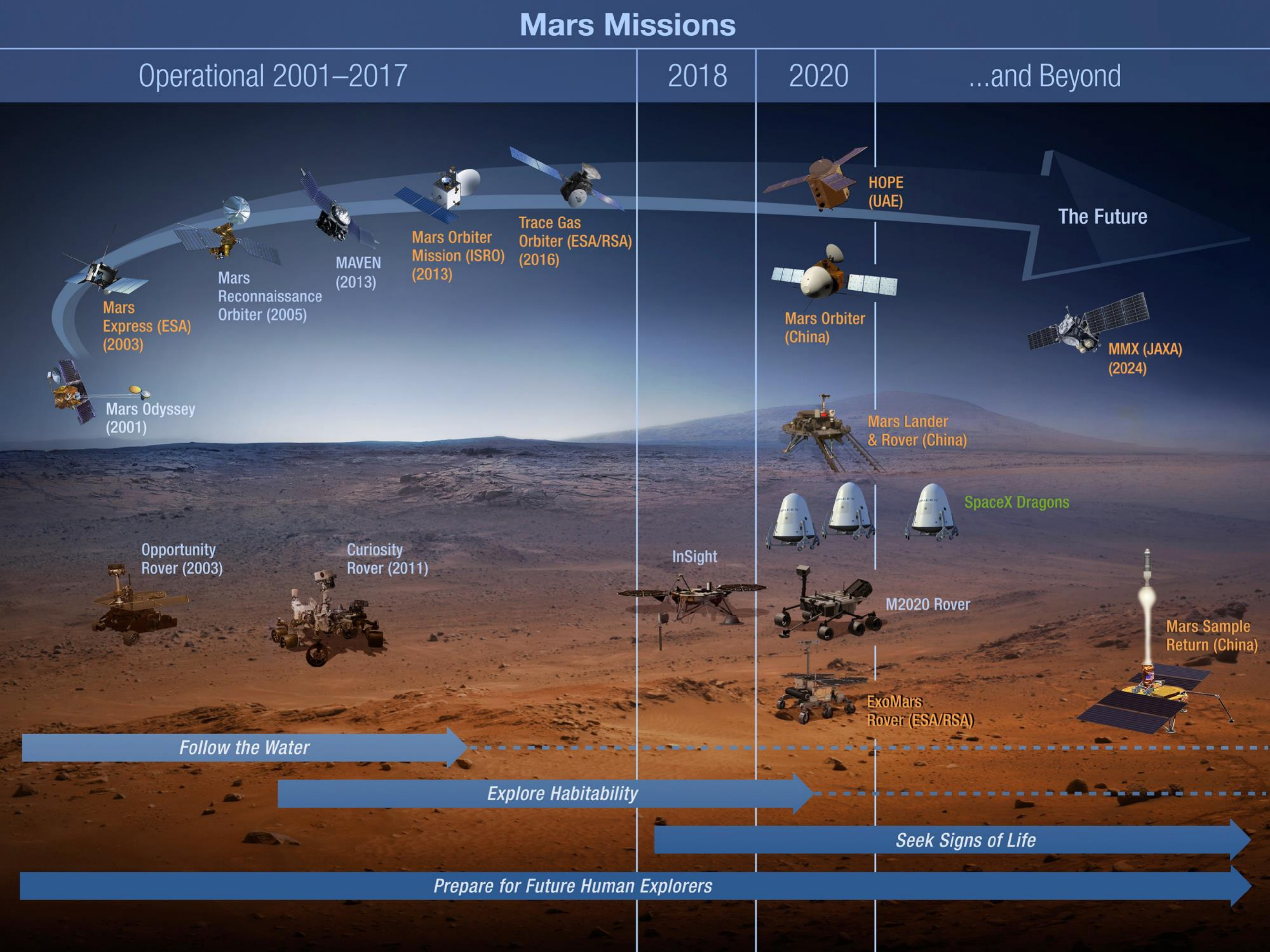




FUTURE MISSION PLANNING

The World Looks to NASA for Mars Leadership

- Essential Infrastructure – comm relay, critical operations
  - Mars Orbit Insertion (MOI)
  - Aerobraking
  - Entry, Descent & Landing (EDL)
  - Surface operations
  - Orbital conjunction surveillance
  - Enabling MSR
- Remote Sensing
  - Landing sites
  - Strategic/tactical maps
  - Resource identification
- Potential future opportunities for returning samples to Earth
- Pushing the Science Frontier Forward



