Microfabricated Organic Analyzer for Biosignatures (MOAB): Demonstration of a versatile, autonomous, and sensitive organic analyzer for the Enceladus Orbilander Mission

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Microfabricated Organic Analyzer for Biosignatures (MOAB) is a flight-format high TRL microfluidic sample processing and capillary electrophoresis instrument with laser-induced fluorescence detection having sub-part per billion analysis sensitivity for intact biosignature compounds in the Enceladus plume or on the surface that could be indicative of past or present life (1-3). ***MOAB***, consisting of a PDMS microfluidic processor, a glass capillary electrophoresis (μCE) wafer, and a laser-induced fluorescence (LIF) detector, was fabricated and integrated for flight testing at the University of Utah and UC Berkeley Space Sciences Lab (*Figure 1*). By integrating a modular design consisting of individual subsystems, autonomous operation including sample intake, on-chip labeling chemistry for targeted analysis, and the core analytical detection system for high sensitivity analysis of biomolecules has been demonstrated. This instrument has now been field tested in a series of ZeroG flights and this unit will be operationally demonstrated for amino acid analysis at the meeting.

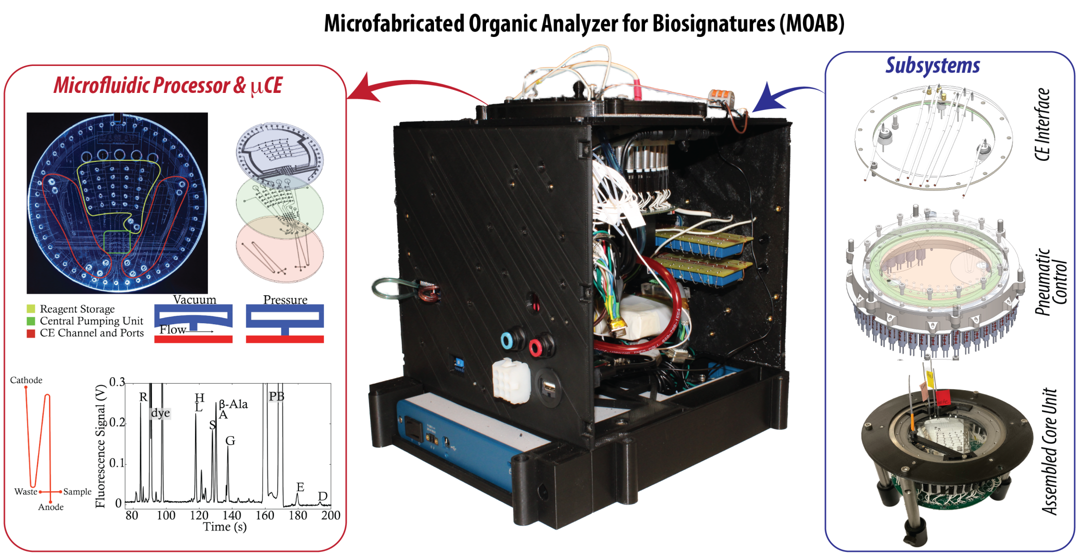

Figure 1: Flight-tested MOAB system including a PDMS microfluidic processor, a glass capillary electrophoresis (μCE) wafer, and a laser-induced fluorescence (LIF) detector along with all sensors, electronics and high voltage CE power supplies needed for stand-alone operation.

Microfluidic Processor: The microfluidic processor illustrated in Figure 1, consisting of a microvalve array and sample reservoirs, is fabricated using standard soft lithography techniques. Nanoliter fluid volumes are metered, mixed and transported through microchannels using a series of microvalve actuations by programming fluidic sequences. Detailed engineering and environmental tests have been successfully performed under harsh vibrations, longevity, and microgravity (4-7).

