N75 20362

COMPOSITIONAL MEASUREMENTS BY OUTER PLANET ENTRY PROBE

Dr. John S. Lewis
Massachusetts Institute of Technology

DR. JOHN S. LEWIS: I think you have already seen illustrated in Dr. Hunten's talk one of the basic principles of atmospheric physics, which is the tendency for one's attention to sediment down to ever higher levels of density. I think you noticed that he several times found himself dangling down into the lower atmosphere where he felt he had no business being. This is understandable, because we just agreed on the guidelines about half an hour ago, long after he had prepared his talk.

I would like to start ab initio with the formation of the solar system and make it for you in two or three minutes according to my recipe at least and to derive from that very brief discussion a number of things which one ought to do or must do using planetary entry probes as the platform for investigation.

First of all, I think it is almost universally accepted that all of the planets in the solar system owe their parentage rather directly to a solar composition cloud of gas and dust which occupied the entire volume of the present solar system some 4.6 billion years ago. This cloud of gas and dust is called the solar nebula. We believe that we see today in the solar system several bodies which approach rather closely to the composition of this primordial material out of which all of the planets originated.

One of these, of course, is the Sun itself, which seems to be the product of gravitational collapse in such a gas and dust cloud without fractionation between components. Another appears to be Jupiter, which is quite close in its bulk composition to the composition of the Sun. Saturn deviates somewhat in the direction of being composed of intrinsically denser material than Jupiter, yet nonetheless, very close to that of the Sun. Uranus and Neptune, interestingly enough, continue in this sequence, being hydrogen-rich or volatile-rich material, yet progressively farther from the composition of the Sun in the direction of having a higher abundance of heavier elements, these being the so-called ice-forming and rock-forming elements.

Thus, what we see as the density trend of the outer planets is a compositional variation with distance from the Sun, caused ultimately by processes in the solar nebula. Those processes in the solar nebula which directly concern us are, first, the chemical processes (namely the sequential condensation of gases going to ever lower temperatures and ever greater distances from the Sun), and second, the physical accumulation processes by which a planet is assembled out of the gas and dust mixture.

We see in the outer planets a progressive enhancement of the abundance of the condensate component of the planet relative to the gas component of the planet. When we get to Uranus and Neptune we find that these components certainly are comparable in mass; indeed the component of condensed material may be dominant over the component of solar-type gaseous material.

Therefore, one of the things that we most urgently need to know, in investigating the atmospheres of the outer planets, is the chemical composition of the atmosphere down to the greatest depths manageable, for purposes of comparison with the elemental abundances in the Sun. Dr. Owen has already told us a bit about what has been done with spectroscopic studies of the atmospheres above their cloud layers. As you have already heard, those materials which are observable on Jupiter and Saturn: hydrogen, methane and ammonia - have abundances which are compatible with the planets being close to solar composition. But we must recall here that we are sampling one part in 10^{10} or so of the mass of the planet and this is a remarkably small sample on which to base far-reaching conclusions. Furthermore, we are looking at the coldest portion of the atmosphere of the planet, which means that most atmospheric constituents are condensed out and not visible to us.

Finally, we are looking at a portion of the atmosphere in which the majority of the gases present at levels greater than one part per billion are spectroscopically inert gases; hydrogen, which is a very weak absorber, marginally falls into that category, visible on the outer planets only because of its enormous abundance, and then, of course, helium, neon, argon, and the other rare gases. These are not detectable by remote observations with the possible exception of some very specific experiments which may be made in the immediate vicinity of Jupiter by remote sensing.

One point that is extremely important in understanding the fractionation process which distinguishes the outer planets from one another, is the way in which the abundances of the major elements vary from planet to planet. Classically, models for the outer planets have been generated by varying the hydrogen-to-helium ratio in these planets. I think that there is very little ground for believing that such fractionation occurs, but unfortunately, there are no data which we can bring to bear on this issue. It is extremely urgent to determine whether there is variation in the hydrogen-to-helium ratio in these atmospheres. This requires either upper-atmosphere measurements plus a firm knowledge of the location of the turbopause, or a direct measurement in the lower atmosphere. In some ways, since the latter measurement is not much harder and more reliable, that seems like the thing to do.

