NEW IR OBSERVATIONS OF TITAN AND POTENTIAL OF IN-SITU ATMOSPHERIC ANALYSIS OF THE OUTER PLANETS

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DR. TOBY OWEN: The main message I have to offer today is that we really need outer-planet probes. What I will describe is not so much what we know about the outer planets but a number of very confusing problems which we are uncovering at a remarkable rate, thanks to the successes that Ichtiaque has already recounted. It is all very well to have all this success with probes, and so on, but we are lagging a little in terms of understanding the significance of the results.

A. JUPITER

In particular, let me begin with a brief discussion of Jupiter. There are going to be other people this morning talking about the Pioneer 10 atmosphere results. These are extremely interesting and, at the present time, very difficult to reconcile with the other information that we have built up over a period of years on the structure and composition of the atmosphere.

Let me try, first, to review the previous work very briefly. Figure 2-1 is a reproduction of a plot made quite some time ago to show the abundances of various gases in the atmosphere of Jupiter as functions of the temperature or its equivalent, the depth in the atmosphere (Owen, 1969). In those days we thought that we could explain things pretty well by simply assuming solar abundances. In fact, that seemed to fit the infrared spectroscopic data very nicely: an adiabatic lapse rate terminating somewhere near a temperature of 225° at some kind of cloud layer in the Jovian atmosphere. At somewhat lower temperatures, i.e. higher up, another cloud layer existed in the region where ammonia condensed. So, the picture at that point was that when we look at Jupiter in the near infrared, we are looking through this ammonia haze layer

