Life Detection on Mars: Technical/Strategic Approach

Pamela Conrad and Wayne Zimmerman
~~NASA~~ Jet Propulsion Laboratory
California Institute of Technology
Conrad@jpl.nasa.gov

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Team In-Situ: P. Conrad- Principal Investigator
K. Nealson- Co-Investigator
W. Zimmerman- Lead Engineer, CISSR
D. Bottjer- USC
A. Chutjian- JPL
S. Douglas- JPL
F. Grunthaner- JPL
D. Hammond- USC
M. Hecht- JPL
M. Hild- CalTech
D. Kossakovski- JPL
A. Lane- JPL
D. Paige- UCLA
A. Tsapin- JPL

Introduction/Problem Statement

- **Introduction**

The search for past/extant life on Mars is a major theme of the current NASA Mars Program. The primary component of that search is to locate and sample sites which offer the strong possibility of either having provided a source of water at one time; or, offer the chance of containing water now.

- **Problem Statement**

Identify a near-term and far-term survey/sampling strategy, and accompanying suite of instruments, which offers the best chance of finding past/extant biosignatures. This strategy must be sensitive to launch windows and resource limitations.

Life Detection Background

- **Recent research (e.g., Conrad, P., Nealson, K, Astrobiology, 2001) strongly suggests that we must re-think our Earth-centric biases about what constitutes life in order to increase the probability of detecting it in other places like Mars;**
- **Spatial scales for identifying bio-signatures**

- Past/current orbiter efforts perform **global scale surveys** (100's km) looking for chemical signs of life like atmosphere/water vapor, surface water, sulfides, nitrogen, etc.or structural evidence suggesting subaqueous sedimentary deposition and/or weathering----instrument technology for remote global surveys is well established;

- In-situ mobile science labs (e.g., Pathfinder rover, MVACS, MER, cryobot) perform **macro scale surveys** (10's of m to mm) looking for water, complex carbonates, metals, carbon istotopes, etc.---instrument technology for in-situ surveys is in development now;

- **Micro-scale surveys** look at electron-microscope scale chemistry/organics (e.g., mm to nm)-- instrument technology only used in terrestrial labs;

Conclusion: Macro scale survey/instrument suites picked as focus based on:

- Likelihood of technology availability for near term Mars missions (i.e., 07-11);

- Limitations on R&D development resources for significant technology advances in micro/nano scale sampling, sample prep, and instrumentation.

Background cont'd

- **What Are We Looking For?---Defining Life in Measurable Terms**

- **Structure-** Life can be looked at as a machine which converts physical/chemical energy into products, in both useful form and waste---therefore it, must have some type of physical structure for facilitating this conversion;
- **Unique Chemistry**- Life converts nutrients into a usable energy source and discards metabolic by-products that leave traces inconsistent with the mineral phases of the surrounding environment;moreover, life is simple made of chemical components that are related to, but in different proportions than the surrounding environment
- **Energy Uptake/Conversion**- Life employs catalysts that allow it to speed up reactions with its environment in order to convert nutrients to a usable energy source and is very efficient about the ordering of that conversion process (e.g., chemically layered microbial communities are formed based on competition for energy/oxidants). Life alters the kinetics of abiological chemistry;
- **Replication**- Life will copy its structure/migrate dependant on the availability of energy/nutrient sources;
- **Evolution**- Life will replicate itself with accommodation of changes based on flaw repair and the presence of environmental stressors;

Conclusion: Life Detection focus is on structure, chemistry, and energy conversion since replication/evolution follow from these three measures and may require extensive data taking intervals (e.g., several yrs) which may represent an impractical mission timeline.

Define Mars Site Selection Criteria

- **Site Selection Drivers**

  Follow the water!

  - Pick sites where water may once have been present;
  - Pick sites where water may still be present;

- **Site Selection Criteria**
  - Sites where water may have been present would include alluvial fans and/or deep basins;
  - Sites where water may-have-been-present/still-is-present include:
    - Deep basins
    - Subsurface aquifers
    - Polar caps

Extrapolate Potential Mars Habitats Based on Earth Analogs

The most abundant and adaptable Earthly life paradigm, microbes, may also represent the most likely life form we might find on Mars;

- **Microbial life forms are best bet in search for life because:**

- They represent the bulk of Earthly biodiversity
- Here on Earth, they have proven to be **extremely robust** with respect to extreme environments such as: high-radiation, high salinity, pH extremes, nutritional depletion, extreme pressures/temps like hydrothermal vents, deep oil wells, cryptoendoliths in Antarctic or Arctic habitats, etc
- They are **very efficient in how they conserve energy** and how they seek/process nutrients—
- They **use synergism and dormancy** as means of maintaining viability in changing/variable environments;

Extrapolation to Mars

Mars represents an extreme environment which may have existed for a long period of time---microbes would have had the best chance of adapting.