Mars Missions
Operational 2001–2017
2018
2020
...and Beyond
Mars Odyssey (2001)
Mars Express (ESA) (2003)
Mars Reconnaissance Orbiter (2005)
MAVEN (2013)
Mars Orbiter Mission (ISRO) (2013)
Trace Gas Orbiter (ESA/RSA) (2016)
HOPE (UAE)
The Future
Mars Orbiter (China)
MMX (JAXA) (2024)
Mars Lander & Rover (China)
SpaceX Dragons
Opportunity Rover (2003)
Curiosity Rover (2011)
InSight
M2020 Rover
Mars Sample Return (China)
ExoMars Rover (ESA/RSA)
Follow the Water
Explore Habitability
Seek Signs of Life
Prepare for Future Human Explorers

Mars 2021 Arrival Season: Loading Analysis

- Multiple missions are planned for launch to Mars in the 2020 Mars launch opportunity, potentially creating deep space and relay telecommunications support challenges during the 2021 arrival period

- In addition, a number of other missions may be in continuing operations at this time

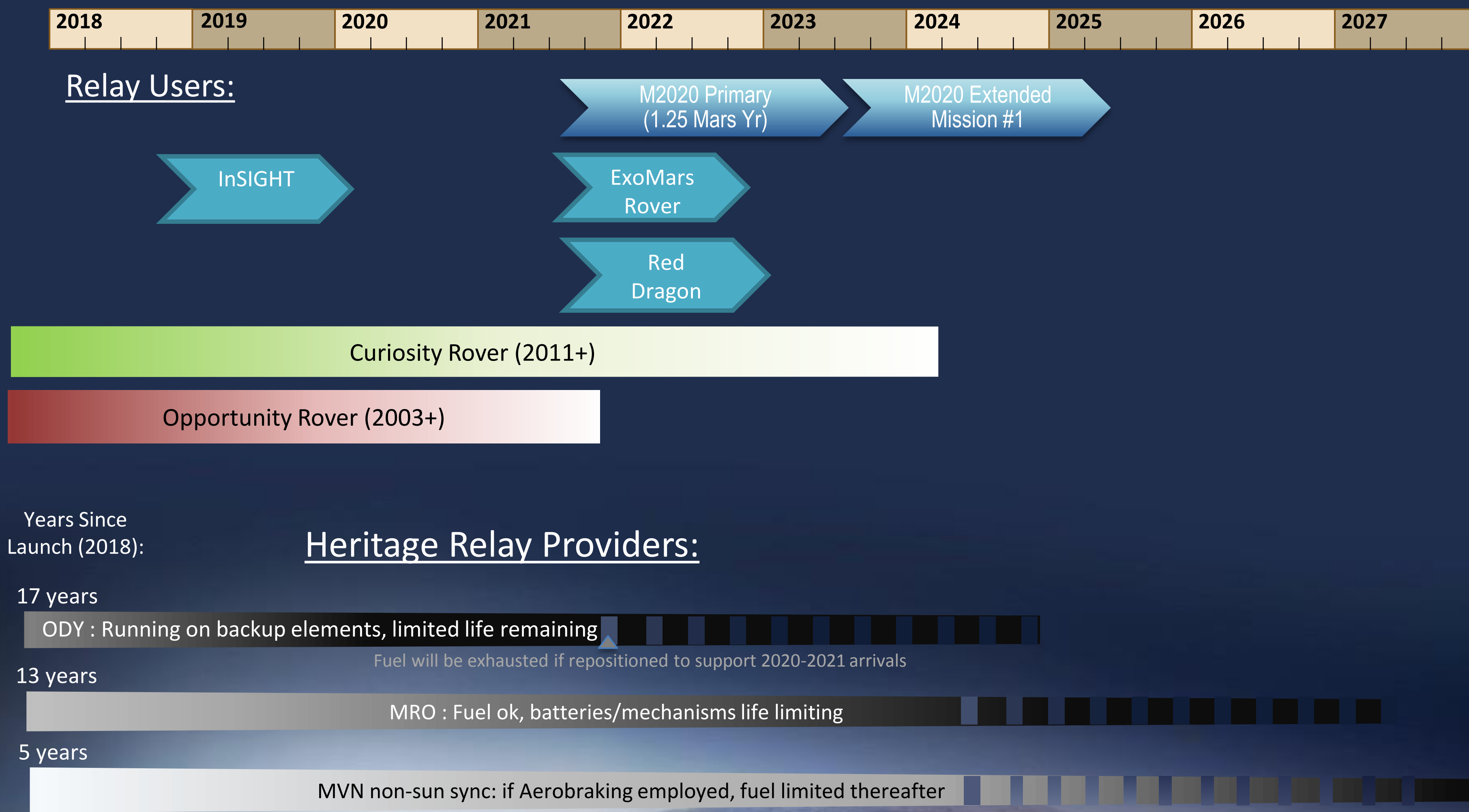
Arriving Missions:
- NASA Mars 2020 Rover
- ESA ExoMars/Rover and Surface Platform (RSP)
- Space X Red Dragon Lander(s)
- UAE Emirates Mars Mission (Hope Orbiter)
- China NSSC 2020 Mars Mission (Orbiter, Lander/Rover)

