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A buoyant life investigating mobile platform (BLIMP)

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Abstract

The search for life in new environments, e.g., Mars/Titan, will be scientifically challenging and have great engineering difficulties. In this paper the authors discuss an approach to field-testing methods relevant to three scientific thrusts in the detection of life and pre-biotic organics on other worlds. We describe how this can be accomplished through a series of field trials using a mobile aerial vehicle that is a proxy for the exploration approaches and instrument techniques necessary for the next stage of life detection on other planets. We do this by deploying a mobile organic laboratory on Earth to demonstrate the requisite techniques. We show how terrestrial field trials provide new insights on the colonization by life of fresh volcanic flows, and the competition between biotic and abiotic processes on a newly cooling piece of the Earth's crust. This paper suggests that such work could be very effectively conducted on Hawaii, where the erupted lava is basaltic, an important crustal component for terrestrial planets. The presence of water is generally agreed to be a prerequisite for planetary habitability but the combination of basalt and water is chemically unstable at the temperatures to which basalt cools after eruption. The subsequent chemical reactions occur because the total energy of the products is lower than that of the precursor materials and on Earth biological processes result from organisms harvesting that difference in energy. For life processes to succeed they must out-compete the rate at which abiotic chemistry might accomplish the same tasks. Monitoring the rate at which chemical processes occur is therefore a life-detection approach. Biotic involvement in the rate of weathering of basalts is the test case for this new, generic life detection paradigm. This approach would be applicable to the periglacial zones of Mars, if liquid water were proven to be present there. We show that a 15 m autonomous BLIMP could carry various instrument packages including camera, visible spectrometer, tunable diode laser spectrometer (TDLS) for gas and gas isotope analysis, gas chromatograph/mass spectrometer (GCMS). These could be calibrated followed by ground-truthing using field experiments in the interior of Meteor Crater in Arizona. This well understood system could then study the extreme environment of the still active volcanic caldera of Kilauea and the adjacent older lava flows. For Mars the BLIMP is a proxy for a lighter balloon or even a Martian Rover, which could carry a similar suite of instruments and take a similar set of measurements. For Titan, with its dense and high-molecular weight atmosphere calm winds and low gravity, a BLIMP will be the vehicle of choice. The experiments would be directly relevant. We discuss how a Titan BLIMP could search for organic compounds in the post-Cassini exploration of Titan.

Keywords: Life detection; Astrobiology; Airships; Instrumentation; Mars; Titan; Volcanic caldera

1. Introduction

Exploring new objects in the solar system is always a risky business and this is especially true of the exploration of surfaces using mobile vehicles. When the high priority given to Life Detection is added to the mix the situation becomes challenging indeed. The authors

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believe that the risk inherent in such explorations can be addressed, and thereby minimized, by conducting analogous experiments on Earth first. To be truly convincing, such experiments should have scientific merit of their own and not simply be technological in nature. The authors believe a set of experiments can be conducted on Earth that will provide exciting terrestrial science and also validate the technologies needed to explore planetary surfaces.

Earth has an abundance of life, which is, in many ways, an obstacle both physically and chemically, to a search for scarce or extinct life – there is so much of it, it will get in the way. Consequently, from a science standpoint, the search should be made starting in those few areas that are known to have a very low biomass level. The most straightforward of these areas is fresh lava, where the temperatures will ensure that the initial conditions do not contain life. As the lava ages there will be chemical weathering followed by colonization by life. These changes that affect fresh new lavas are of scientific interest but have significant challenges to their access and exploration. Exploration using personnel is risky and there is much to be gained by providing access via autonomous vehicles. The physical challenges are such that a wheeled rover approach is unsuitable and the exploration vehicle of choice is an aerial vehicle. The most straightforward approach is to use a lighter than air craft that has the inherent ability to hover over areas of interest and take the necessary scientific measurements – that is a "BLIMP". In the context of planetary and solar system exploration this vehicle must be considered a proxy for unpowered balloon exploration in the thin atmosphere of Mars but BLIMP exploration is directly applicable to Titan, where the dense atmosphere and lower gravity make heavier, powered airships an obvious choice.

In our study, we addressed the science that can be accomplished, the measurements that are needed, the instruments that can make the measurements and the vehicle that would provide access to the areas of interest.

Fig. 1. Concept of BLIMP deployment over Kilauea, Hawaii.

Fig. 1 is a conceptual illustration of how the measurement system would appear, deployed above Kilauea, in Hawaii.

2. Science

2.1. Terrestrial science

We believe that the following goals are achievable for the terrestrial science component:

(1) Determination of biotic colonization of abiotic geological material.
(2) Determination of the limit of detection of life in an active volcanic caldera and the biomass in basalt at various stages of weathering.
(3) Measurement of the compositions of materials, which could be, but are not, involved in biotic processes; volcanic gases and freshly erupted lava and the related equivalents to prebiotic compounds.
(4) Determination of the rate of biotic exploitation of the chemical potential energy in newly available material by making time series observations of lavas of different ages.