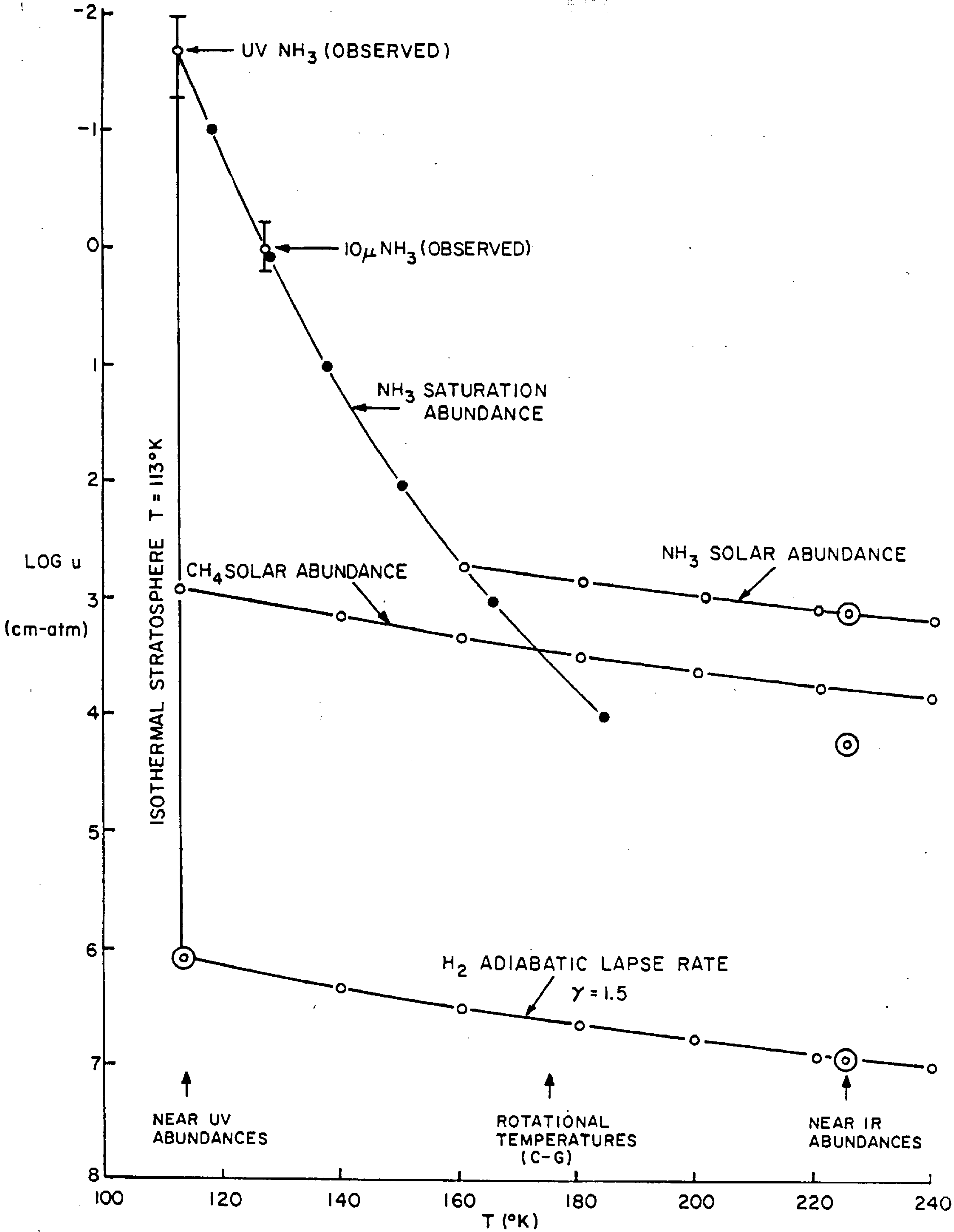


FIGURE 2-1 - Jovian Gas Abundances

down to a thick lower cloud whose upper boundary is at about 225°. In other words, we have two cloud layers and the kinds of temperatures that were deduced, either from analyzing methane molecular bands or using the ten-micron mean temperature or the ultraviolet temperature determined by the saturation vapor pressure of ammonia, all seemed to fit together very nicely with this picture (c.f. Figure 2-1).

One can combine these results very schematically into a kind of standard atmosphere plot for Jupiter, showing pressure versus temperature, again, assuming an adiabatic lapse rate, and adding the ten-centimeter radio emission which corresponds to a temperature of 300° Kelvin while at twenty one centimeters the thermal emission seems to be something on the order of 400° Kelvin. These points correspond to high pressure levels in the Jovian atmosphere (Figure 2-2 Owen, 1974).

All of these data seemed to fit together very nicely until Pioneer 10 went past Jupiter. What we then learned from the occultation was that the atmosphere was much hotter at higher levels than any of the previous data we had accumulated would have indicated (Kliore et al. 1974). So that, whereas, at a pressure of one atmosphere, we had deduced temperatures on the order of 150° or 180° Kelvin, the Pioneer 10 data seemed to indicate temperatures close to 400° Kelvin.

Now, how do you reconcile these two sets of data? As far as I know, there is no reconciliation, yet that really fits everything together; that can explain how the spectroscopic data and the Pioneer 10 data can be brought into agreement with each other.

The additional point I wanted to make this morning is that it isn't just the spectroscopy that one has to worry about.

