

# The Potential for Chemical Evolution on Titan

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*Abstract*—Saturn's moon, Titan, is a Mercury-sized body that is rich in organics and water ice. The Cassini-Huygens mission will arrive at Saturn in July 2004 and deploy the European Space Agency (ESA) Huygens probe, which will descend to the surface, providing in situ chemical analysis, images, spectra and other data that will characterize in detail the atmosphere and, if it survives, a region of the surface. The Saturn Orbiter instruments will map Titan's surface at a range of wavelengths over 4 years and approximately 45 flybys. Radar and near-IR mapping will distinguish between areas of water ice, ammonia-water, and organics, as well as provide perhaps sufficient data to distinguish liquid organics from solid organics. We then need to be prepared to examine what scientific questions would follow from these results and what subsequent mission will enable a more complete picture of Titan to be developed.

We propose that Titan is an exciting astrobiological target. If the Cassini/Huygen's data show that there is no variation in the composition of surface organics then atmospheric photochemistry has dominated the production of organics with little further evolution. However, if there is variation from region to region, this might suggest that additional organic chemistry has acted on the products of stratospheric photochemistry. Should evidence for variability in the organic phases on Titan be found, subsequent exploration of the surface ought to be undertaken, with an eye toward understanding the extent to which organic chemistry has proceeded. Sampling of organics to determine oxygen content, extent of acetylene polymerization, existence of chiral molecules and enantiomeric excesses, and searches for specific polymer products, would be of interest in assessing how organic chemistry evolves toward biochemistry. Such efforts would require fairly sophisticated chemical analyses from landed missions. This paper examines this chemistry and the potential instruments that could distinguish chemical evolution.

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## I. INTRODUCTION

Saturn's moon, Titan, is a world larger than the planets Mercury and Pluto, with a dense, nitrogen and methane-rich atmosphere and a surface temperature of only 95K [1]. Hydrogen gas is continually formed as a by-product of the photochemical destruction of atmospheric methane, and escapes rapidly in the low gravity environment of Titan [2]. Significant accumulation of organic materials may have occurred over time, perhaps even resulting in the formation of hydrocarbon seas [3]. While water forms a significant part of Titan's crust, it remains deeply frozen, except for rare episodes of heating associated with meteorite impacts [4]. The surface of Titan is shrouded in a dense organic haze that is a byproduct of the photochemistry, making it (with Pluto) among the most poorly mapped surfaces in our solar system. Recent Hubble Space Telescope, and ground-based adaptive optics images reveal brightness variations that could result from a combination of topography and variation in surface organic deposits [5–7]. The existence of methane and ethane-based weather cycles has been proposed, and may have been confirmed in recent Earth-based observations [8].

Details concerning Titan's organic chemistry are restricted at present to the atmosphere. The Voyager Infrared Spectrometer (IRIS) detected general signatures of hydrocarbons and nitriles in the atmosphere, with some interesting but poorly understood latitudinal variations [9]. Simulations of Titan's atmospheric organic chemistry have produced a variety of simple hydrocarbons, olefins, nitriles and polymeric materials [10].

## 2. THE CASSINI-HUYGENS MISSION TO TITAN

Our knowledge of Titan is expected to increase dramatically when the Cassini-Huygens spacecraft (Figure 1), launched in 1997, arrives in 2004 to study the Saturn system [11]. Upon arrival, Cassini-Huygens will fly by Titan and release the specially designed Huygens probe [12], which will descend through the atmosphere, performing a variety of physical measurements. The Huygens probe contains a gas chromatograph and mass spectrometer combined instrument (GC/MS), with a total weight of only 17 kg [13]. Although this instrument does not have any chiral analysis capability, it will be crucial for identifying gases and low to moderate molecular weight organic molecules in the Titan atmosphere. A pyrolysis device will volatilize aerosols and allow their fragments to be sampled with the GC/MS. During the probe's slow descent by parachute to the Titan surface, it will collect and analyze samples, hopefully providing an understanding of the vertical distribution of compounds within the atmosphere. As an added bonus, when the probe finally comes to rest on the surface, a single surface pyrolysis-GC/MS measurement may be possible, hopefully shedding some light on Titan's surface chemistry. At this point, the Huygens probe component of the mission will be finished, and the Cassini Orbiter will pass out of radio range and continue its exploration of the Saturn system.

If all goes well with the Cassini-Huygens mission, a fairly detailed understanding of Titan's atmospheric organic chemistry should emerge, with some additional information about surface chemistry also being possible [14]. As the Cassini orbiter flies by Titan repeatedly over four years, a detailed physical mapping of Titan's surface will be obtained, shedding light on surface features such as mountains, craters, oceans, and rivers.

## 3. THE TITAN ORGANICS EXPLORER: A FOLLOW-UP TO CASSINI-HUYGENS

NASA's Jet Propulsion Laboratory and others are studying missions to Titan beyond Cassini-Huygens [15]. One concept, called the Titan Organics Explorer, is a roving robotic analyzer capable of detailed studies of the chemical composition of Titan's atmosphere, surface, and oceans. Such a follow-up to the Cassini-Huygens mission would logically focus on the chemical composition of the Titan surface, and how surface and atmospheric chemistries interact. Evidence for changes in Titan's chemistry over time will also be sought, as will any signs of chemical evolution or pre-biological chemistry. Of particular interest is a proposed search for enantioenriched organic materials on Titan. While not strictly a signature of life (a point that is often misunderstood) the presence of significant enantioenrichment on Titan's surface would indicate an interesting level of organization and complexity suggestive of a system "on the road to life" [16, 17].