Hawaii, Kilauea, offers an accessible sequence of recent and historical flows situated in a range of climatic conditions (Fig. 2), and, therefore, is well suited to experiments aimed at achieving goals 1–4. The young Kilauea lavas provide a matrix of age, rainfall, elevation, and temperature that is ideal for testing the rate and extent of biological colonization as well as the small amounts of abiotic organic products from volcanoes (Schwandner et al., 2004) that could be trapped in lava flows. Lava flows on Hawaii can be: (1) dominantly

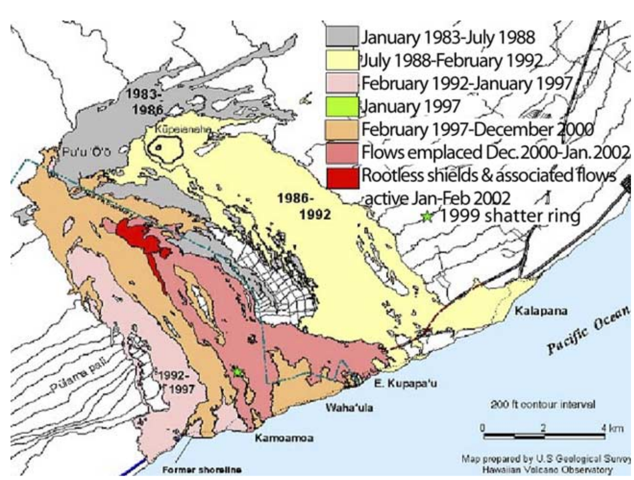

Fig. 2. Chronology of recent eruptions of Kilauea. Rainfall decreases from 250 cm/year over 1986–1992 flows to 100 cm/year over 1992–1997 flows.

abiotic due to toxic gas emissions (e.g., HF) and/or lack of moisture and high temperature, (2) covered by silica-rich inorganic rock coatings (Curtis et al., 1985; Farr and Adams, 1984), (3) colonized by microorganisms, (4) covered by lichens and other epilithic organisms (Jackson and Keller, 1970; Cochran and Berner, 1993), or (5) colonized by vascular plants (Vitousek et al., 1992; Karpa and Vitousek, 1994).

All lava flows initially are abiotic because of their high temperatures but upon cooling are substrates on which an ecological succession occurs at a rate determined by local conditions. The style and rate of the biotic succession is strongly controlled by temperature and moisture (Brady et al., 1999).

In situ measurements could determine the compositions of toxic gases, which even at these high temperatures contain small amounts of organic as well as inorganic species. Methane is detectable but also fluorinated, chlorinated and brominated hydrocarbons exist in small quantities. These may be considered as part of the suite of pre-biotic organics. Halorespirer bacteria can degrade these compounds (Holliger et al., 1993) suggesting a possible link between these compounds and microbial colonization of the surface of the rocks.

Outgassing of HF, HCl and H_2S from the hot lavas fuels the initial stages of chemical reactions that produce lava surfaces depleted in Si and O and enriched in Ca, Mg, Al, F, and Cl (White and Hochella, 1992). The surface chemistry is controlled by acid reaction with the lava minerals. This is particularly true for HF because when temperatures decrease below about 750 °C, HF reacts with Si on the lava surface transforming the gas to SiF_4 in a reaction that leaves Ca, Mg, and Al salts of F as the dominant surface coatings. These coatings persist for about a year under high rainfall (White and Hochella, 1992), but probably are stable for much longer periods in low rainfall environments. Presumably acid degassing and fluoride salts are not conducive to vascular plant or lichen colonization, but even in this environment there may be microorganisms, particularly where rainfall is high enough to afford a favorable growth environment. Microbial colonization of basalts is a widespread phenomenon in the oceans (Fisk et al., 1998; Furnes et al., 2001) and on land (Thorseth et al., 1991, 1992; Stevens and McKinley, 1995). Microbial colonization of basalt glass can be as high as 10^{10} cells per cm^2 of glass surface (Thorseth, pers. commun.). The timing of the microbial colonization of fresh basalts is not well constrained, however, the BLIMP measurements may be validated with laboratory analyses of samples collected.

The first macroscopic colonizers are epilithic organisms of which the lichen Stereocaulon volcani has been best studied (Jackson and Keller, 1970; Cochran and Berner, 1993; Brady et al., 1999). This lichen accelerates lava-weathering rates by 2–18 times over the background abiotic rates in the same temperature and rainfall zone. Whereas abiotic weathering rates vary linearly with rainfall, the lichen-mediated rates are nearly proportional to the square of rainfall. The role of lichen in enhancing weathering is ascribed to several processes: organic acid secretion along extensive hyphae and preservation of water in rock pores (Brady et al., 1999).

In moderate to high rainfall regimes, Ohia, tree ferns and other forest species colonize flows rapidly, but in arid areas the flows remain largely unvegetated for hundreds of years. Lavas of different ages in various environments allow us to make a time-series of observations which cover a greater span of time than would otherwise be possible but which allow us to explore the comparison of biotic and abiotic rates of processes more conveniently.

2.2. Mars science relevance

Current presence of water, as ice, on Mars is now established but its extent and depth are not yet well understood. The methodology of rate of change as a response to change of environmental conditions could be applied here. Three different instruments in the Gamma-Ray Spectrometer instrument suite on board the 2001 Mars Odyssey spacecraft [the Gamma Ray Sensor (GRS), the Neutron Spectrometer (NS), and the High-Energy Neutron Detector (HEND)] have provided evidence for large amounts of ice in the Mars regolith. All three instruments detect signatures most likely due to the presence of water ice in the regolith. Significantly, the signal distribution is heterogeneous with local accumulations at the south pole (as expected), but also at multiple sites nearer to the Mars equator. If these preliminary findings hold up, selective monitoring of these sites across the Martian year and search for co-existing mineral or biological signatures is of fundamental importance to Mars exploration.