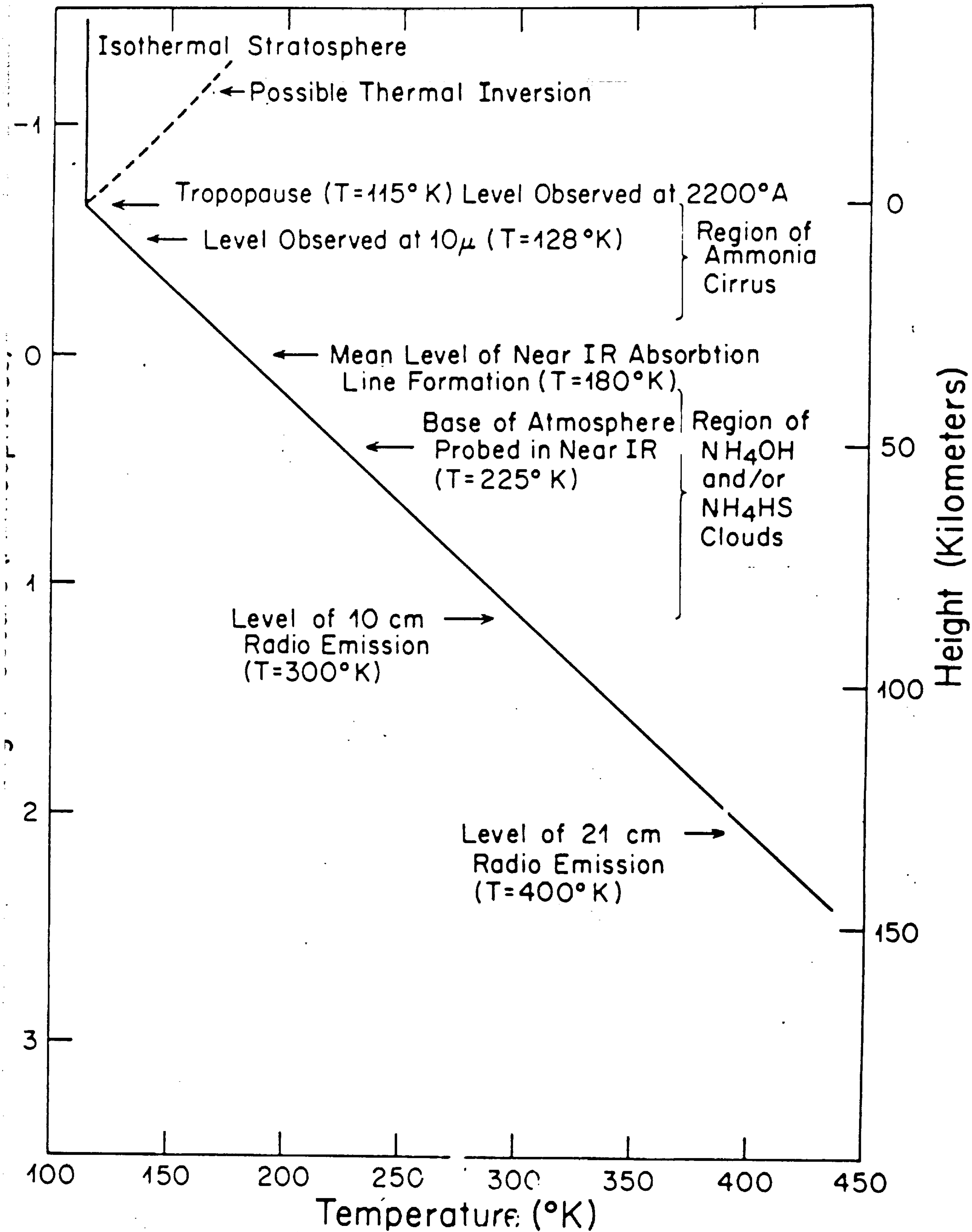
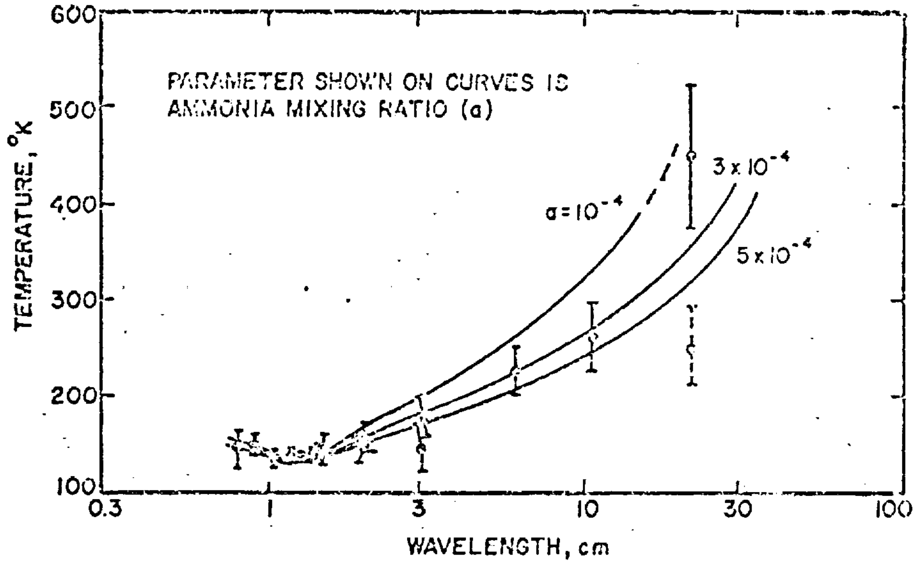