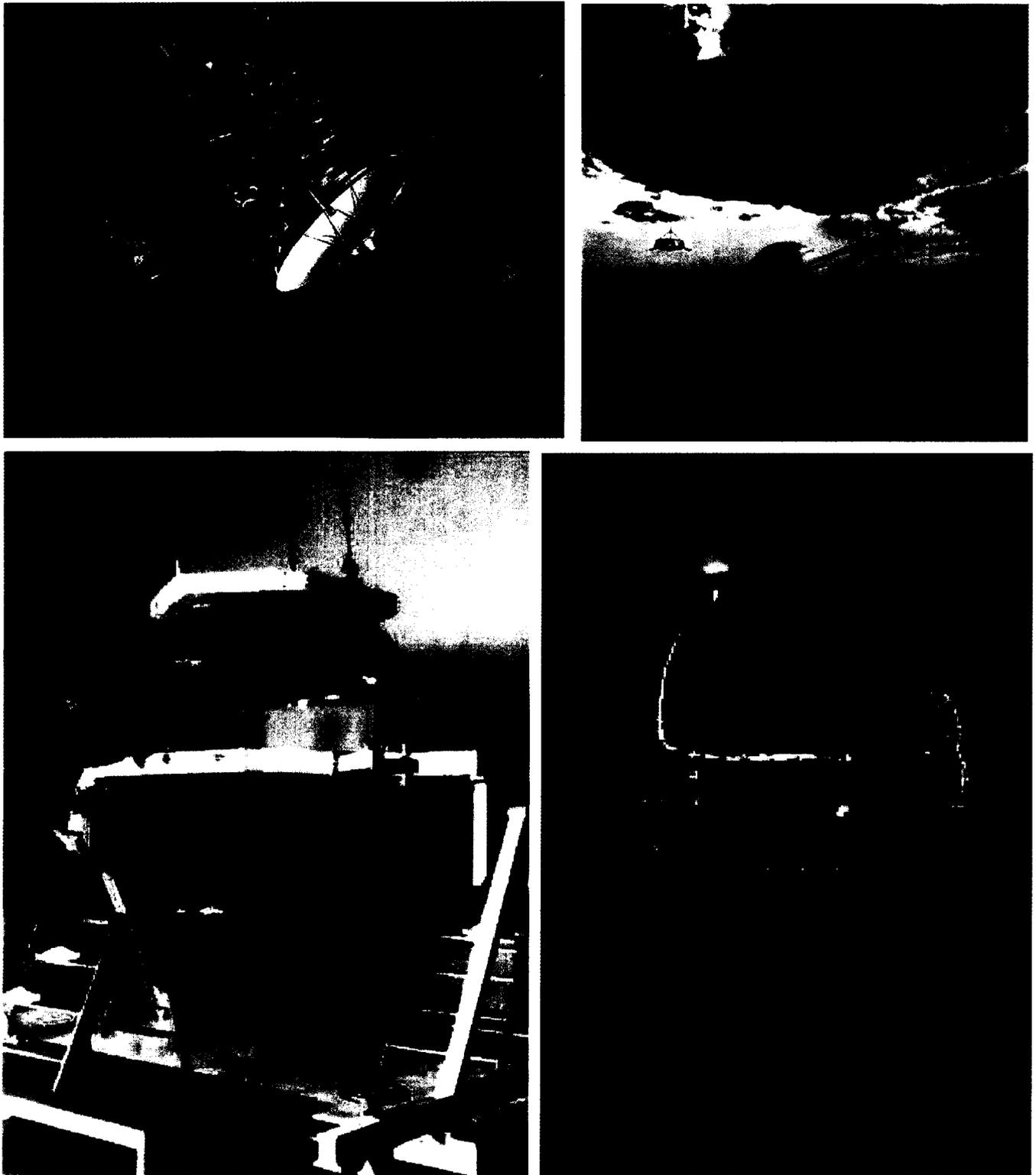
An in-depth study of Titan's surface chemistry will require a mobile exploration laboratory. The combination of a nitrogen-rich atmosphere four times the density of Earth's

air at sea level and a weak gravitational field only 1/6 that of Earth means that flight on Titan will be relatively simple. A variety of interesting vehicles have been proposed for flight on Titan [15] with the two balloon-based vehicles designs pictured in Figure 2 being possible candidates for a mobile vehicle capable of exploring widely on Titan's surface.