Recent analysis of MOC images (Horváth et al., 2001) has shown seasonal changes in appearance of the dunes in the southern polar region (Fig. 3). Their analysis of these observations are that the dark spots which appear persistently in the same places are the first to be defrosted in spring and they believe they have detected water flows from them. They attributed these effects to the presence of biological activity, but their case is not yet proven to general satisfaction. Nevertheless, this sort of observation is susceptible to test by time-series observations in which in situ or remote (spectral) chemical observations would provide a better framework in which to interpret these effects.

Exploration of the impact of water availability on biological weathering of Hawaiian basalt and the limits of detection of these changes as proposed in this study will be directly applicable to the interpretation of the Odyssey data illustrated in Fig. 3.

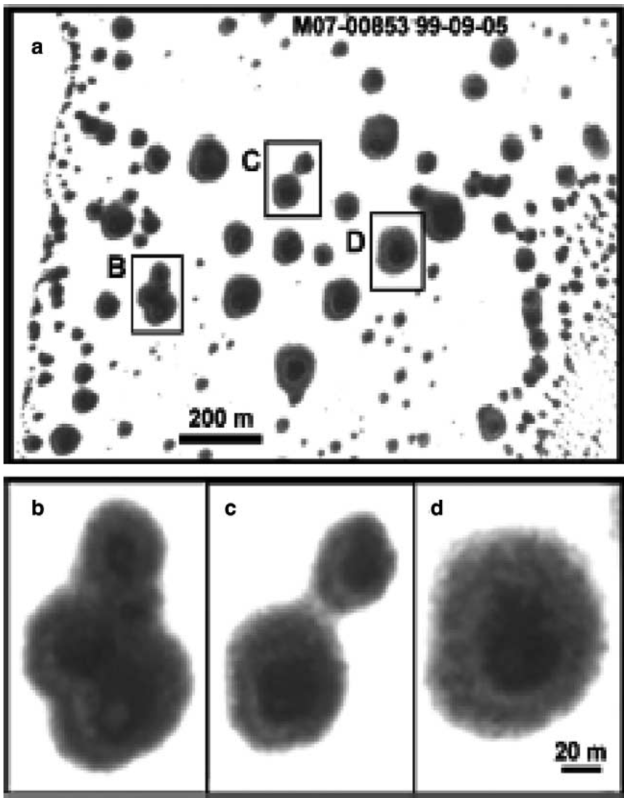

Fig. 3. Seasonal features in the Martian Southern Polar Region (Horváth et al., 2001).

2.3. Titan science relevance

Titan is a key astrobiological target because it may contain large amounts of organic deposits at its surface. In these deposits some of the chemistry leading to the origin of life may have occurred here too. Rich in methane, Titan's atmosphere plays host to a large number of organic photochemical reactions from 100 km above the surface and upward (Lunine et al., 1989). Virtually all of the products of methane and nitrogen photolysis are lower in vapor pressure than the two starting components, and hence the products condense out and fall to the cold (95 K) surface. Thus over time, assuming photochemistry on Titan has proceeded in a steady-state fashion, a layer hundreds of meters thick of higher hydrocarbons and nitriles has accumulated on the surface of Titan (Lunine, 1993). However, the chemistry should not end there, in spite of the exceedingly low temperatures, because additional sources of energy are available in the form of volcanism (Lunine et al., 1998), impacts and exothermic polymerization of acetylene and other products. The long temporal and large spatial scales available for further evolution, and the prospect that this has occurred recently somewhere on the surface, make Titan one of the highest priority targets for astrobiological exploration. Prior to such a mission, the Cassini-Huygens explorations of Titan from 2004 to 2008 (and probably up to 2010+, in the case of an extended mission) will map out the occurrence and variability of appearance of the surface organic phases on scales down to hundreds of meters over much of the surface (Lorenz and Lunine, 1997).

Particularly intriguing is the fact that the organic products of methane photosynthesis will be devoid of oxygen to the level of 10 parts per million or maybe much less (Bernard et al., 2003), based on the atmospheric composition. However, the bulk composition of Titan is as much as 50% water ice by mass, most of which is likely concentrated in a crust and partially liquid upper mantle (Stevenson, 1992). Hence, volcanism or impacts will occasionally produce liquid water to which the surface organics are exposed (Welch and Lunine, 2001). Formation of carboxylic and amino acids will then certainly occur, with perhaps the initiation of peptide synthesis depending on the time available. How far and to what level of complexity the chemistry will proceed is unknown, because organic chemistry on lengthy spatial and temporal scales is difficult to predict. Enantiopurification of chiral molecules, selectivity of preferred molecular weight distributions, and other steps on the poorly defined evolutionary ladder from abiotic organic chemistry to biochemistry, may have occurred or be occurring on Titan.

Impacts of kilometer sized or larger bodies into the icy crust of Titan produces several percent of liquid water in the process within the newly formed crater (Artemieva and Lunine, 2003). As Fig. 4 shows, while much of the organic material is shock heated in the impact, a tail on the lee side of the impact is only lightly modified and falls into the water. The top of the liquid water layer freezes over quickly but complete freezing does not occur for hundreds to thousands of years, sufficient time for interesting organic chemistry as above (Lorenz et al., 2001). Subsequent gardening of the large crater by smaller impactors may garden out some of the organics onto the surface.