FIGURE 2-2 - Jovian Standard Atmosphere Plot

If that were the only problem, perhaps one could postulate some incredible confusion caused by scattering in cloud layers, although that is rather difficult to work out in any quantitative way that is convincing. There is an additional data set that must be dealt with, viz., the radio results. A plot for some model atmospheres developed by Gulkis and Poynter (1972) is given in Figure 2-3. Here temperature is plotted against wavelength and the parameter "a" is the ammonia-hydrogen mixing ratio. A solar value for this ratio would be between the upper two lines ($a \sim 1.5 \times 10^{-4}$) and that value seems to fit the data pretty well. Gulkis and Poynter concluded that Jupiter exhibits solar abundances, which was the same result one derived from the infrared spectroscopy. With a rather simple model atmosphere, using the hydrostatic equation, assuming the gases were mixed, one could fit the observational data in the radio range. The Pioneer 10 occultation data were obtained at a wavelength of about 12 cm where the ground-based radio measurements appear to correspond to a temperature of about 400°K at a pressure of about 10 atmospheres. It may be that the reason for the disagreement again lies in the model atmospheres that are used to interpret the ground-based data, but now scattering by clouds cannot be the culprit. Clearly much more work is needed in order to achieve an understanding of the relation between pressure and temperature in the Jovian atmosphere.

The other exciting thing that has happened recently in observations of Jupiter has been the discovery of trace constituents, namely ethane and acetylene and, most recently, phosphine in the ten-micron region of the spectrum (Ridgway, 1974 a, b). The reason this is exciting is that these constituents would not be predicted on the basis of simple thermodynamic equilibrium in the planet's atmosphere. They must be caused by some kind of photochemical effects in the upper



The radio spectrum of Jupiter, corrected for non-thermal emission. The lines shown correspond to fluxes predicted by model atmospheres with various ammonia-hydrogen mixing ratios. Note the rise in temperature with increasing wavelength (Gulkis and Poynter, 1972).

Figure 2-3 - Jovian Radio Spectrum

atmosphere and such effects have been suggested for many years as being responsible for the production of the chromophores, the material that colors the clouds on Jupiter. Ethane and acetylene have frequently been suggested as precursors for these more complicated organic polymers if, indeed, organic polymers are the responsible coloring agents. One has to be a little cautious here because there are other alternatives. There are polysulfides that could cause some of the coloration and I would like to remind you of a suggestion made by Rupert Wildt (1939) many years ago that solutions of metallic sodium in ammonia at the (pre-Pioneer 10) temperatures expected in the upper atmosphere of Jupiter, might be brown, red, or blue depending on the concentration of the solution, the temperature, and the amount of other trace metals. The reason for returning to this suggestion is that lately it has been discovered that there is a sodium cloud in the vicinity of Jupiter, apparently associated with the Satellite Io (Brown, 1974). This cloud provides a source for the sodium, thus removing an objection that has been voiced in the past to Wildt's suggestion. There are other difficulties but, again, the point I want to make is we are just beginning to uncover some of the clues to these chromophores which promise to be some of the most interesting chemical substances in the Jovian atmosphere. This is an example of a basic problem that will probably require the use of direct probes for its resolution, and that is not going to be a very easy thing to do either.

B. SATURN

A low resolution spectrum of Saturn was recently obtained by Gillett and Stein (1974) in the spectral region 7-13μm. Once again there are intriguing indications of non-equilibrium products in the planet's atmosphere. Phosphine is indicated, and the big hump at 13μm may well be due to ethane. There is no high-resolution spectroscopy in this region yet but the general shape of the spectrum is certainly similar to the spectrum of Jupiter where, in fact, some of these identifications have been made. We should get some much better observations of Saturn from the ground in the next couple of years. At least the identifications of these substances should become fixed. To determine how they relate to the chemistry in the atmosphere will probably again require the use of probes.

