National Aeronautics and
Space Administration

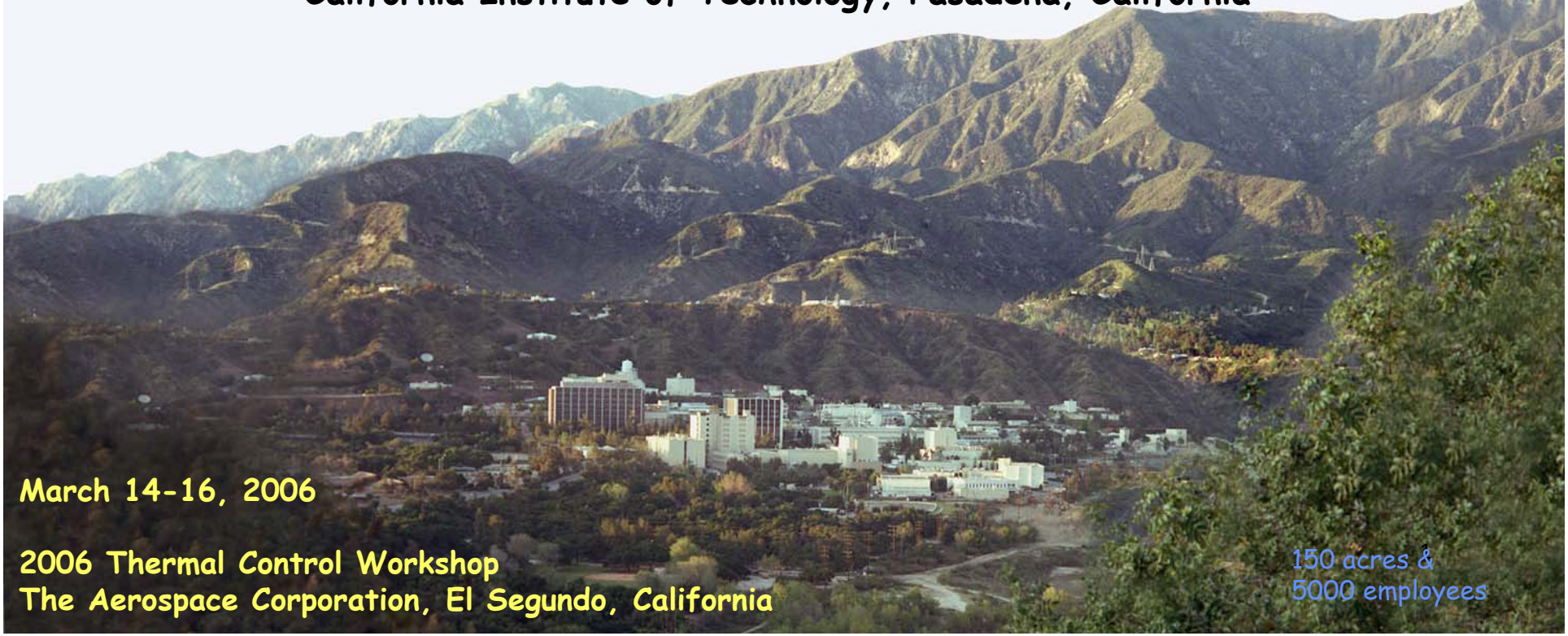
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Advanced Thermal Control Technology Roadmap - 2006

Gaj Birur

Jet Propulsion Laboratory

California Institute of Technology, Pasadena, California



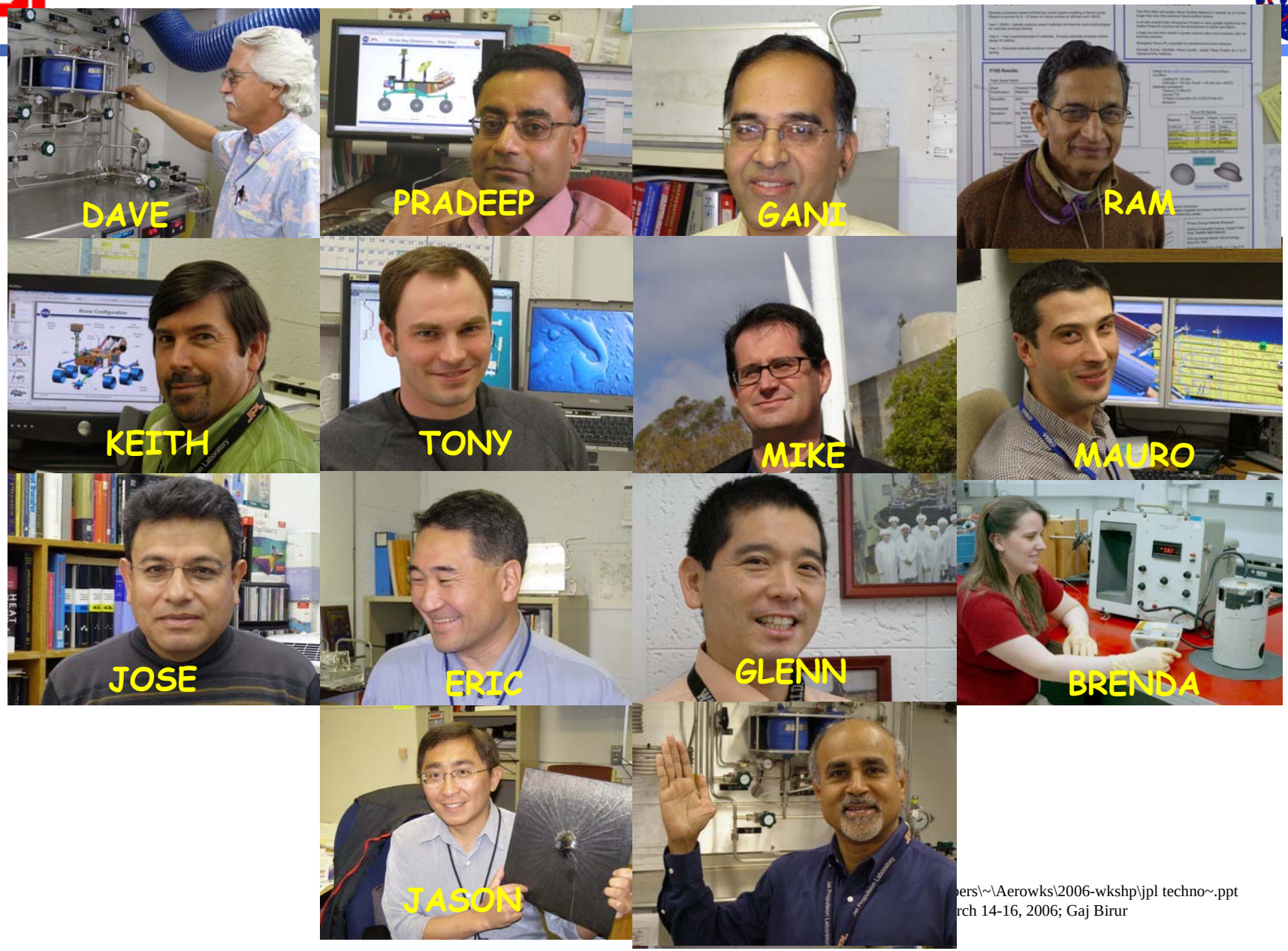
March 14-16, 2006

2006 Thermal Control Workshop
The Aerospace Corporation, El Segundo, California

JPL Advanced Thermal Technology Team

- **Dave Bame** — MER & MSL Pumped Fluid Loops
- **Pradeep Bhandari** — Pumped Fluid Loops Design
- **Gaj Birur** — Advanced Thermal Control Technologies
- **Gani Ganapathi** — MER Heat Rejection System
- **Ram Manvi** — Venus Thermal Control Technologies
- **Keith Novak** — MER Loop Heat Pipe and Heat Switch
- **Tony Paris** — High Temp. Fluid Loops; Micro-cooling tech.
- **Mike Pauken** — LHP; Venus/Titan Thermal Technologies
- **Mauro Prina** — High Temperature Pumped Loops
- **Jose Rodriguez** — TES Loop Heat Pipe
- **Eric Sunada** — MER Heat Switch; Thermal Stability Techs.
- **Glenn Tsuyuki** — MER Pumped Loop; Mars Lightweight Insul.
- **Brenda Watkins** — Lightweight Radiator Development
- **Jason Yeh** — Lightweight Radiator