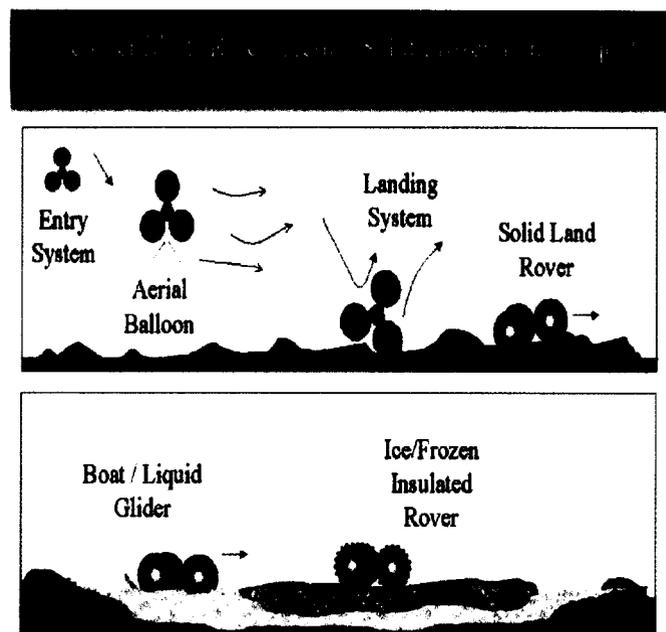
## 4. HOW CAN A COMPLETE ORGANIC LABORATORY FIT INTO A SHOEBOX?

The constraints on the design of what we will call the Titan Organics Explorer are formidable. Launch vehicle considerations and a mobile design argue strongly for an analytical package with the minimum possible payload, ideally only a few kilograms. The analytical equipment must also be very rugged, able to survive the 7-year voyage, then spring into action and perform. Obviously, any reagents or components in the analysis package must have a considerable "shelf life," and valves, pumps, and other moving parts should be kept to an absolute minimum. Given the potential complexity of the analytical package, parallel analysis capability and redundancy should be built into the robot. Finally, with a one-way communication delay time exceeding an hour between Titan and Earth, the robot should possess sufficient intelligence and autonomy to allow it to independently go about its mission without the need for earth-based approval and direction.

Notwithstanding considerable efforts at detection and modeling, Titan's surface chemistry is an almost complete mystery at present [7]. When faced with such a challenge, a complete mobile organic laboratory would seem to be preferred, so that any conceivable contingency could be addressed. The organic analyst is naturally drawn to state of the art multidimensional separation/analysis instruments, where many of the tools of an organic analytical laboratory are combined into a single instrumental setup. In this approach, multidimensional chromatography serves to resolve a complex mixture into individual components, which then travel through an array of detectors to provide information about their chemical identity. The retention of a given compound on a group of different chromatographic materials, combined with information provided by the various detectors, can provide a "fingerprint," which may allow for unambiguous assignment of the chemical structure of the unknown. Ideally, such an instrument would be capable of performing gas chromatography, supercritical fluid chromatography, capillary electrochromatography, or liquid chromatography with a variety of eluents. A battery of different columns, including chiral columns, would be available, and could be plumbed together to permit different column-column arrangements. The inclusion of chiral columns of opposite absolute configuration, as well as the racemic version, is known to be useful for making sense of complicated samples, especially when combined with the use of chiroptical detectors [18]. Ideally, the detector bank would include everything useful for complete organic characterization, UV-Vis, IR, NMR, CD, ORD, fluorescence, electrochemical and especially, mass spectrometry detectors.



**Fig. 1. The Cassini-Huygens Mission to Titan.** As part of its exploration of the Saturn system, the Cassini orbiter (upper left) will release the Huygens probe upon arrival at Titan in late 2004. The Huygens probe will descend through the atmosphere (upper right) performing a variety of physical measurements, including achiral GC-MS measurements made with a specially designed 17-kg instrument (lower right). (<http://www.jpl.nasa.gov/cassini>)



**Fig. 2.** Aerobot (left) and Aeroover (right) approaches are two options being considered for the Titan Organics Explorer. These vehicles would be outfitted with miniature analytical laboratories and would be able to travel freely throughout the atmosphere, oceans, and surface of Titan.

information about their chemical identity. The retention of a given compound on a group of different chromatographic materials, combined with information provided by the various detectors, can provide a "fingerprint," which may allow for unambiguous assignment of the chemical structure of the unknown. Ideally, such an instrument would be capable of performing gas chromatography, supercritical fluid chromatography, capillary electrochromatography, or liquid chromatography with a variety of eluents. A battery of different columns, including chiral columns, would be available, and could be plumbed together to permit different column-column arrangements. The inclusion of chiral columns of opposite absolute configuration, as well as the racemic version, is known to be useful for making sense of complicated samples, especially when combined with the use of chiroptical detectors [18]. Ideally, the detector bank would include everything useful for complete organic characterization, ultraviolet-visible (UV-Vis), infrared (IR), nuclear magnetic resonance (NMR), Circular Dichroism (CD), optical rotary dispersion (ORD), fluorescence, electrochemical, and especially, mass spectrometry detectors.

While such instrument setups are very useful for solving earth-based organic analysis problems, this approach has many drawbacks for a space mission: it is too heavy, contains too many pumps, valves and other moving parts, and only some of the detectors would be feasible for space flight. Recent advances in the development of miniaturized chromatography and "lab-on-a-chip" technologies suggest

that at least some of these problems may be surmountable [19–23]. Relatively new "column-on-a-chip" approaches suggest a working miniaturized array of chromatography columns, each containing a different adsorbent, could be developed in the next few years to enable space qualification by the middle of the decade. Many of the requirements for moving parts such as pumps and valves can also be eliminated. For example, in a capillary electrochromatography (CEC) approach, electro-osmotic flow occurs when a voltage is applied to the system, eliminating the need for a mechanical pump. In addition, advances in the field of microfluidics in the past year or two suggest that micro-mechanical pumps and valves could be available for incorporation into the design of the robot.