Now, the other piece of news about Saturn that I have is that Therese Encrenaz, Jerry Woodman and I have found, again, the elusive ammonia absorption around 6450 angstroms which was, I think, discovered for the first time by Larry Giver and Hyron Spinrad (1966). It definitely seems to be present but the amount of ammonia we find is very much less than the amount present on Jupiter, even though the hydrogen and methane abundances in the atmospheres of the two planets are roughly identical. We interpret this as an indication that, whereas on Jupiter one can see beneath the ammonia cirrus clouds down to the region where the ammonia and the other gases are mixed, on Saturn that does not happen and, so, the ammonia abundance is fixed by the local saturation vapor pressure. This, in turn, will depend on the local temperature so that fluctuations in cloud density and cloud height could easily lead to the variations in the ammonia abundance which have been reported.

C. TITAN

For the last three years, Titan has seemed to be some kind of perverse machine that's been put into orbit around Saturn by a superior race as a kind of intelligence test for earthlings, to see if they can unravel what's going on out there. So far, I have to report that we haven't done very well. The basic problem that has aroused so much interest is that the temperature of Titan at 13μm is much higher than one would have expected for a small satellite with a rather thin atmosphere at that distance from the sun. On the other hand, at somewhat longer wavelengths one finds the low temperatures that one would have anticipated. How does one reconcile these two sets of measurements? There have been two basically differing interpretations of this. One is based on a hydrogen greenhouse effect which suggests that light is getting down to the surface of the satellite, warming it up and then the resulting infrared radiation is being blocked at the longer wavelengths by large amounts of hydrogen in the satellite's atmosphere.

This view seeks support from the detection of hydrogen by Larry Trafton (1972a) in the 8200 angstroms region of the spectrum of Titan. The kind of greenhouse that results depends on various assumptions for the atmospheric composition. Jim Pollack, who's also here at Ames, has developed a series of models and concluded that the best of these corresponds to a surface temperature of 155° Kelvin (Pollack, 1973). Carl Sagan has gone to the extreme of suggesting temperatures in excess of 200° Kelvin and has stressed the possible biological importance of Titan (Sagan, 1973).

Sagan's extreme greenhouse models, I think, are ruled out on the basis both of thermal measurements at five microns, and microwave measurements which correspond to radiation from the surface of Titan and indicate temperatures below 175° Kelvin (Briggs 1974).

Unfortunately, the true surface temperature is still unknown because the microwave measurements have a very large uncertainty. An alternative explanation for the high temperatures on Titan involves the presence of a dust layer, a kind of thin, high cloud in the atmosphere which is absorbing a lot of radiation in the ultraviolet, warming the upper atmosphere and leading to reradiation by the gases at that level. Once again, we expect that methane emission is present at 7 - 8μm and ethane is in emission at 13μm. With this model, proposed by Bob Danielson and his colleagues at Princeton, one can have rather low surface temperatures (Danielson et al, 1973).

Roger Knacke, Dick Joyce and I made some measurements at KPNO this last winter to try to distinguish between these two basic alternatives. Last year we tried and failed to detect the flux from Titan at five microns (Joyce et al, 1972). We chose five microns because we know that in the atmospheres of Saturn and Jupiter this is a "window" region in the spectrum. In other words, the principal atmospheric gases do not absorb at this wavelength and one has the chance of looking very deep into the atmosphere, possibly to the surface of Titan itself. We did not detect any radiation on this earlier measurement but last winter we did (Figure 2-4, Knacke et al, 1974). If one assumes that the radiation is reflected sunlight then the curve sloping down from the left represents the flux expected from a perfect reflector at Titan's distance from the Sun. So the fact that the Titan flux is far below this curve indicates a very low reflectivity at five microns, about 7 percent. In other words, Titan is very black there. Alternatively, if what we are really seeing is thermal radiation, and not reflected sunlight, then we can look at the family of black body curves sloping up toward the right and we