2.4. Extra-solar system science relevance

Identification of a generic "Signature for Life" has remained an elusive goal. Achieving such a signature for both in situ and remote sensing applications has appeared even more unattainable. Work in progress makes it clear that such in situ signatures can be obtained (Storrie-Lombardi et al., 2001). However, remote sensing of signatures of life until recently has seemed to be an almost intractable problem. Even Sagan et al. (1993), using the Galileo December 1990 fly-by data, found it difficult to accomplish remote detection of life on Earth. This experiment underlined the need to ground-truth the relationship between remote sensing and in situ detection of life on Planet Earth. We propose a new paradigm for life detection based on identifying

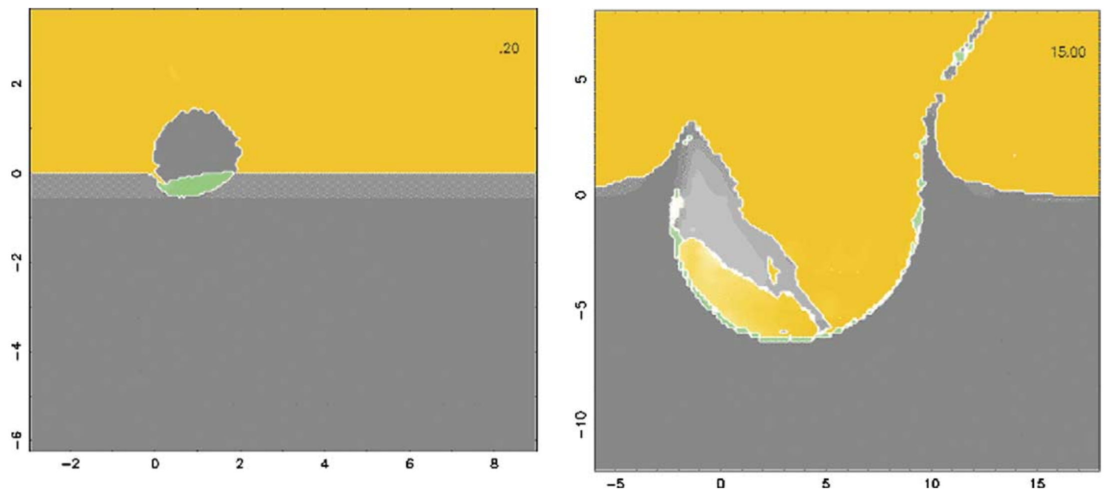

Fig. 4. Crater formation model on Titan.

biotic-induced compositional change across time using linked remote and in situ observations.

The critical item for extra-solar science in this project is to calculate the limits of detection of biomass expressed as ΔG processed per unit time for a planetary surface and to estimate the proportion of a planet that would need to be colonized to permit detection by remote sensing efforts such as the Terrestrial Planet Finder. We suggest sampling multiple abiotic and biologically weathered sites using reflectance spectra obtained by our autonomous vehicle at varying altitudes. These data could then be compared to portable Raman in situ data and laboratory phospholipid fatty acid bioassay data (PLFA) (White, 1993). This strategy can provide statistically valid field measurements of specific signals of biological activity in sites where potential signatures can be detected in remote sensing data. Limits could also be set for remote detection of these signals. Such findings would be directly applicable to the JPL Virtual Planet Laboratory and would help constrain the biological and geological modules fundamental to this modeling effort. Extra-Solar system science.

3. Measurement approach

3.1. Measurement methods

Sampling and (subsequent) analysis of volcanic gases is not only hazardous but also potentially flawed scientifically. As the samples condense the condensates may represent different components from those initially present. In situ analysis is therefore preferable but much harder. One should measure both the major and trace gas components and also the stable isotope compositions of some of them. Stable isotope compositions are particularly characteristic of biotic processes. To detect biotic signals methods should be used that are applicable to Mars exploration. This would also demonstrate their use in this challenging environment before deployment for planetary exploration. A BLIMP is the most appropriate vehicle for carrying any chosen instrument up to and into terrestrial volcanic calderas; it is a proxy for a Mars Rover. Care must be taken for the BLIMP to avoid extremely hot vents of gas, which could create navigation and buoyancy issues. We suggest the use of a long tube, or proboscis, to sample gases safely. Chosen analytical targets are gases, which may be metabolic products of microbial or other life forms and their isotopic compositions, especially $^{13}C/^{12}C$ ratios (Craig, 1953), detection of organic compounds and their chirality and also simple inorganic compounds. The rate of change of inorganic reagents, which potentially could react, is a biosignature, which is more susceptible to remote observation, especially by spectral signatures.

The instruments of choice must be validated by determining their real limits of detection in an initial field campaign conducted in situ by a science team. This field campaign should collect rocks from flows in each of the environments that will be subsequently visited by the BLIMP. An exception is the caldera, which is considered too risky for personnel. Independent laboratory analyses of samples collected in the field will also be used to calibrate the instruments in the lab.

One of the most sensitive tests for quantitative biomass assay is PLFA, which measures components of the cell membranes of viable organisms (White, 1993). Laboratory tests of total biomass from samples collected from sites to be visited by an aerial vehicle will be performed with this method – results can be compared should also be used to calibrate flight results.