A miniaturized chromatographic approach means that the amount of sample under analysis will be too small to permit easy measurement by less sensitive detectors. Consequently, detectors such as MS, UV, IR and electrochemistry, may be used in preference to approaches such as NMR, CD, and ORD. From a space utilization viewpoint, electrochemical detectors are especially interesting, since it may be possible to manufacture these detectors directly on a chromatographic chip [24]. Mass spectrometry detection has been the backbone of most previous robotic extraterrestrial chemical explorations [e.g., 25] and will undoubtedly play a major role in a post-Cassini/Huygens Titan mission as well. The technology for integrating chip-based separations with MS detection is evolving very rapidly.

## 5. MINIATURIZED SENSORS

A skeptic could maintain that even with recent advances in miniaturization, the aforementioned 'lab on a chip' or 'lab in a shoebox' approach is just too complicated to be assembled in the next few years and flown reliably on a mission as complex as the exploration of Titan. Perhaps rather than trying to send an entire organic laboratory into space, we should simply send a battery of rugged sensors to detect the presence of a defined set of organic compounds. Of course, the downside of such an approach is that if we select the wrong target analytes, we run the risk of getting nothing more than an uninteresting collection of negative readings. There are a number of reasons to argue in favor of inclusion of specific sensors in this mission, and the best approach to the chemical exploration of Titan may utilize some intelligently selected combination of both approaches. Some advantages of sensors include the fact that they are small, have low power requirements, and they can be relatively stable. Some sensor and assay technologies have been used in commercial devices for the medical diagnostics industry for a number of years, and it may be possible to glean some useful production and design tips from product development specialists in this area.

There has been some recent excitement in the development of electronic and optical nose technology, a new sensor technology with considerable promise [26, 27] these approaches utilize a panel of sensors which each respond to the presence of an analyte with a change in electrical resistance or in an optical property. An array of sensor pixels is used, each containing a material that responds to different types of analytes. A given compound elicits a certain pattern of responses on the pixels of the array, which provides a 'fingerprint' for the identification of the unknown. One great advantage of the technology is that a broad categorization into general compound classes may be possible even when the unknown compound is not uniquely identified [e.g., 28, 29].

The measurement of enantioenrichment using sensor technologies presents an interesting challenge. An approach in which the signals from opposing pairs of enantiomeric sensors are compared may be the most reliable method. Unless proteins composed of d-amino acids are used, antibody or other protein-based sensors cannot be truly enantiomeric, and must therefore rely upon non-enantiomeric reagents for the two enantiomeric target molecules. Consequently, the paired sensors required for enantiomeric analysis may differ slightly in 'activity' or may age at differing rates, potentially giving rise to false positive results. Sensors can be based on truly enantiomeric starting materials, as for example when enantiomeric monomers are used in the preparation of chiral polymers for a matched pair of pixels in an electronic nose application [30]. Nevertheless, the possibility for differential activity or aging of the pixels still exists, suggesting that sensor "zeroing" using a known racemic compound may be required. The ability of individual sensor pixels of a nose to respond to a variety of different analytes implies that zeroing with one racemate, say 2-butanol, doesn't necessarily mean that the sensor panel will be zeroed for

another analyte, say 2-butylamine. It may be necessary to zero against a known racemic sample of any analyte, which would be a likely candidate for measurement, although perhaps a single zero-calibration standard containing a mixture of known racemates with a broad range of chemical properties could be sufficient.

## 6. GENERAL ENANTIOENRICHMENT DETECTORS

A general strategy for a search for enantioenriched molecules on Titan might involve a broadly focused search using rapid assays in order to identify likely enantioenriched sites for more thorough subsequent analysis. General detectors with the ability to rapidly identify enantioenrichment would be useful for this first level of detectors/sensors. Several technologies seem well suited to this task.

Chiroptical spectroscopy techniques show no signal for achiral or racemic analytes, but may give a signal with enantioenriched materials. The nonlinear autocatalytic asymmetric amplification system developed by Soai could provide the basis for another type of general enantioenrichment detector [31, 32]. A third option for a general enantioenrichment detector involves the use of liquid crystal technology. In addition, recent work by Nakanishi, Berova and co-workers [33, 34] suggests that chiroptical solvating agents may be another approach to a general enantioenrichment detector.

## 7. HOW LOW CAN YOU GO? IS ANALYSIS AT TITAN'S ULTRA-LOW TEMPERATURE FEASIBLE?

The extremely low temperature at the surface of Titan presents some unique engineering and chemical challenges. Almost any device manufactured at laboratory ambient temperatures and cooled to 95K will experience problems owing to thermal expansion and contraction. These problems are certain to be compounded when dealing with fluidics systems where tight seals of valves and pumps and precise interfaces between different materials are required.

Enantioselective chromatography at reduced temperature has been studied in some detail [35–38]. In most cases, chromatographic enantioselectivity ( $\alpha$ ) increases at lower temperature, although this benefit is often offset by broader bands resulting from slower adsorption, desorption, and diffusion. Consequently, decreasing column temperature is rarely used to improve chromatographic resolution. Nevertheless, the technique is sometimes useful, and enantioselective liquid chromatography at temperatures as low as 200K has been performed.