Micro-capillary electrophoresis: The μCE system is fabricated in multilayer glass wafers using standard microfabrication techniques and serves as the bottom layer of the microfluidic processor. μCE separates sample components into individual zones via charge-to-size ratio with high efficiency and resolution. When coupled with LIF detection, high-sensitivity analysis of targeted analytes can be realized. Prior lab and field work in the Mathies group at UC Berkeley has demonstrated the efficacy of targeting amines and amino acids (including chirality) using the Pacific Blue dye and carboxylic acids and aldehydes/ketones with Cascade Blue to achieve highly selective and sensitive detection of the respective analytes using μCE-LIF (6, 8-12).

Miniaturized Optical System for Fluorescence Detection: A miniaturized laser-induced fluorescence system has been fabricated with all necessary components including a diode laser, lenses, excitation and emission filters, and dichroic filters to achieve **high-sensitivity detection (< 100 pM) to easily meet the desired sensitivity level of 1 nM or 0.1 ppb in raw ice samples prior to sample processing.** The compact confocal design enables the sensitive transduction of fluorescence emission as each fluorescently tagged μCE zone passes through the detection volume.

The integrated MOAB was recently tested under microgravity in a series of 4 ZeroG flights to evaluate overall functionality and operation. The sample manipulation (mixing, metering, transporting microliter samples), μCE, and detection capabilities of the MOAB were unaffected by gravitational conditions, demonstrating strong linear trends under various gravitational conditions (13). ***MOAB is the first autonomous μCE analyzer that has been demonstrated and validated in microgravity.*** The microgravity demonstration of MOAB justifies its high TRL and performance for extraterrestrial chemical and biochemical analysis applications.

Figure 2: In flight view of the MOAB apparatus being operated and monitored under microgravity.

Relevance: Enceladus Orbilander Mission offers the unique opportunity to conduct in situ analyses of a habitable subsurface ocean without drilling or melting through kilometers of ice by placing a spacecraft in orbit around Enceladus or on its surface. To achieve the science goal of the Enceladus Orbilander Mission, searching for multiple features of life (or biosignatures) with repeatable measurements are required. In the Enceladus Orbilander Mission Concept, the most critical science objectives are to characterize the plume material and surface of Enceladus to define the relative abundance and diversity of organic functional groups (14).

The MOAB provides a reliable, robust, and low-mass autonomous processor with unique capabilities for plume and surface analysis that transcend legacy approaches. MOAB is currently on track to reach TRL 6 with a well-defined pathway to 7. We have also worked extensively with the JPL Europa Lander Team to develop detailed plans for spacecraft accommodation, con-ops and for integration and system testing. MOAB enables us to characterize intact organic amines, amino acids, and carboxylic acids that could provide information on habitability and/or indicate the existence of past or present life at ppb levels requiring less than 15 μL of ice grain samples from both the plume and the surface. MOAB uniquely provides sub-ppb sensitivity for the detection of intact organic molecules that are critical for mission goals. With the MOAB system, the list of tasks has been confirmed below.

1. **Detection of a wide range of organic compounds**: amino acids, carboxylic acids, aldehyde/ ketones, and lipids have been tested with high sensitivity.

2. **Autonomous operation**: Typical μCE-LIF requires multiple samples preparation procedures, including metering, labeling, transporting, and washing steps. All steps are automated using a programmable microfluidic processor unit and detailed concept of operation plans have been developed.
3. **Highly sensitive detection**: In the Enceladus Orbilander Mission Concept, the desired sensitivity is 1 nM (0.1 ppb) sensitivity level in raw ice samples with ≤ 5 % accuracy for amino acid profiling and chiral detection. MOAB can detect with 100 pM (0.01 ppb) sensitivity providing a wide margin that will help to ensure a successful mission. These sensitivity limits for intact organic molecules transcend the capabilities of typical mass spectrometer approaches.
4. **General and power specification**: 11x10.5x13.5-inch footprint for main components, 10 lbs. total weight, and 30 watts at peak to operate MOAB with high stability
5. **Low data transfer**: MOAB has extremely low data return, since estimated data per μCE are less than 1 Mb per measurement. Thus, the overall usage of Earth communication can be very minimal. Furthermore, our vetted con-ops plans do not require ground in the loop operations.

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