We would like to know the abundance of the major condensible components of the atmospheres, the components containing the major elements which make up solar material after hydrogen and helium; these are: oxygen, carbon, nitrogen and neon. Then, a factor of ten less abundant than these are iron, silicon, magnesium and the other rock-forming elements. We will not get deep enough into the atmospheres of the outer planets, in the next few centuries, to be able to assess the abundances of the rock-forming elements directly, but it is entirely possible that by penetrating to pressures of a few tens of bars, one can measure directly the abundances of methane, ammonia, water vapor, neon, and so on.

We also would like to have isotopic evidence on these gases. We would like, particularly, to know the isotopic composition of hydrogen - the H:D ratio - which has been reconstructed for the early solar system in two ways: first, by the study of hydrogen compounds in meteorites and, second, by spectroscopic studies of the atmosphere of Jupiter. We would also like to know the helium isotopic composition, and that of carbon, nitrogen, oxygen, and neon.

The precisions to which these isotopic analyses must be known vary greatly from element to element because very different processes are involved. If one measured the H:D ratio in the atmosphere of Jupiter or one of the other planets to a precision of plus or minus ten percent, that would be an extremely valuable experiment. On the other hand, getting the carbon 13 to carbon 12 ratio to a precision of plus or minus ten percent would be almost not worth doing unless, of course, you discovered some phenomenal, enormous isotopic effect which no one had anticipated.

Also, the analytical problems that must be faced in looking at the outer planets are made somewhat more interesting and somwhat more demanding by the fact that there are photochemical products present; materials such as ethane, ethylene, acetylene, methylamine, and other simple carbon-nitrogen compounds. These, however, are largely produced very high in the atmosphere and are high enough so that they may be chemically destroyed, reprocessed, and made back into methane and ammonia.

Thus, the experiments designed for looking at these interesting organic materials will be conducted above the cloud tops, a regime in which the entry probe would normally be traveling quite fast. These are intrinsically difficult measurements.

Other extremely important considerations for the outer planets concern their overall thermal structure. It's been known for some time that Jupiter is a net emitter of energy; that it produces approximately three times as much energy as it receives from the Sun: it has an internal heat source. This has been confirmed in somewhat less detail but still fairly convincingly for Saturn and Neptune. Uranus remains something of an enigma in that the data to date serve to prove neither that Uranus has an internal heat source nor that it does not, and one can only imagine that the middle apple in the row out there should not be different from the others in this respect. Nonetheless, the question remains unanswered: Does Uranus have an internal heat source? If it does, then all of our notions regarding the circulation structure of the atmosphere are strongly conditioned by that conclusion. It means that the atmosphere's motions are driven from below by the release of internal heat rather than driven from above by absorption of sunlight. This means, then, that the motions of the atmosphere will essentially penetrate all the way down into the deep interior of the planet. Since the outer planets are essentially gaseous in composition, this means that we are talking about the processes throughout the entire body of the planet being mirrored by our understanding of thermal balance in the upper part of the troposphere. That is a very important kind of thing to understand.

Skimming the cream off all that, there are, I think, a few reasons why a Uranus entry probe looks perhaps slightly more interesting than even a Saturn or a Jupiter one right now. Some of these reasons are quite obvious and are familiar to most of you. One of these reasons is that for the past few years we have been told repeatedly that one cannot confidently plan on surviving entry into the atmosphere of Jupiter with a probe which is not essentially all heatshield. Therefore, we have thought in terms of flying a payload which had a larger weight fraction of instruments in it, relative to heatshield, and putting it into a planet that was somewhat easier to enter. Many of our conclusions are conditioned upon, or predicated upon, the assumption of a very difficult atmospheric entry on Jupiter. This issue, unfortunately, changes every six months. There is a sort of a flip-flop in opinions: it gets harder, then it gets easier. I am predicting that by October it will get harder again.