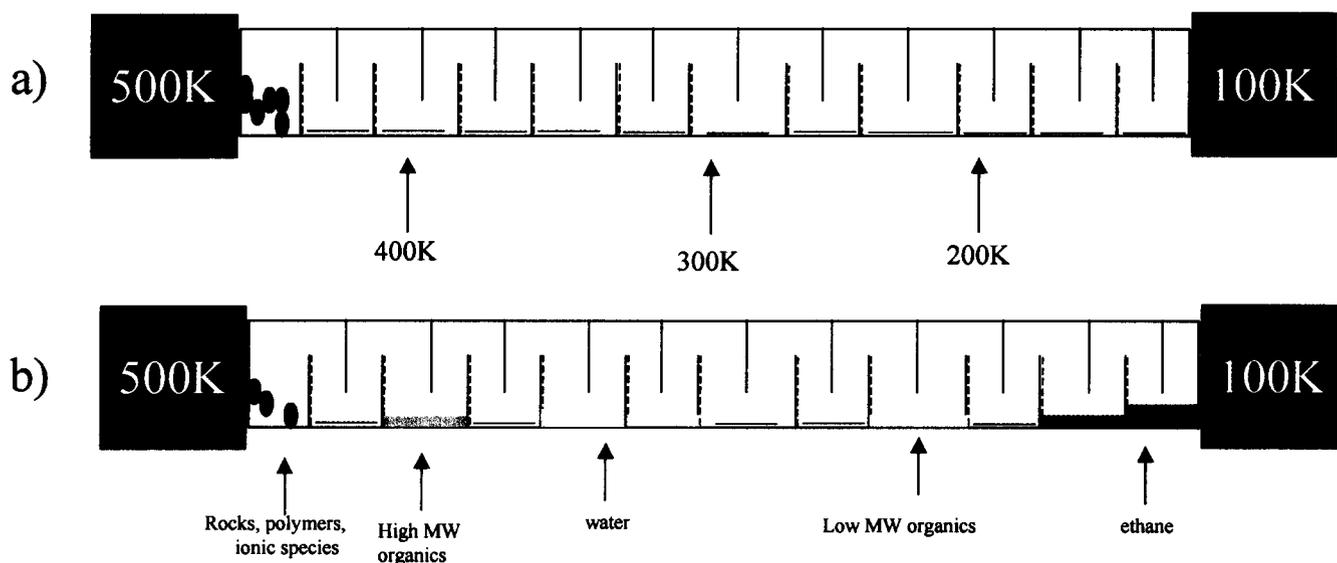
Analysis at 95K presents some additional challenges. For example, what eluent systems could be used at this temperature? It may be that any analytical method based on reversible adsorption will come to a grinding halt at this ultra-low temperature. Heretofore, there has been little reason to push the lower limits of low temperature chromatography. An alternative is to choose techniques and

approaches that we know well, namely separation and analysis within 200–300K. Sending a heated analysis robot will present no major design or engineering challenges (though it is highly consumptive of power, which is an expensive spacecraft resource) and is the approach utilized in most other robotic planetary explorations. (Indeed, the Huygens probe will have completed its mission before its internal components reach Titan ambient temperatures.)

### 8. SAMPLE PREPARATION: CAN THERMAL-GRADIENT DISTILLATION CHIPS BE USEFUL?

With a significant potential for a highly complex mixture of organics, the issue of sample preparation is of utmost importance. Recent advances in column switching approaches allow single components to be separated from complex mixtures, and incorporation of a number of different column types, from size exclusion to ion exchange to hydrophobic interaction, may permit acceptable levels of single compound resolution. When considering how a sample would be introduced into the instrument and analyzed the first consideration that we must face is the fact that the analysis temperature of 300K is higher than the ambient temperature of 95K. In addition, the most prevalent organic materials on the surface of Titan are likely to be relatively volatile materials like ethane and acetylene. Consequently, as samples are heated for analysis, the escaping volatile material should be analyzed and characterized. A preliminary idea for a device that would allow for parallel sample preparation is illustrated in Figure 3.

With this device an attempt is made to change the conventional separation in the time domain of a classical distillation into a separation in space. Imagine a chip into which sample is introduced at one end at a temperature of 95K. The sample end is then brought in contact with a heat source, which gradually ramps to a final temperature, perhaps about 500K. Meanwhile, the opposite end of the chip stays in contact with a 95K thermal sink. The change in temperature through the various chambers of the apparatus can be read by built-in thermocouples, and may reveal differential scanning calorimetry (DSC)-like information that may be useful. As the volatiles boil off, the vapors move toward the cold end of the device, working their way through a baffle system with many distillation plates. Ultimately, liquids condense at the zone in the device that corresponds to their boiling point. Once the desired temperature gradient has been achieved, heating is discontinued, and collected liquids are allowed to cool. The system ultimately reaches a state in which the components of the sample are partitioned among a number of different wells. The amount of material in each well can be gauged by built in level sensors, or perhaps by optical addressing. Spectroscopic analysis of individual wells may allow further characterization, and additional fractionation and analysis of the contents of individual wells may be possible if the contents can be transferred to another device through a port or septum. One advantage of this approach is that many samples could be run in parallel, and the results rapidly sorted into general categories, i.e. mostly ethane, mostly water, mostly non-volatiles, etc. This could allow for focused searches where many samples are collected, but only a few are chosen for in-depth analysis.