Potential Continuing Missions:
- ODY, MEX, MER, MRO, MSL, MAVEN, InSight

- MEP is working with DSN to study of deep space communications loading
  - Particular emphasis on final approach, and initial surface and/or post-MOI phases with periods of high tracking requests and potential need for anomaly response

- MEP is independently assessing Mars Relay Network loading in this period
  - Very difficult to meet EDL coverage requirements for M2020, ExoMars/RSP, and 1-2 Red Dragon landings over a 1-2 month period
  - Surface relay support will also be challenging, given number of potential simultaneous surface users
  - Assessing contingency scenarios corresponding to loss of one or more relay orbiters

MEP Infrastructure



NASA Recognizes the Importance of Mars Sample Return expressed by the Decadal Survey

Return of scientifically selected samples from Mars to address key objectives across the field on Planetary Science has been and remains the highest scientifically endorsed priority by both of last two decadal surveys

- *“Because of its potential to address essential questions regarding planetary habitability and life, Mars sample return has been a primary goal for Mars exploration for many years. It directly addresses all three of the crosscutting themes …, and it is central to the committee's Planetary Habitability theme “ (Chapter 9)*

- *“The highest priority Flagship mission for the decade 2013-2022 is MAX-C [now, Mars 2020], which will begin the…Mars Sample Return campaign ... "(Chapter 9)*

- *“MAX-C [now, Mars 2020] is the critical first element of Mars sample return and should be viewed primarily in the context of sample return,”... (Chapter 6)*

- *“The [Decadal Survey] committee has therefore taken the unusual step of recommending a plan for the coming decade that also has significant budget implications for one or even two decades beyond. The committee does this intentionally and explicitly, with the realization that important multi-decade efforts like Mars Sample Return can only come about if such recommendations are made and followed”... (Chapter 9)*

MARS

Mars Sample Return – Why?