JPL Advanced Thermal Technology Team



OUTLINE

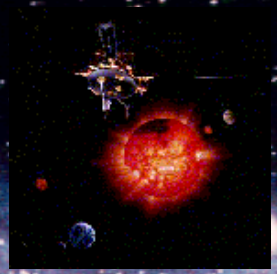
- NASA/JPL Robotic Space Science Missions
- JPL Thermal Control Technology Roadmap
- Specific Technologies Under Development
- Conclusions

JPL Missions Under Development 2006-2013

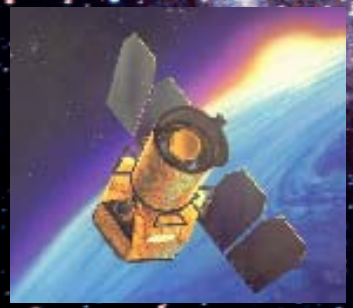
- *Dawn:* ***August 06***
- *Phoenix:* ***Aug 07***
- *Kepler:* ***October 07***
- *Ocean Surface Topography Mission:* ***08***
- *Orbiting Carbon Observatory:****08***
- *Wide-field Infrared Survey Explorer (WISE):* ***09***
- *Aquarius:* ***09***
- *Mars Science Laboratory:* ***09***
- *Nuclear Spectroscopic Telescope Array (NuSTAR):* ***09***
- *ST8:* ***09***
- *Hydros:* ***10***
- *Juno:* ***10***
- *Space Interferometer Mission (SIM):* ***12***
- *Major instruments (AMT, Herschel, Planck, LISA, MIRI, Lunar Spectrometer)*

18 Spacecraft and 5 Instruments in Flight Across the Solar System.

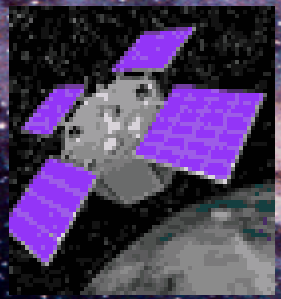
Spitzer studying stars and galaxies in the infrared



Cassini studying Saturn

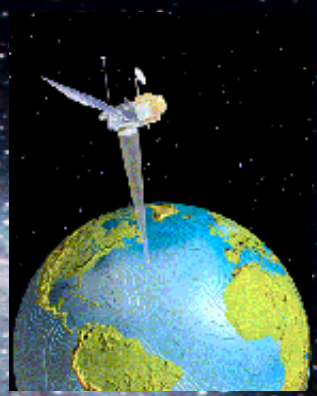


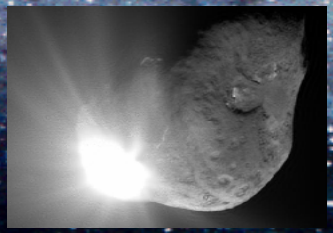
GALEX surveying galaxies in the ultraviolet



Ulysses and ACRIMSAT studying the sun

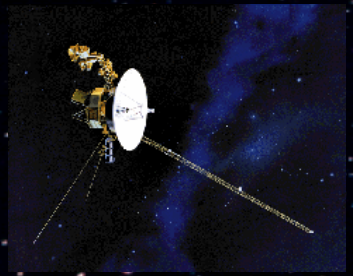
Stardust returning comet dust



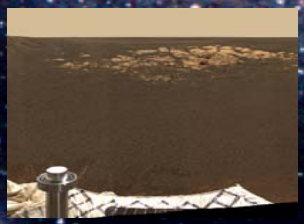


Deep Impact hitting comet Tempel 1

TOPEX/Poseidon, Quickscat, Jason 1, and GRACE (plus ASTER, MISR, AIRS, MLS and TES instruments) monitoring Earth.



Two Voyagers on an interstellar mission



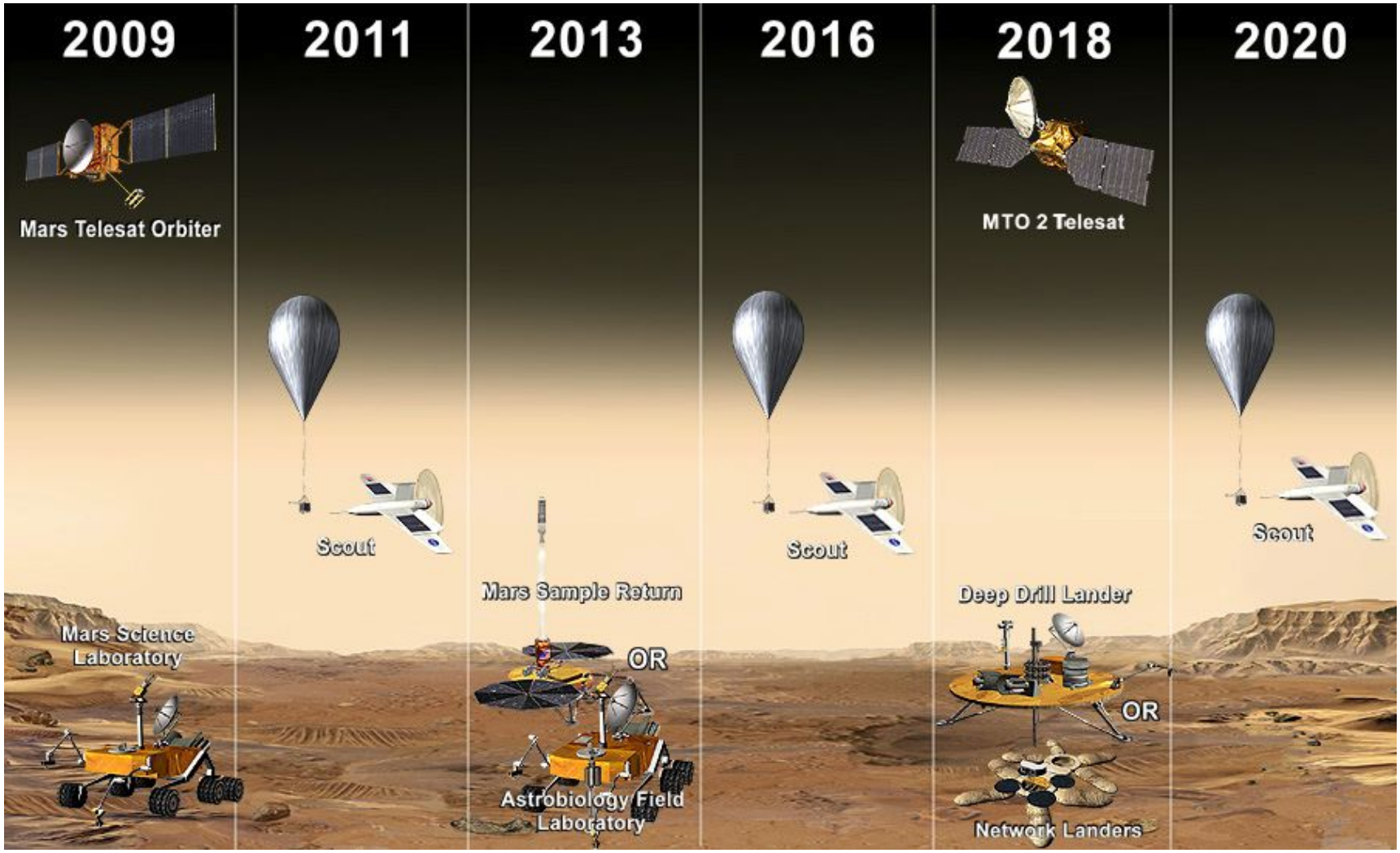
Mars Global Surveyor and Mars Odyssey in orbit around Mars. “Spirit” and “Opportunity” in extended missions. MRO in cruise to Mars.