**Fig. 3.** Thermal gradient distillation chips for sample preparation? a) At ambient surface temperature of about 100K sample is loaded into the left side of the device, which is then heated to 500K while keeping the right side of the device in contact with a 100K heat sink. As heating progresses, a thermal gradient is established. b) As the volatiles boil off from the sample, the vapors move toward the cold end of the device and condensing as liquids at the zone in the device that corresponds to their boiling point. The relative distribution of materials within the chambers gives some indication of the general type of sample being analyzed, and material within the chambers can be available for further fractionation and analysis.

## 9. REMOTE DETECTION OF ENANTIOENRICHMENT

As a putative Titan organics explorer floats above the surface, what techniques can be used to identify areas where enantioenrichment might be found? Most chiroptical spectroscopy methods appear to be unsuitable for this task. Raman optical activity of backscattered light may be useful, but is likely to have a very limited range [39]. Similarly, the detection of circularly polarized phosphorescence or luminescence following UV irradiation could be used to detect the presence of some unusual types of enantioenriched compounds, but the range of the technique would be extremely limited, probably no more than a few meters [40]. The detection of polarization in "glints" of reflected light could be useful for identifying areas with flat surface such as liquids, ice surfaces or crystal faces, but would probably not be useful for detecting enantioenrichment [41]. Further study of laboratory analogs of candidate Titan surface organics is required to assess whether remote sensing of enantioenrichment is feasible.

## 10. IS ENANTIOENRICHMENT A UNIQUE SIGNATURE OF LIFE?

Contrary to popular perception, enantioenrichment is not a unique signature of life. It is simply an indication of an interesting, complex system [42, 43]. Abiotic generation of local areas of enantioenrichment is to be expected whenever one deals with the 5–10% of organic solids that crystallize as conglomerates. Since an individual crystal of a conglomerate contains only a single enantiomer, simple sorting processes involving winds, waves, or similar forces can act to deposit individual crystals into unique environments. Subsequent dissolution may afford nearly enantiopure solutions.

This idea is illustrated below in Figure 4. A puddle containing a racemic solution evaporates in the sunlight on a planetary surface. As the puddle evaporates, conglomerate crystals are deposited. After drying, a wind blows the crystals onto a pockmarked surface, where they land in a variety of different environments. A rain falls, and the crystals dissolve, forming a variety of different microenvironments with differing enantioenrichment, some of these environments being essentially enantiopure. It should be evident that this small pool of enantiopure material could, with the aid of forces such as winds, waves or tides, lead to high levels of enantioenriched products on a much larger, perhaps even a global scale.

## 11. IMPACT CRATERS MAY BE INTERESTING LOCALES TO SEARCH FOR ORDERED MEDIA ON TITAN

Some possible environments where enantioenrichment could be found on Titan can be identified. It is not known whether volcanism or geothermal heating occurs on Titan, though these are plausible based on the amount of radioactive elements likely to be in the silicate component of Titan's interior [44]. However, it is certain that like all solar system objects, Titan has suffered numerous impact events over the course of its history [45]. It has been estimated that impact of an object

of intermediate size with Titan's surface could lead to significant heat generation, which may melt ice to release water that could remain liquid for times exceeding  $10^4$  years [46]. Since the crust of Titan is likely to be mostly water ice [47], such an impact event is interesting from several perspectives. It provides:

1. A mechanism whereby water can become involved in the organic chemistry of Titan.
2. A mechanism where volatiles such as ethane and acetylene are blown off and higher molecular weight compounds can become concentrated.
3. A mechanism whereby organic compounds can become partitioned according to their solubility in organic or aqueous environments. In this view, an organic chemist might see an impact crater as nothing more than a giant separatory funnel.
4. An environment where crystallization can occur and where compounds can become segregated according to solubility.

If formation of conglomerate crystals occurs, mechanisms related to that illustrated in Figure 4 could lead to local areas of enantioenrichment.

One can imagine the possibility that different organic compounds could become segregated within the cooling crater, forming bands akin to the crystal layers seen in a cross section of an agate geode. Such an environment would be highly interesting as a site for organic analysis for the Titan organic explorer. Ideally, a cross section of the crater could provide a wealth of information, although a digging robot capable of performing such excavation would be beyond the scope of this mission. If we are lucky, a section of such a structure could be found, perhaps crosscut by an ethane/methane river channel [48] or split by a geologic fault.

Much easier to access than crater contents would be ejecta thrown from the gurgling crater-lake as it cools. Perhaps frozen water droplets, akin to rocky terrestrial tektites, could be easily collected in the vicinity of a crater. Those lying on top would presumably be the last deposited, and could be substantially depleted in volatiles, and may reveal some interesting fractionation.

It is interesting to consider the consequences of a secondary impact in the vicinity of a frozen, volatile-depleted, fractionated crater-lake. As most of the volatiles would already have been depleted, a greater fraction of the thermal energy of impact might go into the formation of higher molecular weight compounds from the segregated precursors, perhaps leading to some interesting chemistry. Numerical modeling of impacts into such an ice-organic milieu is required to quantify such speculations.