Reliable detection of a biological signature against a rock background depends on preliminary characterization of the abiotic background itself. Major advances were made in analyzing the mineralogical data from Pathfinder by employing reflectance spectral data

(400–1000 nm) from analog samples including unaltered, palagonitic, and sulfatetic tephra from Mauna Kea Volcano (hydrolytic and acid-sulfate alteration), steam vent material from Kilauea Volcano (hydrolytic alteration), and impactites from Meteor Crater (Morris et al., 2000). The effort has produced a scientifically rich data set applicable to measurement sets that can be obtained by autonomous aerial vehicles. As in situ mineralogical characterization on the Mars surface can best be accomplished using Raman spectroscopy (Wang et al., 1999), it is appropriate to use aerial vehicles to conduct surveys of the Earth-analog test sites using reflectance spectroscopy (400–1050 nm) followed by portable in situ ground assay using both reflectance spectroscopy and a portable deep UV Raman spectrometer that has been proposed for Mars in situ biological exploration (Storrie-Lombardi et al., 2001). It is important to note that the latter technique is currently employed in our laboratory for characterizing Hawaiian deep core basalts, Titan tholins, and polyaromatic hydrocarbons (see equipment below).

LINF (Laser induced native fluorescence) is the single most sensitive analytical technique available for organic compounds that does not require sample preparation. Practical detection limits on real samples are in the part-per-billion (ppb) range. Raman spectroscopy produces characteristic, definitive, vibrational spectra for a wide variety of mineral and organic targets. Raman experiments using laser excitation wavelengths between 220 and 250 nm produce a resonance phenomenon for homocyclic (ring structures containing only carbon) organic compounds such as the aromatic amino acids and heterocyclic (carbon, nitrogen, etc.) molecules such as the nucleic acids. This resonance enhances Raman S/N by $10^{6–8}$. The detection of a resonance Raman organic signature following excitation with only microwatts of energy to sample identifies the target as one containing these complex essential components of living systems. The high sensitivity of fluorescence permits rapid exploration of a target surface. The high specificity of the resonance Raman event permits clear classification of organic targets. Laser excitation at 224.3 nm produces a complete Raman spectrum below 260 nm. Fluorescence emission occurs beyond 260 nm, making it possible for both experiments to be performed simultaneously without interference. It is of particular importance that bound and unbound water, calcite, and silica exhibit significant Raman cross-sections at these wavelengths and are easily identified. Preliminary experiments in our laboratory have employed the deep (1.3 km) core drillings into the vesicular basalts of Mauna Kea on the island of Hawaii (Storrie-Lombardi et al., 2002), and kerogen-containing fossils (Czaja et al., 2002) using the laboratory test bed instrument for MUVRE. Fig. 5 shows some of these results. We have also obtained spectra from Titan tholins (McDonald et al., 1994) and type II kerogens. A resonance Raman spectrum for Titan tholin appears in blue (Fig. 5(b), sample courtesy of G. McDonald). Organic fingerprint peak activity is shifted for the tholin (1555 cm^{-1}) compared to the microbial signature (1652 cm^{-1}). The Raman water band has also shifted, most likely as a function of increased binding of the –OH in the tholin. In other work in progress we have obtained fluorescence images of a PAH, perylene, in situ on silica grains at concentrations down to <20 ppb. Perylene has been detected in Mars meteorites and the interstellar medium. Detection of localized PAH accumulation in the fissures of Mars rocks would imply the occurrence of water-mediated diffusion processes at an earlier epoch in Mars history.

The instruments aboard the aerial vehicle are suitable also to examine basalt surfaces for signals that could be attributed to life. The suite of instruments could be deployed initially over lava flows that can be visually identified to have life (lichen). The instruments (see Section 4) must be deployed at appropriate distances from the samples and be able to register signals over these flows. The vehicle would then be deployed in more extreme environments to determine where signals indicative of life are no longer obtained. A transect should also be conducted from older (1986) lavas to new (2002) lavas along the southeast coast of Hawaii, while yet another transect should climb up a single flow of known age from a region of high rainfall to a region of low rainfall.

Ground truthing of measurements: Laboratory tests of various field samples are needed (Blatt and Brown, 2002). We suggest using a camera, a light microscope, an SEM, an XRD, and XRF or XPF for surface samples and ICP,

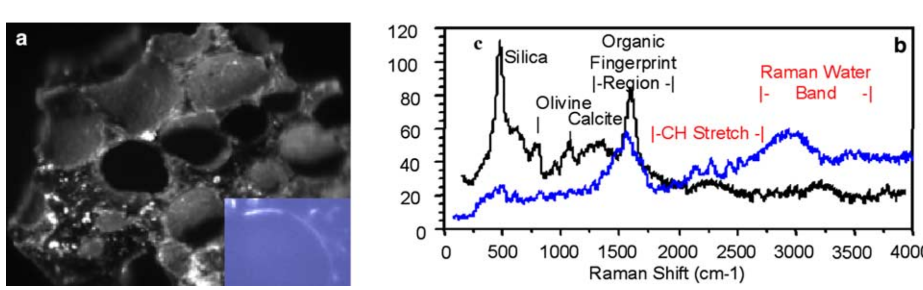

Fig. 5. Mauna Kea vesicular basalt: (a) is the visible image (60×) of Mauna Kea vesicular basalt extracted from 1335 m below sea level. A portion of the sample was illuminated by a 224.3 nm laser to produce the native fluorescence image in (b).

gas analysis, bio-assay for amino acids, PLFA and PCR. In situ measurements are highly desirable and we suggest using the Microscopic Ultraviolet Raman and Fluorescence Explorer (MUVRE) available at JPL.