Thermal Control Challenges for Future Space Missions

- **Thermal control requirements of many of the future NASA space science missions are expected to be very demanding**
- **Mars and Lunar Surface Missions**
  - Extreme diurnal thermal environment (-129 C to 40 C for Mars and -180 to +120 C for Lunar surface)
  - Thermal management of Radio-isotope Power Sources (RPS)
  - Rover mobility challenges to thermal control (configuration, dust etc)
- **Deep Space Science Missions** (Missions to other Planets)
  - Extreme environment: -180 C to 460 C and pressures up 100 bar (Venus, Jupiter, Titan)
  - Venus Surface Sample Mission, Jupiter Multiprobe,
- **Other Space Missions -**
  - Extreme temperature stability requirement for telescopes (Space Interferometer Missions) and science instruments
  - Inflatable/deployable spacecraft requiring flexible thermal hardware
  - High heat flux removal from electronics and science instruments

Mars Exploration Program (2004)

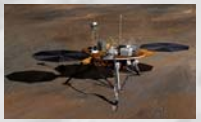
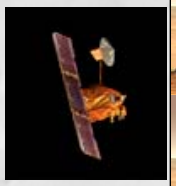
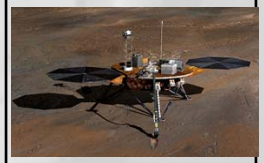
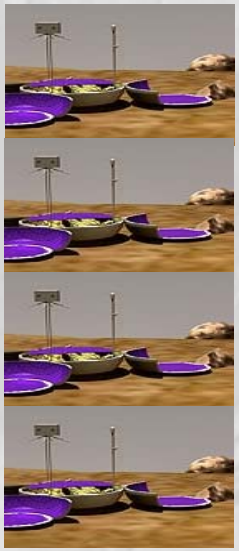
Launch Year



Draft Mars Exploration Architecture

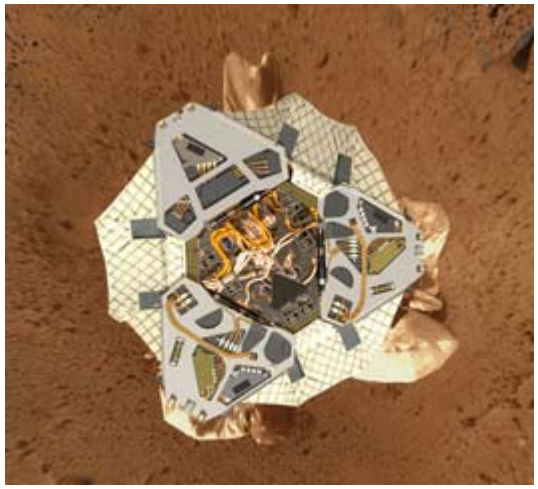
(Under consideration, not approved)

2009 - 2024

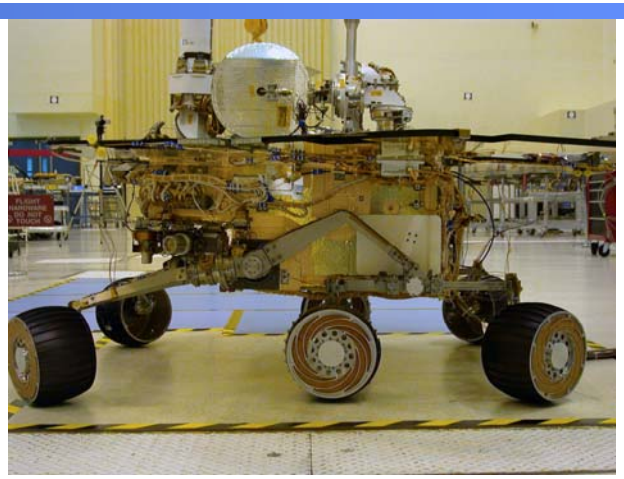
2009	2011 / 2013	2016	2018	2020	2022	2024
Mars Science Laboratory (MSL)	Scout or Mars Science Orbiter with Telecom   OR	Midrovers or Astrobiology Field Laboratory (AFL) OR	Scout 	Planetary Evolution And Meteorology Network 	Mars Sample Return (MSR) Orbiter and Return Capsule	Mars Sample Return (MSR) Mobile

Mars Exploration Rovers (2003)

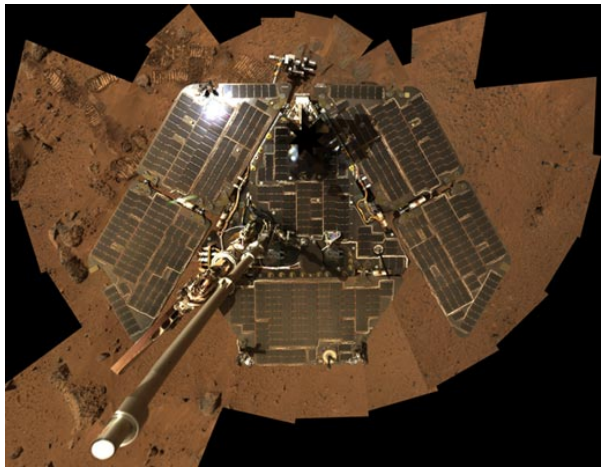
- 90-sol science missions
- Equatorial landing sites
- Deep temp. swings (- 90 to 10 C)



Lander after the Egress of
Spirit Rover at Gusev Crater (sol 19)



MER Rover (2003)



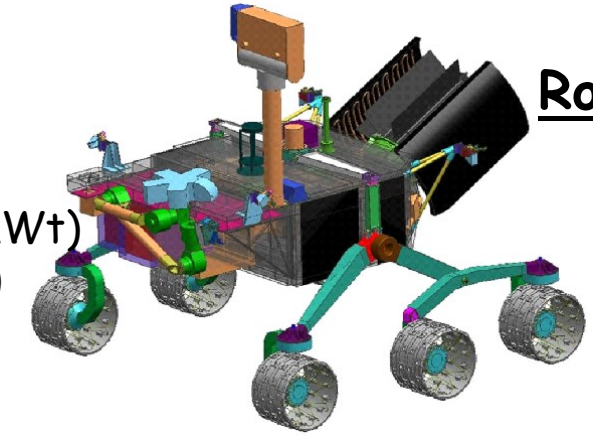
Spirit Rover self portrait
(Two Earth years later)