There is also a telemetry problem, in that if a probe enters to great depths into an atmosphere which contains a large quantity of ammonia, it will have trouble transmitting through the ammonia gas. Studies of space probes common to Saturn, Uranus and Jupiter have to date largely been sized, and had their transmitters designed, on the assumption that the same package would be landed on each of the three planets. This means that entry into Jupiter, because it is so demanding on the communications performance of the spacecraft, would tend to cause design decisions which would hinder the applicability of that same entry probe to deeper investigation of the atmospheres of Saturn and Uranus.

In particular, it leads to the conclusion that, because of communication problems on Jupiter, a pressure vessel need not be included to protect any outer planet entry probe against pressures greater than ten or twenty bars.

Finally, we have the problem of doing analyses of the atmosphere. The questions of composition of the atmosphere are very important; they involve the resolution of questions such as the fractionation of materials between the outer planets; the cosmogonic problems of the composition of the condensed components versus distance from the Sun; the abundance of the isotopes of the light elements in the early solar system; the photochemical products, and so forth and so on; all of which are essentially questions involving analysis of the atmosphere. There is something to be gained, I think, from entering the atmosphere of

Uranus rather than that of Jupiter, because we have fairly good *a priori* evidence that there has been an enrichment of the minor constituents, namely, those which are not hydrogen and helium. Thus, the analysis for these constituents should intrinsically be easier. It is very promising to try to take advantage of that fact and, perhaps, be able to analyze and get the isotopic composition of some trace constituents which, in the atmosphere of Jupiter, would be extremely hard to detect.

We also must include on our entry probe the experiments shown on Dr. Hunten's graph, essentially a pressure gauge, temperature gauge, accelerometer, and nephelometer. I would add visible and infrared, upward and downward-looking sensors as being extremely important additions to the payload, and this suggestion is by no means unique to me or to Dr. Hunter. Then comes the central issue of the composition experiment. I think it is entirely clear that a mass spectrometer has to be the heart of such an entry probe analytical package. We would like to use whatever this analytical package is to analyze the atmosphere at several different discrete altitudes to see how the composition varies with depth. We need, basically, compositional data on the atmosphere in terms of the major chemical species present. If we want to get the isotopic species, we run into ever and ever and ever more demanding technical problems.

Let me just say a few words on the why getting the chemical abundances is relatively easy, the abundances of the chemical constituents of the atmosphere. On the outer planets, one has essentially a fractional distillation system built into the atmosphere. One may begin analyses at high altitudes (and low temperatures), and look at the mass spectrum of hydrogen, helium, methane and neon. Methane and neon do not interfere with each other in the mass spectrometer, in that they do not have any fragments which appear at the same mass number. The analyses can then be repeated lower in the atmosphere where the temperatures are high enough so that ammonia gas may be present. One can then measure the mass spectrum of the mixture of methane plus ammonia; since the fragmentation pattern for the local variety of methane is already known, you can subtract that out to get the isotopic composition of ammonia. Looking only at the sum of the two would defeat the purpose of getting the isotopic composition because the fragmentation patterns of the two overlap each other extensively. Next, at even higher temperatures, water vapor may be present, and one can do the same thing again on water to get the oxygen 18, 17 and 16 relative abundances.

Difficulties lie in the fact that for the two major elements, hydrogen and helium, the rarer isotopes are extremely rare. Also, although the isotopes such as nitrogen 14 and nitrogen 15 have abundances that are not enormously different from each other; nonetheless, the total abundance of ammonia is low. Thus, it becomes a difficult analytical problem.