Habitat Dynamics cont'd

- **Ideal Substrates Identified by Model and Confirmed by Nature**

- Water/thin liquid films
- Clays
- Silicates/sediment
- Mica

- **Limitations of Models**

- Models do not do an adequate job of explaining migration in three dimensions (i.e., substrate models suggest that once bonding sites are taken up on a surface, the process would stop---yet, in reality, species will migrate vertically);
- Models are Earth centric and do not extrapolate well to Mars environments;

Conclusion: While models are helpful in examining factors that might highlight drivers for habitat selection, in order to understand deposition/migration dynamics as observed on Earth and applied to Mars, we need to use controlled laboratory experiments which more closely resemble Mars, and refine existing models to better fit real data---if we can do this, we can begin to understand more clearly what levels of sensitivity we might require for detection.

How best to use lab tests/models:

1. **Project how sparsely a population can be distributed and still be detected;**
2. **Project how small a population can be reduced and still survive;**
3. **Weigh projected levels of instrument sensitivity against need to maybe sample at a higher frequency/greater volume (or both);**

Selection of Mars Sites

Based on what we know from empirical data, what models suggest, and our site selection criteria---most opportune sites for past/extant life are, in order of priority:

- **Polar caps** (we know there is CO_2 and H_2O) Mars N. Polar Cap is ~4km thick ice sheet w. significant stratified layering suggesting presence of dust/sediment--containing both water and substrate material;

- **Deep basins/valleys** (e.g., Barnard Crater, Unnamed Crater MOC2-258b, Coprates Chasma, Valles Marineris) where water can exist in a metastable state based on height of aquifer tables relative to the basin bottom, slightly higher pressures, favored surface geometry which allows just the right sun/shade exposure, and interstitial binding w. soil/dust)--note that these are sites also rich in known microbial preferred substrates

- **Deep aquifers** are possible but not considered a priority due to the scale of the subsurface survey required to locate them and accessibility

Conclusions: (1) Ice presents a simpler chemical system against which to detect a chemical biosignature than the chemical conditions in a mixed mineral sediment. This increases the probability of observing the biosignature, should it be present.

(2) Due to the large volume of material that must be sampled in order to have a reasonable chance of detecting life, the higher chance of finding larger volumes of water at the North Polar Cap vs. basins makes it the prime site candidate.

Selection of Science Instruments

- Must pick science instruments which will allow us to examine bio-signature structure, chemistry, and energy conversion in ice and sediment samples;
- Subset of instruments which meet above criteria include:

Potential Instrument	Science Measure Addressed
Environmental scanning electron microscope	Structure
X-ray emission/absorption	Structure
Reflectance spectroscopy	Chemistry
IR spectroscopy	Energy
GCMS	Chemistry
Laser induced breakdown spectroscopy	Chemistry
UV-visible imaging/spectroscopy	Structure/energy
RAMAN spectroscopy	Chemistry
Wet chemistry	Chemistry
Micro-electrode free oxidation potentials	Energy/structure
Total carbon	Chemistry

Conclusion: Since there is not one instrument which does all types of measurements, a triage approach will be taken using a subset of at least three instruments, ea. one addressing one science measure.

Instrument Delivery Platforms

Must Pick Instrument Delivery Platforms Which:

- Accommodate our site selections for polar cap penetration/deep basin sediment analysis;
- Must allow a **significant** sample survey/analysis to be conducted (i.e., based on what we know about the Mars environment now, it is highly unlikely that bio-signatures will be pervasive);
- Preserve pristine nature of sample as much as possible;
- Must allow both **non-invasive** and **invasive sampling**;
- Must provide capability for **large scale sample acquisition** and **macro-scale (cm-mm) sample processing** and analysis;

- **Possible Instrument Delivery Platforms**

- Cryobot (ice w. dust)
- Augering/coring/ablation (ice or sediment)
- Long range rover w. robotic arm/U-sonic corer (ice or sediment)

Description/Operation of Instrument Delivery Systems

Background

- **Surveying/Probing Ice**
  - Microbe deposition usually wind/dust driven--subsequent wind/ deposition cycles can cover colonies (D. Paige);
  - Earth terrestrial microbial habitats take the form of mat structures in areas where there is passive heating (e.g., rocks) and/or protected areas that allow pooling via conductive or solar heating (P. Conrad, K. Nealson, C, McKay);
  - Microbe deposition/layers usually found at depth or in/at the ice- water IF since nutrient source usually accumulates there (e.g., gas bubbles, trapped substrate material like dust which contains nutrient sources, salts) (H. Englehardt, F. Carsey);
- **Surveying/Probing Sediment**
  - Microbe deposition on sediment driven by availability of nutrient source on substrate--subsequent wind/deposition cycles can cover colonies (D. Hammond, D. Bottjer);
  - Penetration driven by micro-tubes/capillary action within interstitial spaces of sediment resulting in subsequent availability of moisture/ nutrient sources deep inside substrates (P. Conrad, D. Bottjer);

Description/Operation of Instrument Delivery Systems cont'd

Long Range Rover w. Survey/Sampling Capability- Surveying/Probing Deep Basins/Sediment (based on terrestrial analog developed as result of Team Insitu field trip to Death Valley, CA. under leadership of Dr. D. Bottjer, USC)