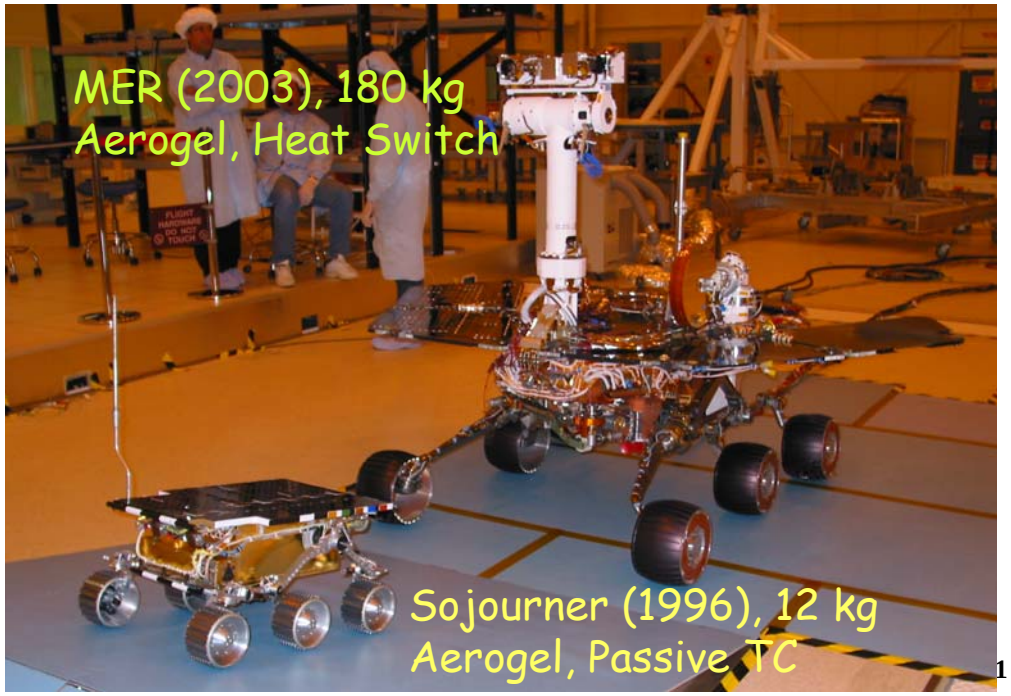
Mars Rovers – Past, Present, and Future

MSL (2009), ~ 500 kg
Pumped Fluid Loops

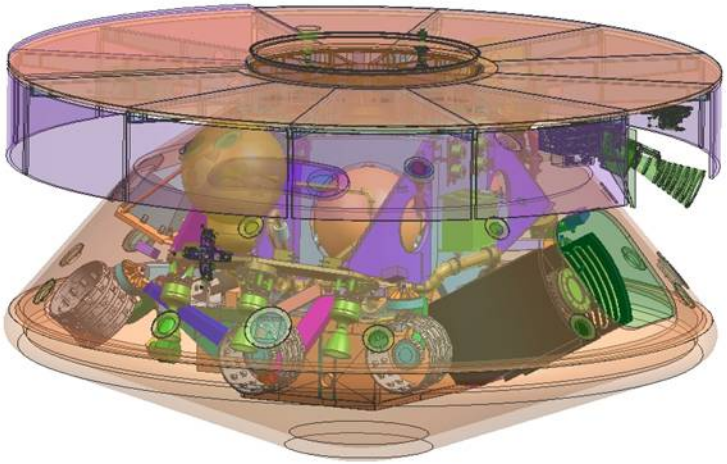
Issues:
- Large Thermal Loads (~2 kWt)
- Lang Life (~2 Earth Years)