Ground truthing of aerial vehicle and instrument package: A suitable calibration site is Meteor Crater in Arizona. We suggest that the BLIMP be transported to Meteor Crater for a demonstration field campaign. During this campaign, the BLIMP will follow a pre-determined route around the layered terrain from the top to the bottom of the crater. This provides a benign yet relevant, environment to end-to-end test operations of the platform and all instruments. It will demonstrate the BLIMP's unique ability to examine and map steeply sloping surfaces.

4. Instrumentation

Our analysis shows that the following instrument suite is appropriate for use from the BLIMP. As discussed in Section 5, a cost effective vehicle may not be able to carry all the instruments at one time. Successive deployments at the same site appear to be scientifically acceptable.

Camera: For both navigation and scientific purposes the authors suggest the use of a CMOS Digital Imager. Such a system could be low-power (25 mW) using at least a 512^2 digital CMOS imager with built-in 10-bit ADC. A wildcard PCMCIA FPGA can provide the interface to a laptop computer. Such a digital imager chip is integrated into the visible camera for the NM-GIFTS mission to be flown in 2004. The CMOS imager pixel pitch is 12 m, and it contains integrated timing and control, bias-generation, and ADC circuits, in addition to the imager core. The FPGA would need 512 Kb of memory, or one full-frame store, for continuous imager operation and a data-link at 10 MHz data rate to the computer memory. We estimate the mass of such an assembly with 1/2 in. optics at less than 60 g.

Visible spectrometer: A visible reflectance spectrometer is needed for determination of inorganic metabolic products. The spectrometer design is based on the Offner reflective relay. Its concentric form can provide good optical correction, compact size and inexpensive fabrication made possible by recent progress in electron-beam lithography. Characteristics of this design are: all spherical concentric surfaces, *f*/4, 12.3 mm slit length, spectral range 400–1050 nm, and spectral resolution of 10 nm (Table 1). There is practically zero distortion. The detector for this spectrometer could be a copy of the Mars Exploration Rover 2048×1024 frame transfer CCD detector and electronics.

Gas and gas isotope analysis by Tunable Diode Laser Spectrometer (TDLS): This could be based on JPL's high-heritage design of the Mars Balloon-borne Laser In Situ Sensor (MBLISS) instrument that was proposed for a Mars Scout mission or more recent developments of that instrument (Webster, 2005). In over 300 aircraft and balloon flights, the JPL Atmospheric Laser Spectroscopy Group has demonstrated the high sensitivity of tunable laser absorption spectroscopy for in situ measurement of atmospheric gases in both the near-IR and the mid-IR wavelength regions. A 2-channel tunable laser absorption spectrometer is needed using cw tunable lasers directed over a path from the BLIMP to the ground and back, nominally about 150 m (500 ft). Channel 1 could use either a QC or cooled Pb-salt at 3.4 μm to scan over the 2924–2928 cm^{-1} region too measure CH_4, HCl, and H_2O. Channel 2 could be a TE-cooled near-IR DFB laser at 2.05 m to measure CO_2 and $^{13}CO_2$ (Table 2). The TDLS can analyze the gases present in the caldera.

Gas Chromatograph/Mass Spectrometer (GCMS): A GCMS should be flown together with the TDLS, enabling comparison of results and assessment of the complementary nature of the two methods of measurement. A suitable mass spectrometer is the JPL-developed quadrupole mass spectrometer array; 16 rods of 25.4-nm length and 2-mm diameter in a 4×4 array form 9 parallel quadrupolar regions. This MS operates at 10 MHz and uses electron-impact ionization. A detection sensitivity of 10^{12} counts/Torr s (1 ppm) is achieved with a Faraday cup for ion current-only measurements at high count rates and a channel electron multiplier for single-ion counting. The resulting data rate is about

Table 1
BLIMP spectrometer parameters

Parameter	Value
Optics with detector volume	$45 \times 40 \times 40\ mm^3$
Electronics box volume	$80 \times 80 \times 35\ mm^3$
Mass	~0.5 kg
Power	<5 W
Spectral range	400–1050 nm
Field-of-view	30°
Spectral sampling	10 nm
Spatial sampling	50 cm
Data rate	400 kpixels/s

Table 2
TDLS minimum detectable amounts

	Expected	Minimum detectable
Channel 1		
HCl at 2926 cm^{-1}	1–10^3 ppbv	6 ppbv
CH_4 at 2928 cm^{-1}	2–100 ppmv	1 ppbv
H_2O at 2925 cm^{-1}	10^3–5×10^4 ppmv	10 ppmv
Channel 2		
CO_2 at 4866 cm^{-1}	370–10^3 ppmv	0.2 ppmv
$^{13}CO_2$ at 4867 cm^{-1}	N/A	Ratio to few per mil

BLIMP TDLS: pressure 1013 mbar, $T = 300$ K, path = 150 m, $A_{min} = 1 \times 10^{-4}$.

10 kb/s. The system mass is ∼3.5-kg with pump, and its dimensions: $41 \times 25 \times 13$ cm.

The gas chromatograph uses a 10 m, 100 μm i.d. DB wax column, described more fully in Shortt et al. (2005).

This QMSA has already been calibrated and flown on the ISS to monitor ammonia, oxygen, nitrogen, water, and the three hydrazines (HZ, MMH, and UDMH).