"The greatest advance in understanding Mars, from both an astrobiology and a more general scientific perspective, will come about from laboratory studies conducted on samples of Mars returned to Earth." *

- Manipulation
  - Sorting
  - Complex sample preparation
  - Sequence sample measurements
- Iteration
  - Not limited by prior hypotheses
  - Can adapt protocol to meet circumstances
  - Can revisit at a later time (new ideas, new instrumentation)
- Sophistication
  - State-of-the-Art instrumentation – Sensitivity, accuracy, & precision
  - Diversity—results could be confirmed by alternate methods
  - Instruments not limited by mass, power, V, T, reliability, etc.
  - Calibration, positive and negative controls
  - Future instrument developments

MARS

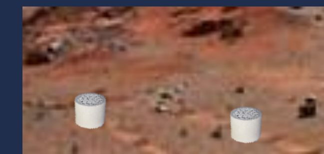
An Astrobiology Strategy for the Exploration of Mars, NRC, 2007

Mars Sample Return

as discussed in Visions & Voyages 2011 Decadal Survey

Sample Caching Rover

Launch from Earth/Land on Mars → Select Samples → Acquire/Cache Samples



Sample Canisters On Mars Surface

"Highest-priority flagship mission"

Mars Sample Return Lander

Retrieve/Package Samples on Mars → Launch Samples to Mars Orbit

Orbiting Sample in Mars Orbit

"Important to make significant technology investments"

Mars Sample Return Orbiter

Capture and Isolate Sample Container → Return to Earth → Land on Earth

Orbiting Sample on Earth

Sample Handling Facility

Retrieve/Quarantine and Preserve Samples on Earth → Assess Hazards → Sample Science

Sample Science

MARS

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Mars Sample Return Affordability

- Perceived cost & cost risk are significant impediments
- Affordability challenges are well understood
  - Robust comm & recon
    - Both mission operability & critical events
    - Orbit flexibility
  - Minimal fetch traverse
    - Enables fixed lander and simplified conops
    - Requires improved landing accuracy
  - Ascent propulsion tolerant of extreme Martian cold
    - Allow for a solar power solution
  - Secure sample containment – break the chain, BSL-4 Curation facility
    - Important planetary protection functions
- Credible partners have expressed interest in participation

Architecture and early tech maturation can reduce risk and cost for MSR

Future Orbiter Studies

- Found the utility of the existing MSR infrastructure to meet new program objectives, based on the Decadal Survey high-priority objectives and new discoveries, throughout the 2020's to be inadequate

- Exploring approaches that lower cost and risk, and provide mission flexibility
  - Conducted Industry studies in 2016 which indicate multiple viable commercial providers available
  - Assessed Safe Sample Containment Technologies for Return Planetary Protection
  - Evaluated Solar Electric Propulsion and associated new trajectory design approaches (including round-trip planning)
  - Worked with MEPAG to identify remote sensing and teaming strategies via NEX-SAG and MIC-SAG activities

MARS

Minimizing Fetch Traverse

- Precision landing
  - Terrain Relative Navigation (flying on Mars 2020) provides precision navigation "fix" during descent
  - Precision landing for future missions can be achieved by simply adding more fuel, and "flying out" any remaining errors

- Versatile fetch technologies
  - Fast rover – focus on speed vs. exploration, returning to previously visited site
    - Power is the limiting resource
  - Exploring the feasibility of using future versions of Mars helicopter for sample retrieval
    - Time of flight (battery capacity) is the limiting resource
    - For longer distances (e.g. extended mission sites) may trade well against longer rover traverses

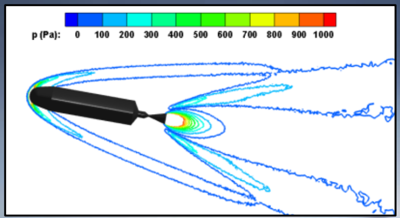
MARS

Ascent Propulsion Tolerance to Extreme Martian Cold

- Historical studies focused solid propellant motors, which require significant heating power to remain within allowable thermal limits
- MAV Motor Technology Maturation for Paraffin-based Hybrid Propulsion emerging as strong candidate technology
  - Enables colder storage temperature and lower survival heater power required from lander
  - Enables simpler single-stage-to-orbit (compared with 2-stage solid)
  - Hot-fire testing of flight-scale motors will validate propulsion technology