Rover



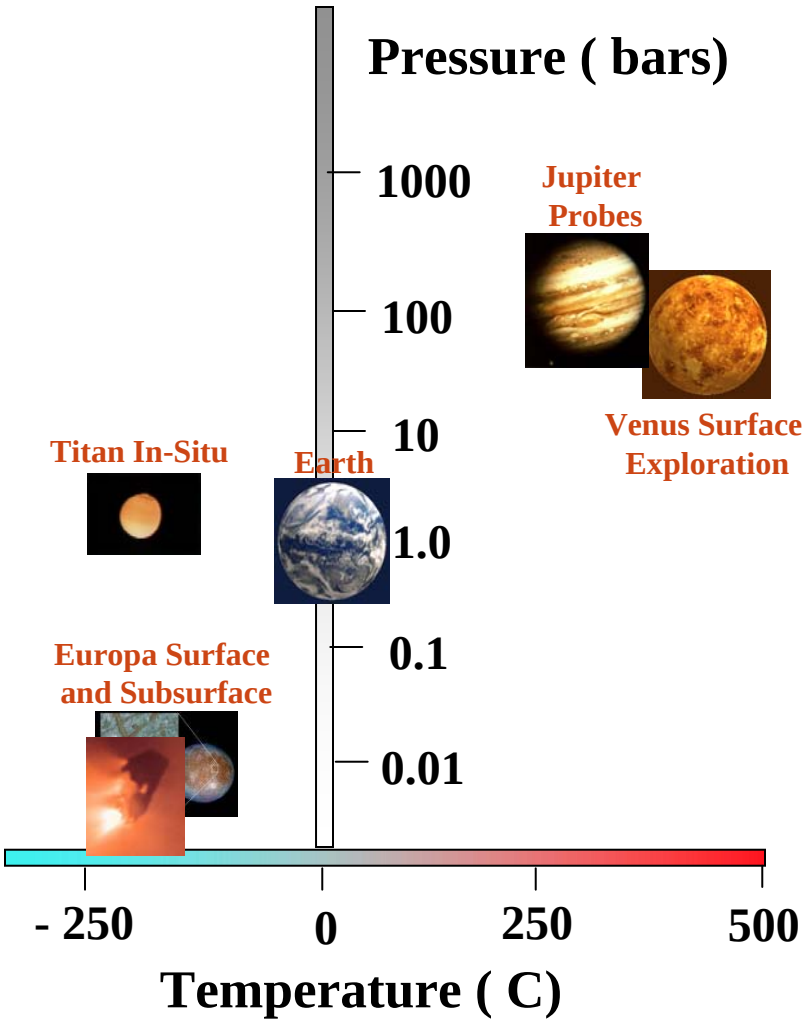


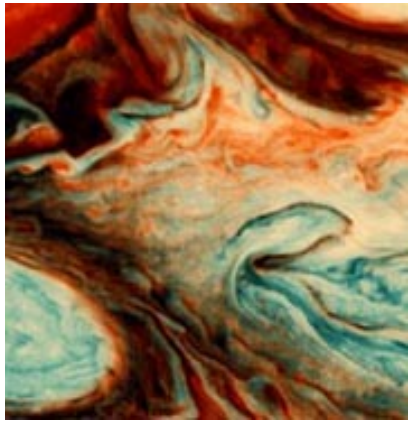
Spacecraft

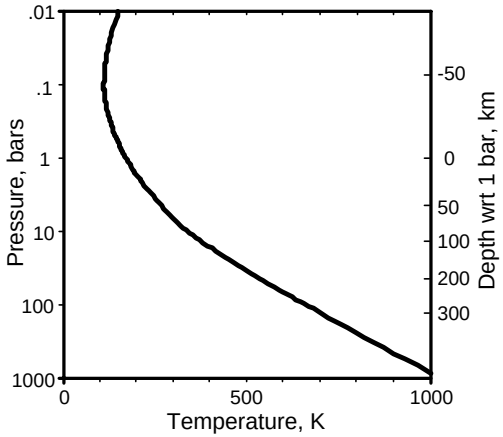


Pre-decisional DRAFT- for Planning & Discussion Purposes Only

Planetary Extreme Environment



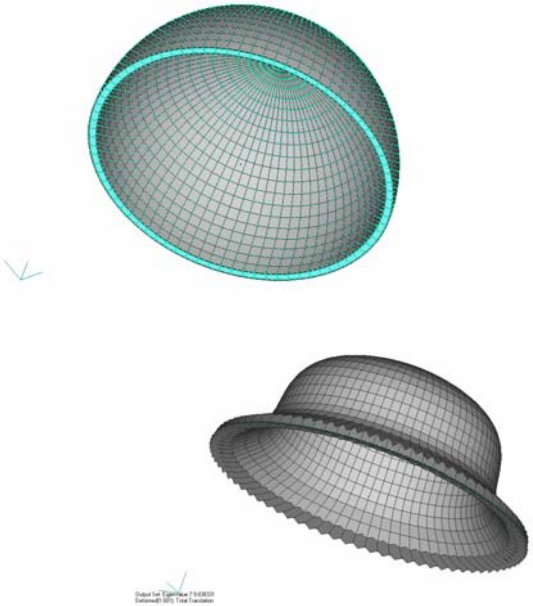




Venus Lander Thermal & Structural Technologies

- Develop a pressure vessel and thermal control system enabling a Venus Lander Mission to survive for 8 - 10 hours on Venus surface at 100 bars and ~500ºC

- Thermal technologies needed are
  - High temperature Insulation
  - Phase Change Material thermal storage
  - Active thermal control (heat pump)

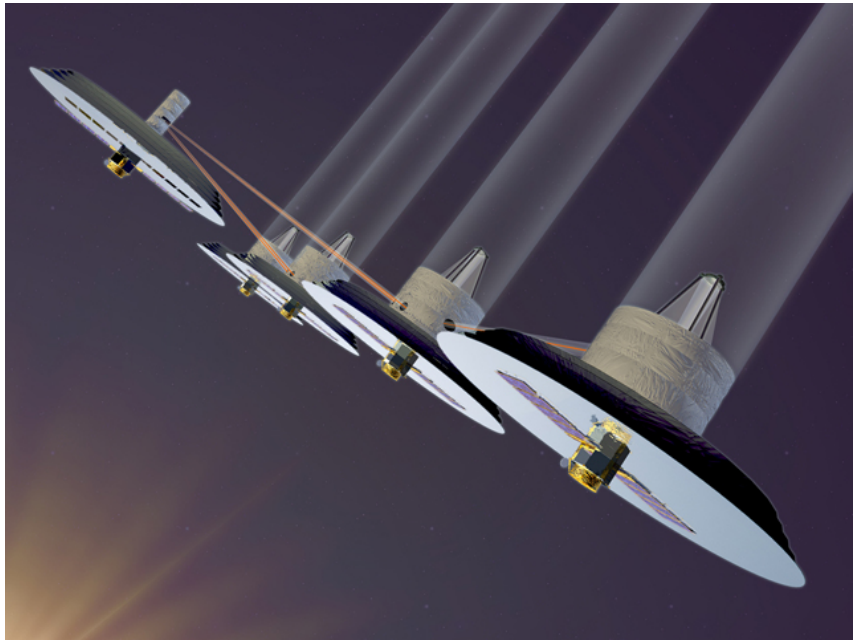


Titan In-Situ and Comet Environment

Thermal technologies needed to protect the science and engineering equipment to survive and operate in Titan/Comets low temperature (- 180 to - 140 C) environment:

Space Interferometer Missions

- Space Interferometer Missions and future space telescope missions need picometer accuracy and 100 micro-Kelvin/min stability