## 12. VOYAGE TO THE BOTTOM OF THE TITANIC SEA?

The possible existence of ethane and methane oceans on Titan is intriguing. Few compounds will have appreciable

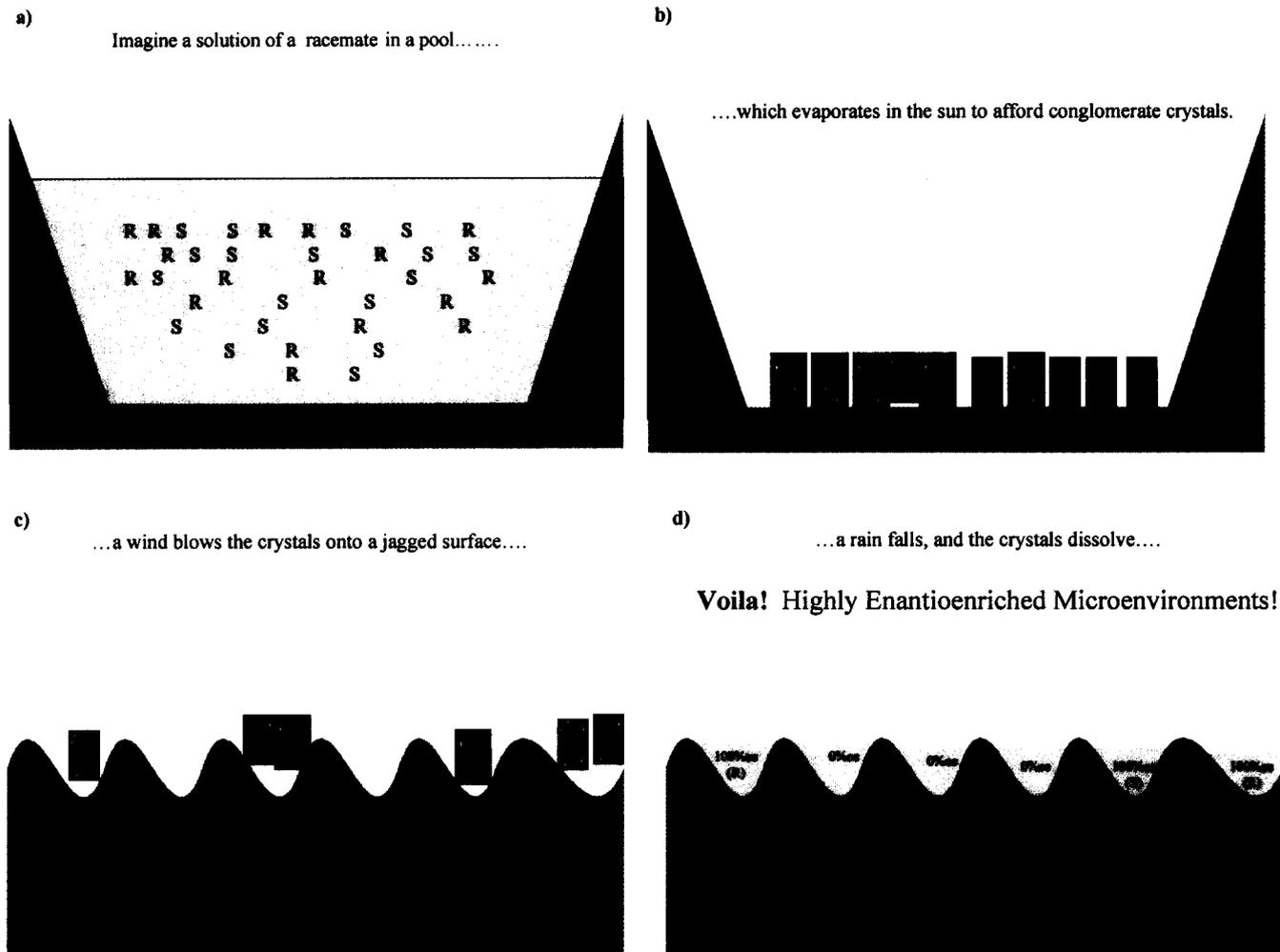


Fig. 4. Abiotic generation of highly enantioenriched microenvironments by stochastic sorting of conglomerate crystals.

solubility in such an ocean at 95K [49]. Places where ordered organic crystals or solids can be deposited from solution represent some of the most interesting sites where order can arise from a chaotic chemical combination. If one imagines the deposition of organic solids from a hydrocarbon ocean, accumulation of material at shorelines, floodplains, and evaporation basins could be imagined. However, because the density of most organic solids is larger than that of liquid ethane and methane, most of these solids will sink to the bottom [50]. Thus, some of the most interesting materials for analysis may well lie at the bottom of ethane and methane oceans, surely an extremely challenging environment to explore.