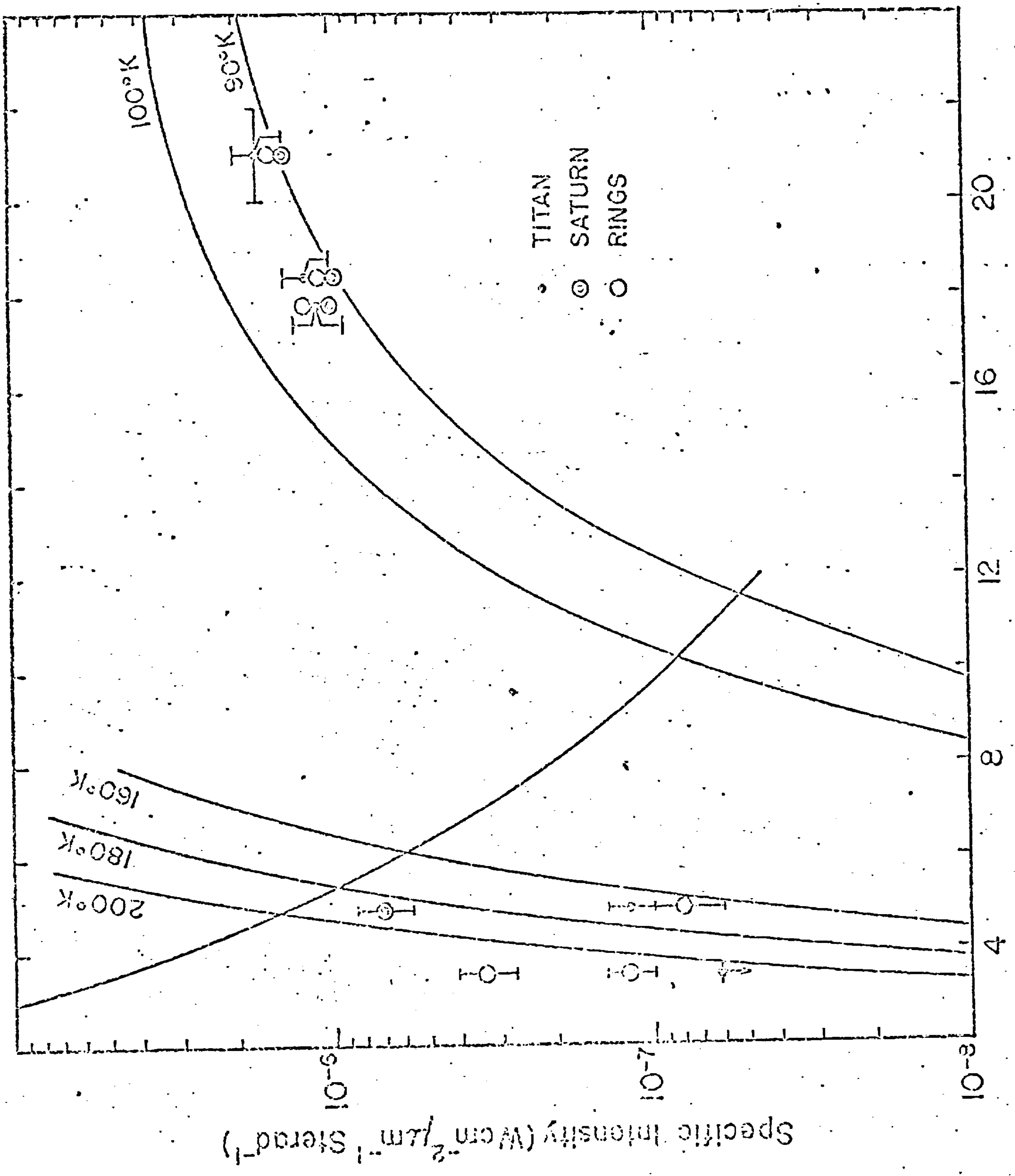
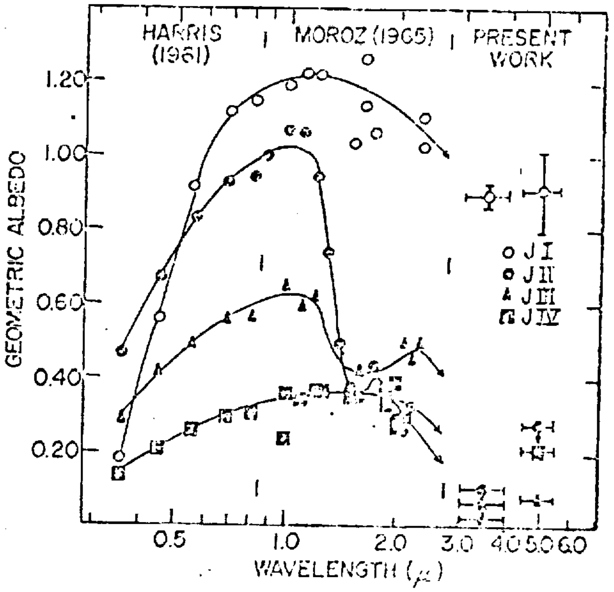


FIGURE 2-4 - Radiation Observations of Saturn and Titan, 1974 can conclude that the temperature must be less than about 170° Kelvin.