Infrared Interferometer based on formation flying telescopes

Space Interferometer Mission based on single large aperture

NASA Exploration Program – the Moon, Mars & Beyond

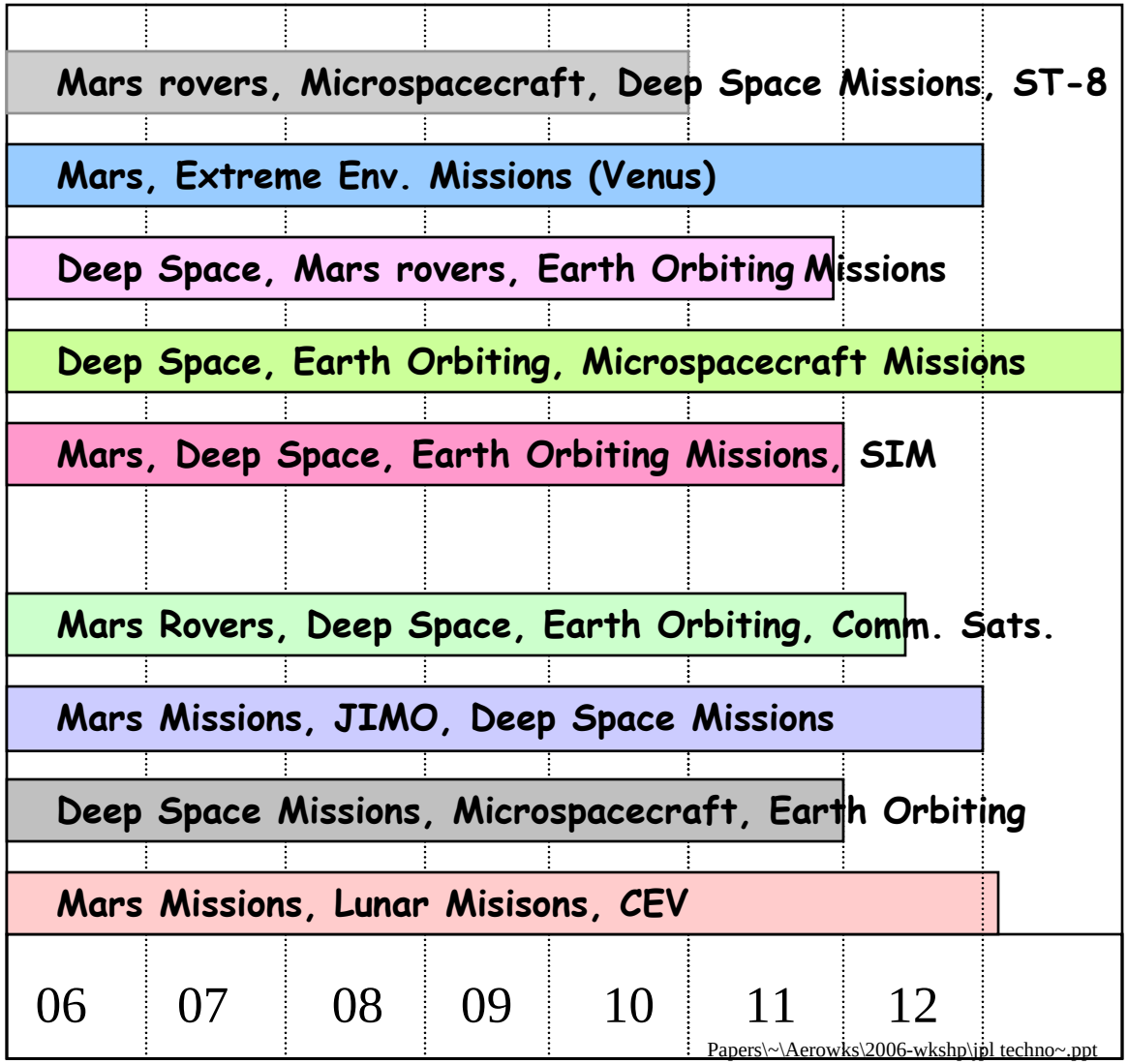
Thermal Control Challenges

- Thermal control of the Crew Exploration Vehicle (CM and SM)
- Thermal control of the Lunar lander, robotic vehicles, habitation modules
- Challenging lunar thermal environment (large 14-day diurnal temperature swings, dust, extreme cold/hot environment)
- Thermal management of large thermal loads (both equipment and human)
- Passive and active thermal control technologies needed for heat collection, rejection and transport

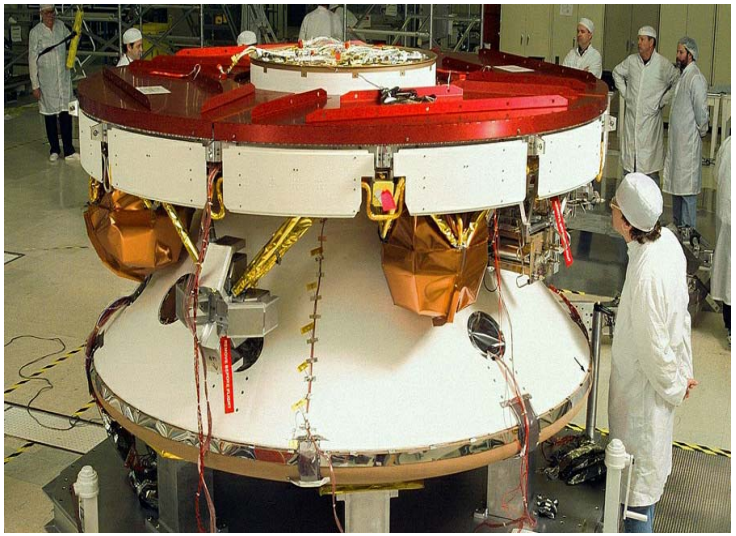
Thermal Control Technologies for Exploration

- **Thermal Control System Development for Exploration**
  (PI: David Westheimer, NASA/JSC,
  Co-I's: NASA/GRC, JPL, GSFC)
  - Vapor Compression Heat pump
  - Lightweight Radiator
  - Multi-environment Evaporative Heat Sinks
  - Contaminant insensitive sublimator
  - TCS fluid for pumped loop

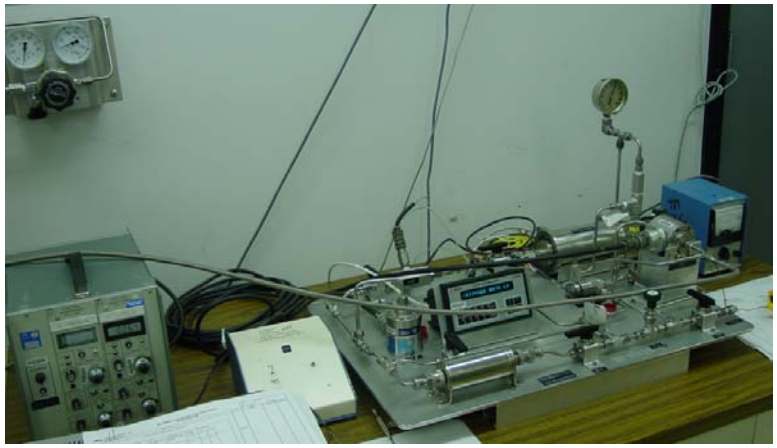
JPL Thermal Control Technology Roadmap



Mechanically Pumped Cooling Loops



Mars Pathfinder MPL HRS (1996)



MER Pump Life Test (2003)

Description

- Mechanically pumped single-phase cooling loop used on Mars Pathfinder (1996) and MER (2003) for thermal control
- A pump assembly of 7 kg uses CFC-11 to remove ~160 W from spacecraft electronics to an external radiator
- A high temperature (~100 C) pump test loop is used for life testing pumps for high heat rejection capacity (>3 KW_t)

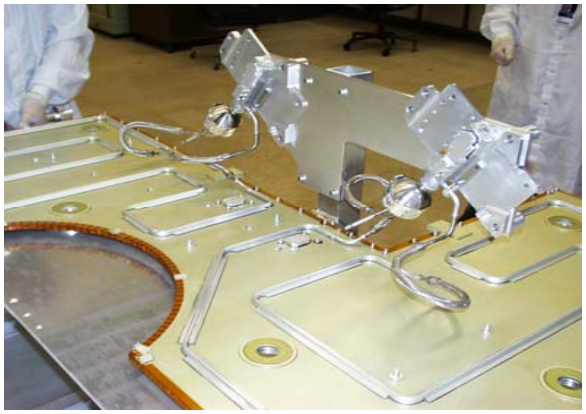
Participants & Facilities

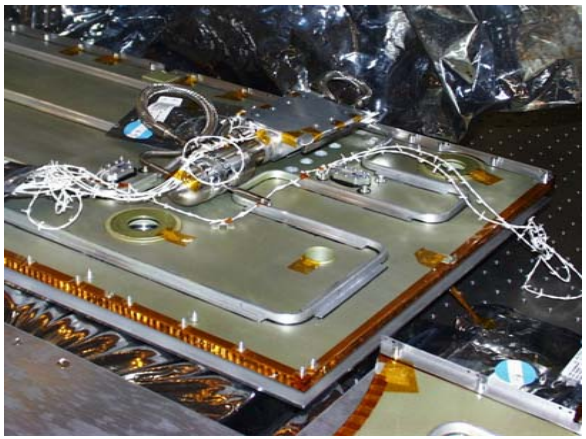
- JPL is investigating this technology for future Mars and deep space missions
- Engineering pump units (Pacific Design Technology, Goleta, CA) are under life test at JPL

Pumped Fluid Loop System Life Tests

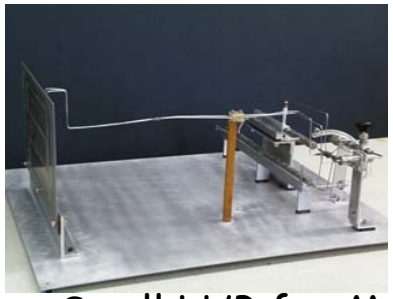
- Designed to maintain pump and fluid at 120 C with a system pressure ~ 200 psia (1 MPa)
- Life tested for 2900 hrs at 120 C with water and 3000 hours in CFC-11 at 90 C
- Chemical compatibility tests for underway for evaluation of long-term degradation of fluids and material