Raman spectrometer: The MUVRE contains a deep UV hollow cathode laser operating at either 224.3 or 28.6 nm, a 1/4 m spectrograph with 3600 g/mm holographic grating, resolution of 4 cm^{-1}/pixel at 248.6 nm, and a spectral spread of 4000 cm^{-1}. The detector is a Hamamatsu 2 stage TE cooled, back thinned, UV CCD Array (1024×64). The imaging camera is either a 0.003 lux, 768×494 pixel, grayscale or a 5 lux 768×494 pixel RGB by Watec. The microscope contains 3×, 15×, 40× deep UV refractive objectives with FOV = 1.3, 0.25, and 0.1 mm^2 (*x*-axis), respectively. Incoherent sources include 254, 370 nm, white epi- and sub-stage white. LINF spectra are acquired via an integrated Ocean Optics S2000 miniature fiber optic UV–VIS–NIR spectrometer with a 2048-element CCD linear array detector responsive from 200 to 1100 nm. The overall size of the portable instrument is $30 \times 20 \times 50$ cm, weight <14 kg, and power consumption between 30 W (standby) and 150 W (operating). Specifications for the breadboard flight version are $7 \times 8 \times 14$ cm, <5 kg, and maximum power consumption <5 W. Instrument control and data acquisition are accomplished using Lab View and a Sony micro-laptop computer. System power for the portable instrument is 48 V DC.

5. BLIMP – aerial vehicle

5.1. Choice of vehicle

A BLIMP is the optimal platform to provide mobility and autonomous deployment of instruments to explore the extreme environments around Kilauea. It avoids surface issues associated with vegetation or hot lava flows and is more effective, both in cost and performance than alternates such as a rover. The BLIMP is also a good proxy for Mars mobility systems, such as helium balloons, solar-heated hot air balloons, and surface rovers. Each of these vehicles shares the same types of experimental approach, instrument suite and autonomous navigation challenges (see Fig. 6).

In addition, a BLIMP is the vehicle of choice for Titan; the atmosphere is dense and of high molecular weight, winds are light, and gravity low. The BLIMP is a stable aerial platform that can cover large distances in the upper troposphere, where laminar wind flows provide fast transport across the surface of Titan, then drop to the quiescent near-surface atmosphere to maneuver around geologic features, identify organic deposits, and land or drop a small package to analyze organics of special interest. BLIMPs do not require rapid and

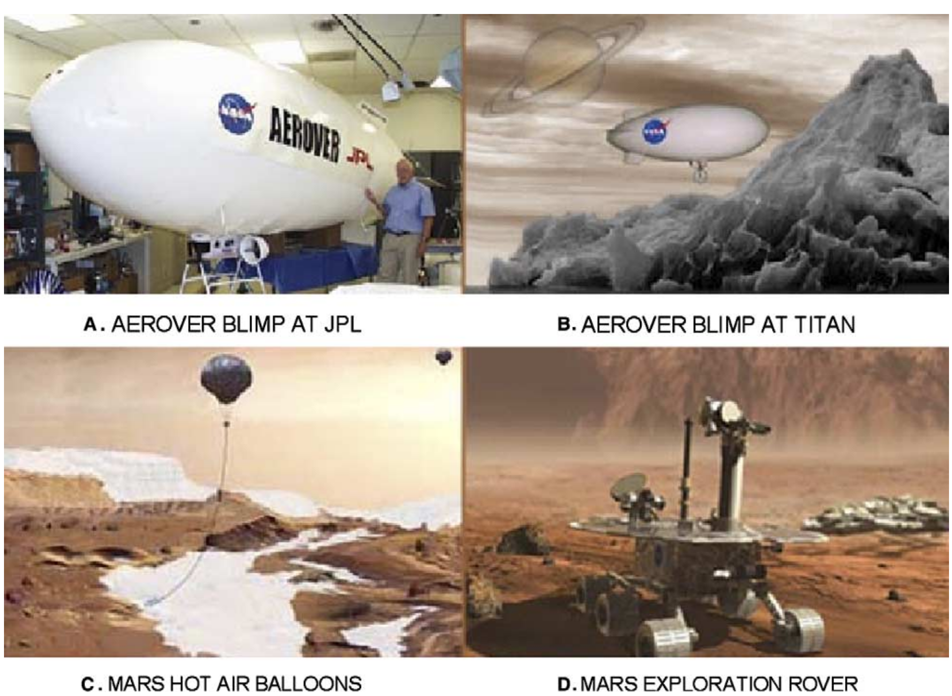

Fig. 6. Applicable mobile platforms for planetary observations.

continuous aero surface control inputs and provide a stable platform for operation.

5.2. BLIMP deployment experiment

The suggested BLIMP design is based on extensive experience with aerial platforms at JPL (see Fig. 6(A)). Off-the-shelf, flight proven subsystems can be combined into a unique design optimized for the necessary performance. The BLIMP can be based on the 15-m envelope available from GSSL, a company with a proven track record at JPL. The inefficient and measurement-polluting gasoline power of the standard vehicle, used for our preliminary tests, must be replaced by a high efficiency electric propulsion system – an ideal technology demonstration for planetary aerial vehicles. Such a system could use state-of-the-art lithium-thionyl-chloride batteries, high-efficiency motors and propellers of the type available for small terrestrial aircraft.

The BLIMP could use GPS as an accurate and inexpensive navigation system. This is a proxy for the inertial measurement units currently planned for future planetary missions. Using the GPS data as benchmark for other sensors is a unique opportunity to safely and cheaply demonstrate navigation approaches more suited to planetary conditions. The autonomous mobility can be based on an inexpensive aircraft autopilot demonstrated on the JPL 2-m BLIMP.