Let us illustrate this briefly, by discussing how to get the hydrogen and helium isotopic composition. One cannot simply analyze the bulk atmospheric mixture containing fifteen percent or so of helium in a mass spectrometer and look at the peaks at mass four and three for the $3H_e:4H_e$ ratio, and two and one for the D:H ratio for the simple reason that what you actually see in the mass spectrometer is a very complex mixture in which the H_2^+ and the HD^+ ions produce very large signals, but the HD^+ signal occurs at the very same mass number as helium three and at the same mass number as the H_3^+ ion, which is formed in the ion source of the mass spectrometer in a hydrogen-rich atmosphere. Thus, there is mutual interference of helium and hydrogen. The H_3^+ ion interference is, under some operating circumstances, very important. This problem can be avoided through dropping helium out of the mass spectrum altogether, by operating at an ionizing voltage which is below the appearance potential of H_e^+ ions, thereby seeing the mass spectrometer hydrogen alone. This is the minimum complexity of handling required to determine such a simple thing as the isotopic composition of hydrogen and helium, the two most abundant constituents of the atmosphere.

If the isotopic composition of minor constituents, such as carbon, nitrogen, neon, are required, usually the situation is quite a bit more difficult. This is especially true if one wants to get the abundances of photochemical products which, in only a very few cases, could have abundances in excess of one part per million. This would require, if pursued to its logical extreme, a GCMS package on the entry probe. However, the complexity of such a package and experience over the last few years with a GCMS package on Viking, leads us to ask if there is not anything simpler that might be done. I frankly do not know what else can be done except by backing off from the original analytical goals. Thinking several years into the future, I would rather remain ambitious for the time being and hope that an instrument package could be worked up to solve these problems.

In the near future, I think there are a few important considerations facing us. One is that, in the case of the outer planets perhaps more than elsewhere in the solar system, the role of Earth-based observations of the planets remains extremely important. There are, as Dr. Owen has shown us, many new results, some of a rather unexpected nature, that have been forthcoming in the last few years. These results shall continue to accrue as new observational techniques are applied to the outer planets. I think that final design of the atmospheric entry probes cannot be done right now on the basis of present observations because there are things such as the degree of enrichment of methane in the atmosphere of Uranus which we will be learning that will strongly condition our choice of analytical instruments. This strongly conditions whether we can use a simple mass-spec type experiment or whether we have to go to some method of separating out methane, such as with gas chromatograph, and then analyzing that separately.

There is an important question of the degree of commonality that is practical between Uranus, Saturn, and Jupiter entry probes; whether they really should all use the same heatshield, the same communications system, and the same analytical package. If, as it now appears, the heavy elements are so strongly enriched in Uranus, its composition approaches that of Titan. Although Uranus certainly would not require anything like a Titan entry spacecraft, it still raises the difficult issue of the degree to which commonality for entry probes to these three planets can be maintained without sacrificing important quantities of scientific return.

I have suggested that chemical analysis of the atmosphere will be fairly easy for constituents with abundances more than a few parts per million, and that the isotopic analysis will in general be hard but subject to cleverness. I particularly wish to raise and keep before everyone the idea that the issue of the nature of the analytical experiment is far from settled; that a plain, pure-and-simple gas chromatograph may be helpful by itself, whether or not connected to a mass spectrometer. There might be some very promising compromises that can be worked out in that area. I think, especially in light of quite a number of recent developments, that Uranus still seems a safe and likely target for the first outer-planet entry-probe mission. It certainly has a great number of exciting aspects to it. But still, it is important to keep in mind that we are looking not only at the phenomena which were common to the origin of all the outer planets, but also the processes which distinguish between them. Therefore, entry into any one of the outer planets is not, by itself, sufficient. This forces us once again back to the difficult orbital issue of the degree of commonality that can be designed into probes which can be sent to three or more of the outer planets.

DR. RASOOL: Thank you, John. Any questions?

MR. DAN HERMAN: No questions, but I do have a comment. Your points on the desirability or lack of desirability of commonality are very well taken.

One of the things that we will probably do when we release this Phase B Study is we would ask the contractors, with the help of the scientific community to optimize the probe to Uranus since that is the entry mission that will occur first, and then to see if it makes sense to both the scientific vane as well as the technical vane, to retain that commonality for Jupiter and Saturn; and it may not. I mean, this is something that I think does need intensive study. But both points are very well taken.