Loop Heat Pipe Development

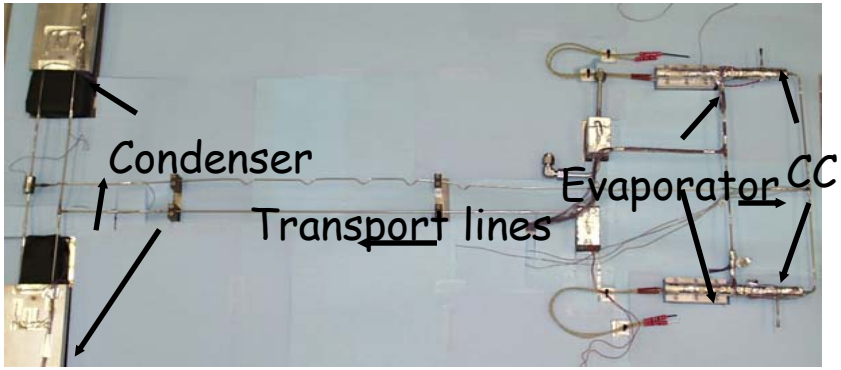




- **EOS-TES is using five Propylene LHPs in the 75 to 150 W range in its thermal design (Jose Rodriguez)**



Small LHP for Mars Thermal Control

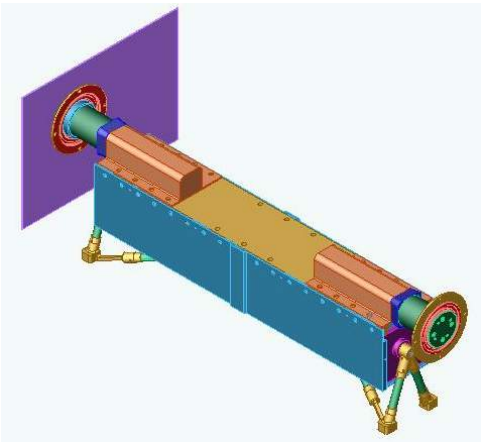


Dual Evaporator Small LHP

- Small loop heat pipe investigated and qualified for Mars Exploration Rover mission (MER, 2003)
- ST-8 investigating dual-evaporator LHP space experiment (Jentung Ku)

Heat Switch for Space & Mars Surface Applications

MER
Wax Actuated
Heat Switch
(Starsys,
Boulder, CO)



Description

- Wax actuated heat switch for Mars with target performance of 0.4 W/C, switch ratio of 30 in 8 torr CO_2, weighing less than 120 gms. Currently functioning well on the two MER rovers

Participants & Facilities

- Wax actuated heat switch for MER was built by Starsys of Boulder, CO
- The heat switches have been operating satisfactorily for over 700 sols on Mars on two rovers

PCM Thermal Storage Technology

Dodecane PCM Thermal Storage Unit

Hexadecane PCM Thermal Storage

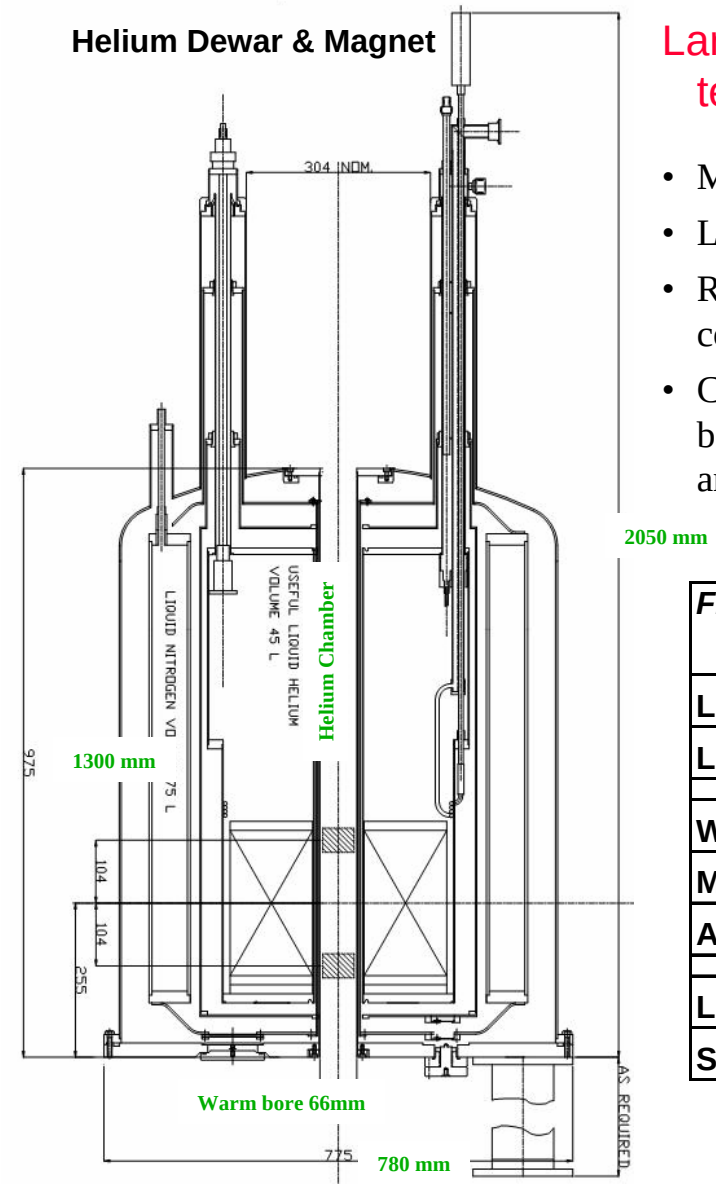
Description

- Phase Change Material (PCM) used for increasing the equipment thermal capacity for thermal control during transient situations (batteries on rover, Venus lander etc)
  - Dodecane (Melting point of 10.5 C)
  - Hexadecane (Melring point of 18 C)
  - Lithium Nitrate
  - Barium Hydroxide

Participants & Facilities

- ESLI has built Dodecane and Hexadecane PCM thermal storage units for Mars Technology program
- XC Associates has built thermal storage unit for Venus Lander Technology

Variable Gravity Testbed at JPL



Large-Bore Superconducting Gradient Magnet with 66 mm room temperature access:

- Maximum B(dB/dz) > 14.5 T^2/cm, capable of levitating water
- Levitation region: 35 mm dia x 30 mm long
- Run in persistent mode – Long steady-state duration (months) and low operation cost (10 liter of liquid helium per day).
- Can be used to study (and/or test) convection-driven heat/mass transfer, pool boiling, heat pipes, two-phase cooling loops, etc. in zero-gravity, hyper-gravity, and planetary gravities.