Before each sortie, the subset of instruments required for the next experiment must be installed and the autonomous flight path defined. BLIMP can depart from a portable shelter off a main road and proceed to a defined set of inactive and active volcanic sites. Upon reaching each GPS waypoint a pre-determined suite of bio detection instruments would be activated. A communications link to the ground simulates both real-time and delayed planetary data return.

BLIMP safety is ensured by carefully combining human oversight and autonomy. Autonomous time/energy management is combined with human override capability to demonstrate the capabilities required for planetary operations. For example, were contact to be lost during volcanic encounters or high temperatures are encountered; the BLIMP is programmed to proceed to a new waypoint. Emergency ascent and descent systems are straightforward and should be used as necessary. BLIMP sorties are designed to fly with strong winds by setting the recovery ground station downwind with respect to the launch and exploration area.

5.3. BLIMP system subunits

BLIMP could use the MP2000 autopilot from Micropilot, which has a lightweight GPS control system with 60 programmable waypoints, a magnetometer heading system, and an ultrasound precise landing/hovering system, all demonstrated on a small, 1.7 m BLIMP. A larger 6 m long JPL BLIMP (see Fig. 6(A)) has two forward propulsion units, which can be vectored for hovering. Ailerons and rudders provide primary altitude and yaw control. A back-up joystick operated radio control system is needed, together with an emergency descent system for safety and to meet FAA requirements. A low-power commercial processor (e.g., G10 laptop) can be the on-board controller and uses commercial interfaces (e.g., PCMCIA) for connectivity to the instruments and other devices. Each instrument must have a demonstrated interface and software source code for the laptop.

A 2.4 GHz spread-spectrum wireless networking device (FCC part 802.11 compliant), could provide several megabits per second in communicating to the ground station. A wireless card on the laptop with external RF amplifier/antenna, can provide an acceptable range of 30 km. Government approval to exceed standard power limits for remote locales such as meteor crater and the Hawaii Volcanoes National Park are readily obtained through the Western Area Frequency Coordinator in Pt. Mugu, CA. Each major device should be switchable, so it can be powered off when not used, which makes it straightforward to get more than 4 h of runtime from less than 1 kg of battery.

5.4. Technology experiments

There are two technology experiments that the authors believe should be a part of any future deployment of an aerial vehicle. These two experiments are:

1. *Visual station keeping:* BLIMP can establish and test, in a realistic environment, the ability of an aerial vehicle to reliably station keep without GPS by using images from the science/navigation camera. These are captured and processed by the on board computer to determine the local motion of the BLIMP. The software uses an "interest operator" to identify high contrast, easily recognizable image features. These are tracked from frame to frame to estimate the BLIMP horizontal motion, sonar in the MP2000 autopilot, gives elevation above the terrain. The GPS system provides ground truth and enables performance evaluation so that this approach is validated for future planetary aerial vehicle missions, where GPS or high-speed location equipment is not available.
2. *Celestial navigation:* A camera on the BLIMP can identify the Sun and Moon angles relative to the local vertical. These two angles, together with the time, uniquely determine the position of the BLIMP. In this experiment, a small camera and inclinometer package are mounted on the top of the BLIMP and connected to the avionics by a thin cable. The fish-eye camera and commercially available MEMS

inclinometer (accuracy of <0.1°) are calibrated as a unit. This defines the relationship between pixel coordinates and zenith angle. The main CPU can process the images from the camera to determine the centroids of the sun and the moon. The moon is an analog for Saturn, as it will be seen from Titan using a near-IR camera. GPS time is an analog for the USO output available at Mars or Titan. The time and known geodesy of the Earth allows computation of the latitude and longitude of BLIMP. GPS data is then used to compute position error statistics. This demonstration enables confident mission design for Titan BLIMP surface missions, even without an orbiter. This approach contrasts with radio navigation approaches that only periodically establish the approximate global position of a rover on Mars or a BLIMP on Titan.

6. Planetary applications

6.1. Titan measurement approach

The strategy for identifying and sampling the significant prebiotic organics is summarized below as consisting of three stages. Our terrestrial field trials will rehearse stage 2, and a significant part of stage 3.

1. *Initial reconnaissance:* Cassini Huygens data from both the probe and from the orbiter's infrared spectrometer and imaging systems identify organic deposits that appear to have been altered from the background photochemical deposits. Those that are correlated with recent features including volcanic rifts or impact craters will be of particular interest because there the organics may have reacted in an aqueous medium.
2. *Mesoscale identification of organic deposits:* A BLIMP is deployed to one of the sites of recent geologic activity (or of a recent impact) in which organics are known to be present from the Cassini data. A remote sensing package on the BLIMP consisting of visible imaging, reflection spectra and hyperspectral imaging maps the organics as the BLIMP moves across the surface. If the site is an impact crater a helical search trajectory is taken by the BLIMP, something that we will demonstrate in this project using terrestrial impact craters. The goal of the search is to identify organic samples that appear to have been altered by liquid water. Once a plausible set of deposits is identified during this phase, the BLIMP sampling instruments are set down on that site.
3. *In situ analysis:* Using an organic analysis package consisting of a GCMS, the organics are subjected to an analysis protocol. Determination of the total oxygen content, the abundance as a function of carbon number, the presence of chiral molecules and the enantiomeric composition are analyzed after the polymers are broken down into monomers. The polymers themselves are analyzed to assess their structure and to determine if there are any unusual structural preferences. If the sample looks promising, additional analyses and drilling are scheduled; otherwise the BLIMP is raised from the site to begin a new reconnaissance or to navigate immediately to a backup site for analysis.

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