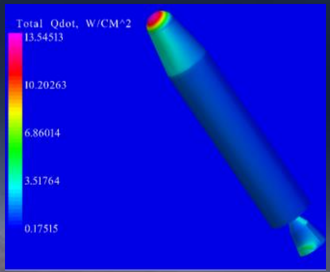

Sub-scale test firings in 2015/2016

Testing auto-restart additives



Aero forces & torques

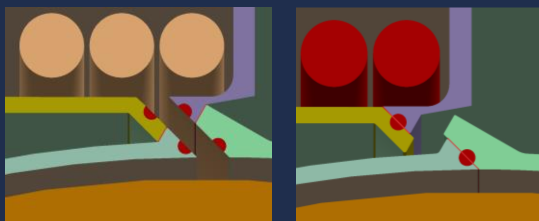
Paraffin Motor “Grain” Casting



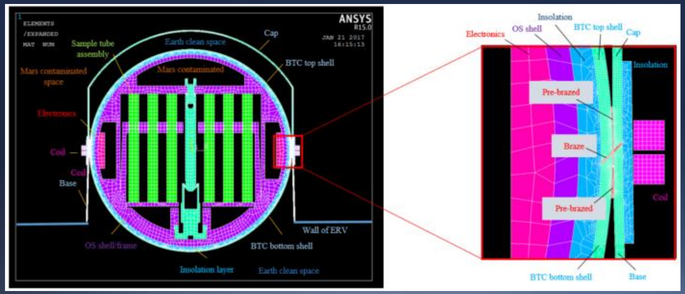
Aero-heating / TPS sizing

Secure Sample Containment

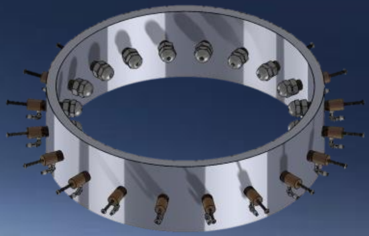
Broad range of alternatives, including ongoing work sponsored by ESA



Sealing via in-flight brazing
(Simultaneous heat sterilization)



Protection of Samples from Heat / Shock During Sealing Operations



Plasma Sterilization Ring Concept

Impact testing for Sample and Seal Integrity

MSR - Progress since *Vision & Voyages 2011*

In Development

Mars 2020

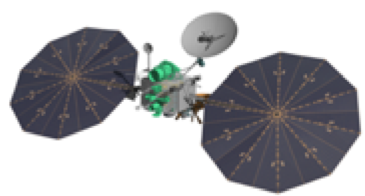
- Breakthrough *In Situ* Science
- Affordable inheritance from MSL
- Select & Acquire Samples
- International participation

Current Mars 2020 Budget: ~$2.1B Decadal CATE cost for Caching Mission: $3.5B, with $2.4B GOAL

Studies & Tech Maturation for Earth Return

Orbiter

- Comm/recon Infrastructure
- Sample Rendezvous
- Sample Containment
- Support return to Earth



Cost estimates for current concepts below estimates developed for Decadal CATE ($2.1B including ~$0.5B for Terrestrial Handling Facility)

Sample Retrieval/Launch into Mars orbit

- Fetch samples
- Support MAV
- Launch samples from Mars surface to 500km orbit

Cost estimates for current concepts remain below Decadal CATE estimate of $4.0B
– Risk reduction investments ongoing

MARS

Planning for Follow-on Meeting in July

- Mars Exploration Program Future Mission Planning and Preparation
  - MEP architecture
    - Studies and results
  - MSR technology challenges and approaches
  - MSR cost assessments
  - International collaboration opportunities
  - Industry capabilities
  - Other initiatives, ground and flight

MARS

Summary

- Ongoing rover and orbiter missions continue to produce valuable and exciting science, although many missions are showing signs of aging
- Mars 2020 development continuing on schedule for planned launch date
- MEP continues to fund mission studies and make technology investments consistent with the last Decadal Survey guidance for potential future missions
  - Emphasis has been on looking for ways to decrease cost and technical risk
  - Exploring opportunities to leverage commercial and other partnerships
  - Recent investments are improving confidence in affordability and risk control
- Mars is evolving to an international focus with many credible opportunities for collaboration
- Follow-on projects for Mars missions, including to retrieve and return samples, have not yet been authorized