### 13. HOW WOULD WE APPROACH ANALYZING THE CHEMISTRY ON TITAN'S SURFACE?

Since a mission to Titan's surface is not likely to happen more than once in our lifetime, it is prudent to make sure that we ask chemical questions that are general enough to enable us to understand the data we receive from the spe-

cific instruments. We, therefore, must decide on an approach to do this. One such approach is shown in Figure 5. Here, we determine a site, based on the data from the Huygen's probe and the remote sensing information from Cassini. Once we land at that site, we want to characterize the organics as thoroughly as possible before we proceed to a hypothesis-based approach. We would look at the organic chemistry by examining both monomers and oligomers found in that region. We look for monomeric compounds with excess oxygen, metal-containing compounds and those oligomers that may have chiral properties. As we follow the decision tree, we obtain more and more specific information. The techniques needed to carry out such a scheme are still under development, but general techniques such as GC/MS and chiral detectors clearly play a large role. However, other methods, including some that have been discussed previously in this paper, need to be developed to meet the sensitivity requirements we know we will need to ensure the data is not ambiguous.

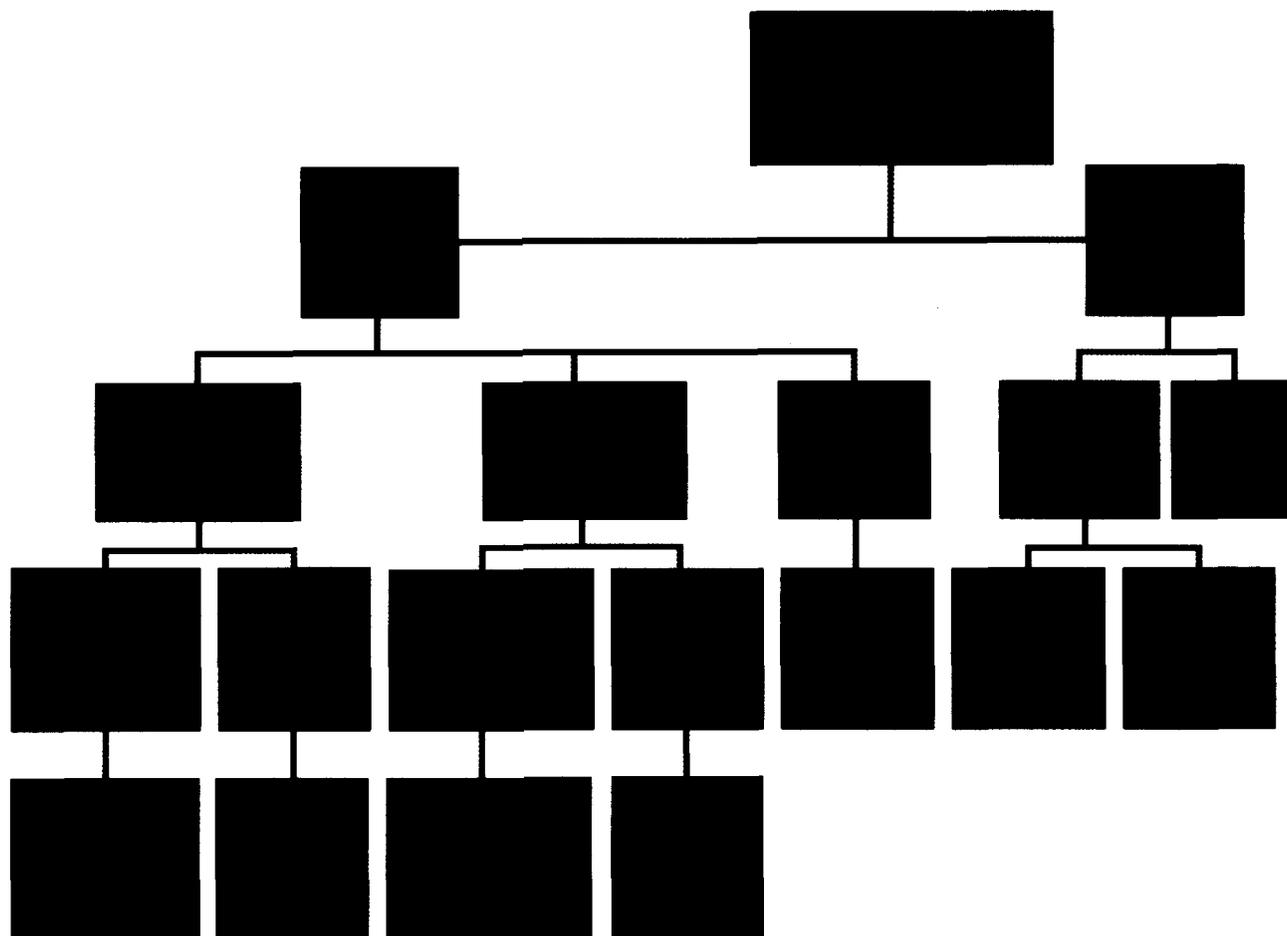


Fig. 5. Compound-based Decision Tree.

#### 14. CONCLUSIONS

The conditions on this hydrocarbon-rich but cold world are radically different than those that are believed to have prevailed on the prebiotic earth. Nevertheless, Titan may be the sole planet-sized body within our immediate reach where complex, evolving organic chemistry may be found and studied. Sending an organic analysis robot on a mission to explore Titan's surface chemistry and stereochemistry is an extremely challenging project that thus may yield some insights into the fundamental chemistry of life and the universe as we know it.

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