- Rover descends near/into deep basin via lander;
- Primary mobility- Mars 03 (MER) or Mars 07 class rover
- Primary sampling- Mars 98/01 class robotic arm (>/=2m's long, 4-5DOF) w. wrist pitch/roll to accommodate both ultrasonic corer and microscopic imager/scoop;
- Primary communication- UHF link to Orbiter;
- Closed loop semi-auto control/fault mgt provided by on-board control syst and vehicle state sensors;
- Rover visual/IR imager on mast looks @ stratified layers of canyon wall and/or exposed bedding planes for signs of rich mineral/metallic strata which represent possible microbial mat substrates;
- Sheltered canyon/basin floor areas that might have interstitially bound ice also examined;
- Once likely vertical wall site found, zoom lense examines bedding planes for exposed layered steps;
- Robotic arm deployed and layered steps examined w. microscopic imager on wrist;

Long Range Rover cont'd

- Microscopic imager shifted side-to-side to pick up surface relief and look for ordered microbial mat structures;
- If presence of potential biology is confirmed, rotate wrist and remove 1-3cm vertical core w. ultrasonic corer (i.e., vertical core desired in order to capture other possible chemical/structural evidence);
- Sediment examined optically and chemically by on-board science instruments for trace bio-signature elements;
- Sampling of basin floor material exhibiting frost/water done using corer to retain stratified layers of sediment/dust for initial survey--follow-up larger scale sampling of potentially rich bio-material done w. scoop;
- Survey/sampling cycle repeated over large area of basin;

Note: Similar rover based survey/sampling technique could be done on **polar cap** w. focus on looking for pooled/iced-over water in sun-cups or dust/sediment deposits with subsequent sampling of water/dust both in and around area (see SURF inflatable rover study, Aug 2000).

Instrument Development Status

Science Inst (in-situ)	Design/Concept	Lab/Prototype	Flt config
Scan elec microscope	-	X	-
X-ray u-tomography	-	X	-
Reflectance spec	-	X	-
IR spec	-	-	X
GCMS	-	X	X
LIBS	-	X	-
Vis imager/camera	-	X	X
UV spec	-	X	-
RAMAN spec	-	X	-
Wet chemistry	-	-	X
Micro-electrode oxid potential	X	-	-
Total carbon	-	X	X

Near-Term/Far-Term Life Detection Implementation Strategy

- **Weight structure, chemistry, and energy conversion equally** (i.e, per previous discussion, **absolute detection** of life rqrs positive test across all three measures, but **reasonable proof** rqrs 2 out of 3 given possibility that we may not recognize structure if we saw it);
- Examine suite of instruments and **establish likely near-term triage combinations** depending on:

- **Science measure** (i.e., >/=3 inst's, 1 for ea. measure);
- Likely **accommodation of instrument delivery platform**;
- **State of instrument** development;

- **Recommend far-term** inst **development strategy** based on;

- **Science return**;
- **State of readiness** (i.e., how far does inst have to go to meet flt constraints);
- **Performance** (i.e., higher resolution, less ambiguous data)

Far-Term Strategy

Based on possible deep basin exploration for 07/post-07 and possible post-10 polar cap exploration, following instrument suite development strongly recommended:

- Micro-electrode oxidation potential--particularly applic to ice/cryobot (excellent for structure chemistry or energy conversion measurements at sub-mm strata resolution);
- X-ray u-tomography--particularly applic to sediment/rover (excellent for invasive imaging of bio-structures in rocks at 10mic resolution);
- Scan electron microscopy--particularly applic to sediment/interstitial ice/rover (excellent for nm resolution bio-structure imaging);
- Reflectance spec--particularly applic to sediment/rover (excellent for broad band chemical signature analysis);

Note: All of above instruments rqr significant design/testing to reach a flt ready configuration (see design spec matrix, in particular, current mass, vol, and power);

Far-Term Strategy cont'd

Current instrument development strategies based on:

- Sensitivity levels tuned to Earth centric bio-signature densities/magnitudes;
- **What the technology can achieve**, **not what we actually might encounter** on Mars;

- **We must expand our experimental database to allow us to better extrapolate instrument sensitivity rqrs for Mars by (see modeling section in this report):**

- Developing controlled ice/sediment laboratory experiments w. ice/sediment micro-organisms;
- Proposed experiment template/structure:

-----Inject ice cell/quartz cell w. active micro-organism colonies;

-----Define primary stressors (temp/temp cycling, H2O deprivation, varying UV levels, CO2 rich env, dust deposition pulses);

-----Expose organisms to ea. stressor independently and observe/record changes in colony size/migration dynamics using non-invasive and mildly-invasive instrument suite (e.g., GCMS mounted over active cells in environmental chamber, micro-electrode bundle samples cell through in-contact membrane);

-----Allow colonies to move through complete life-to-death cycle and record relative instrument sensitivity performance as well as absolute detection limits (i.e., can we detect very small levels of extant life, or, no life at all?)

-----In conclusion, determine which instruments are best suited for "minimal" life detection and establish performance rqrs for other promising instruments;

-----Use empirical bio-dynamic results to fine tune habitat dynamic models and use those models to examine a broader potential range of habitat dynamics;