A list of fluids that can be levitated:

Fluids	*Formula*	*Susceptibility (E6 cm^3/mol)*	*Molar Weight*	*B(dB/dz) (T^2/cm) For Levitation*
Liquid Oxygen	O2	7699	32.0	0.041
Liquid Hydrogen	H2	-5.44	2.0	3.60
Water	H2O	-13	18.0	13.57
Methane	CH4	-17.4	16.0	9.01
Ammonia	NH3	-18	17.0	9.26
Lithium	Li	14.2	6.9	4.76
Sodium	Na	16	22.3	13.66

Contact Information: Yuanming Liu (818-354-5998) or Donald Strayer (818 354-1698)
Thermal and Cryogenic Section, JPL

Advanced pumps & cold plates for two-phase cooling loops (NASA SBIR Phase II Project)

DESCRIPTION:

- Compact, lightweight reliable two-phase pumped loop
- Compact hermetic pump design using direct electromagnetic drive of the impeller
- Positive displacement pump tolerates 2-phase flow at inlet
- Advanced offset strip fin design for cold plate
- Suitable for high heat fluxes or long distances between heat source and radiator
- Useful for distributed sources and sinks on a single loop
- Suitable for loads from <10 W to > 2kW

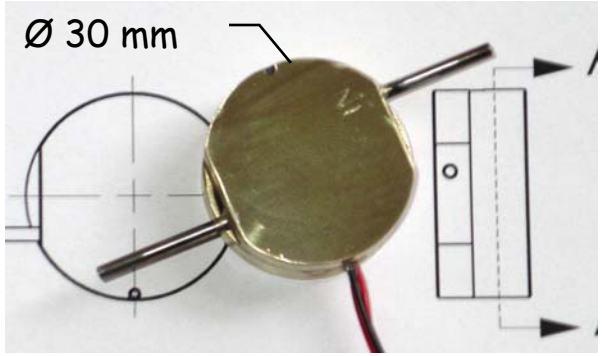
Participants & Facilities

PI: Dr. Jerry Martin
Mesoscopic Devices, LLC, Broomfield, CO

- Joe Marsala, Thermal Form & Function, LLC, MA

Project Duration: Dec. 2005 to Nov. 2007

NASA Technical Monitor: Eric Sunada, JPL



Hermetic pump prototype

- **SCHEDULE and MILESTONES**
- Phase I goal: Demonstrate ~500 W pumped cooling loop (July 2005)
- Phase II goal:

Applications:

- High density micro/nano-spacecraft electronics. High power electronics – JIMO. Laser Diode Arrays for Earth Science Missions
- Rack-mount server computers, power electronics, microwave systems, phased array radar

Hybrid Cooling Loop Technology

(NASA SBIR Phase II Project)

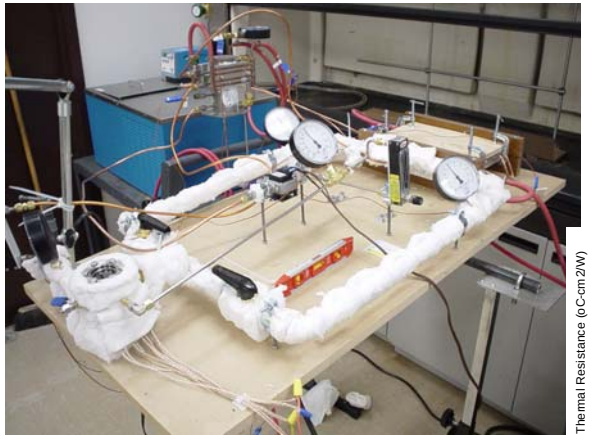
- **DESCRIPTION:**
- Combining robust liquid supply of mechanically pumps with passive flow control of capillary structures
- High heat flux removal: 350 W/cm^2 demonstrated in Phase I
- Cooling of large area: 4cm^2 demonstrated in Phase I
- Low thermal resistance: 0.008 to 0.065°C/W/cm^2 demonstrated in Phase I
- Passive flow control: No active control is needed even at transient and asymmetric heating conditions
- Phase II to test prototypes for space applications

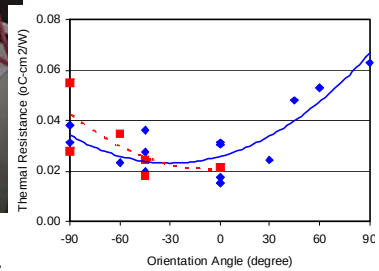
Participants & Facilities

PI: Dr. Jon Zuo
Advanced Cooling Technologies, Inc., Lancaster,PA *www.1-ACT.com*

•Johns Hopkins University Applied Physics Laboratory (miniature adaptive liquid nozzle development)

NASA COTR: Dr. Anthony Paris, JPL





SCHEDULE and MILESTONES

- Year 1 – Develop integral evaporator/reservoir assembly.
- Year 2 – Design, fabricate and test engineering units for spacecraft thermal control applications.

Applications

- Substitute for capillary- and mechanically pumped loops for better performance, greater reliability and more robust operation for satellites and exploration systems thermal control.
- Dual use: Military and commercial high power electronics and opto-electronics.

3D Aluminum Nitride Thermal Packaging

(NASA SBIR Phase II Project)

DECSRIPTION:

- Ceramic substrate with embedded Microchannel Heat Exchanger for high heat flux electronics
- High th. conductivity Al nitride (AlN, 200 W/mK) with single phase, mechanically pumped systems
- Ceramic Stereolithography fabrication – enables monolithic microchannel substrates, automation
- CFD modeling to optimize channel geometry
- Two Application Targets:include Low heat flux (25 W/cm^2): chip cooling, compact package; High heat flux (100 W/cm^2): laser diode arrays

Participants & Facilities

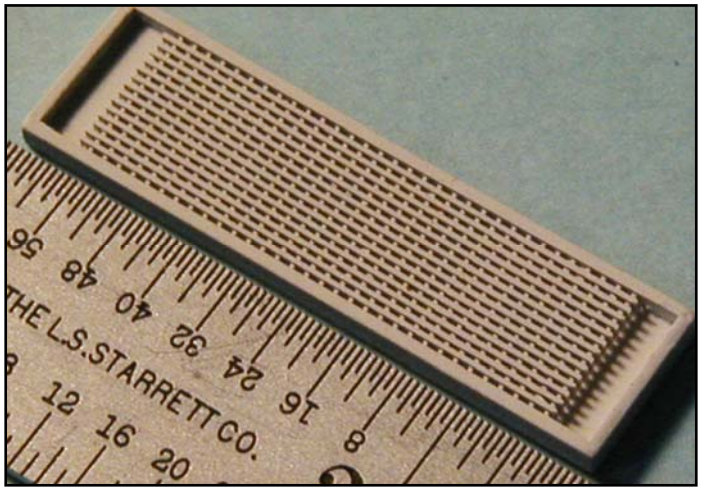
PI: Walter Zimbeck,
Technology Assessment &Transfer, Inc.
Annapolis, MD www.techassess.com

•MicroEnergy Technologies – CFD modeling (Reza Shekarriz)

•Swales Aerospace – Laser cooling system (Dave Bugby)

Project Duration: 12/03 – 12/05

NASA COTR: Dr. Anthony Paris, JPL



AlN Microchannel Structure with staggered bridges for enhanced heat transfer.

- **SCHEDULE and MILESTONES**
- Year 2 – Prototype System Fabrication/Test
  - Deliver 25 W/cm^2 chip cooling system to JPL
  - Demonstrate Laser Diode Array cooling system

- **Applications**
- High density micro/nano-spacecraft electronics. High power electronics – JIMO. Laser Diode Arrays for Earth Science Missions
- Desktop & Laptop PCs, Network servers, Power Electronics for Elec. Vehicles, Ind. Lasers

Conclusions

- Development and infusion of advanced thermal control technologies are important for the future NASA science missions

- Past successful implementation of the technologies into flight indicates a close cooperation between JPL/NASA centers and industry is the key

- Identifying key thermal technologies for the future space missions and teaming between the industry and NASA, Air Force Research Labs etc is important

BACKUP MATERIAL