This has some interesting implications for what the satellite's surface may be covered with, if we are seeing the surface; or what the clouds are made of, if what we are seeing is clouds. To explore this further, we can compare Titan with the satellites of Jupiter. Reflectivities of the Galilean satellites are shown in Figure 2-5 (Gillett et al, 1970). It is apparent that the geometric albedo (reflectivity at zero phase) at five microns is rather different for the different bodies. In fact, most of them are poor reflectors and J-III, in particular, has a very low albedo. It approaches the value of Titan. On the other hand, J-I, Io, which is intriguing in so many ways, has a very high reflectivity in this region. In fact, it's very close to a perfect reflector, despite the fact that it is an exceedingly poor reflector in the ultraviolet. Both Io and Titan are extremely red objects. Their surfaces must be covered with something very different from the surfaces of these other satellites or, indeed from any other satellites in the solar system. But, at five microns, their "colors" are not at all similar. That suggests that the red material on the two satellites may be of two different types.

We also have observations of Saturn's rings at five microns and they are even darker than Titan or the Jupiter satellites (Figure 2-4). That we would expect, because we know that there is ice present in the rings of Saturn and ice is a very poor reflector at five microns.

We can examine laboratory spectra of many substances to see how they behave at five microns. A catalogue of such spectra has recently been published by Kieffer and Smythe (1974), and it is easy to rule out some substances as major contributors to the reflectivity of Titan. For example, methane has a very high reflectivity so a thick methane cloud on Titan or a methane frost on its surface won't work. Similarly, covering the surface entirely with H_2S or NH_3 in a frozen state won't satisfy the data.



Geometric albedos (reflectivities) of the Galilean satellites (JI-JIV) as a function of wavelength Smooth curves are qualitative, but note that all are plotted on the same scale. The high reflectivity of Io (JI) beyond 0.7 μ and its red color (cp. Titan in Figure 1) are especially remarkable. Data for 0.35-0.85 μ are from Harris (1961), for 0.85-2.5 μ from Moroz (1967) and for 3-5.4 μ (labelled 'present work') from Gillett *et al.* (1970).

FIGURE 2-5 - Reflectivities of the Galilean Satellites

On the other hand, NH_4SH is a possible candidate. As mentioned above. Water ice is too dark at 5μm for Titan; something else is needed to brighten it up or perhaps it only covers part of the surface. Most silicates, of course, are rather dark at five microns, too. The possibilities are limitless. You can't do diagnostic compositional analysis on the basis of data like this. It's just interesting that you can exclude a few things.

Now we get into more exotic problems, like what is the red material in the atmosphere - or on the surface? This problem relates to the remarks about the chemistry on Jupiter. We are very interested in the organic chemistry that is taking place in atmospheres like these because of its obvious relation to ideas about what happened on the early Earth prior to the development of life.

Khare and Sagan (1973) have produced a reddish-brown polymer by ultraviolet irradiation of a mixture of hydrogen sulfide, methane and ammonia - all gases we expect to be present in the lower atmosphere of Titan. This doesn't seem to be a very good candidate for the coloring agent on Titan, if it is the only substance present, since it is quite transparent at five microns. On the other hand, a mixture of this material and water ice might reproduce the observations quite well. Tom Scattergood, Peter Lesser and I have also produced colored polymers by using proton irradiation of this same mixture of gases (Scattergood et al, 1974). We found one substance with a rather strong absorption in the five-micron region, which was not present when H_2S was not used in the mixture. So, even starting with the same constituents you can produce different materials if you use slightly different excitation sources. Once again, this is not the ideal way to figure out what the stuff is that's coloring these objects. One can only eliminate some alternatives. This is a prime example of the kind of thing one would love to be able to investigate with a suitably-equipped probe.

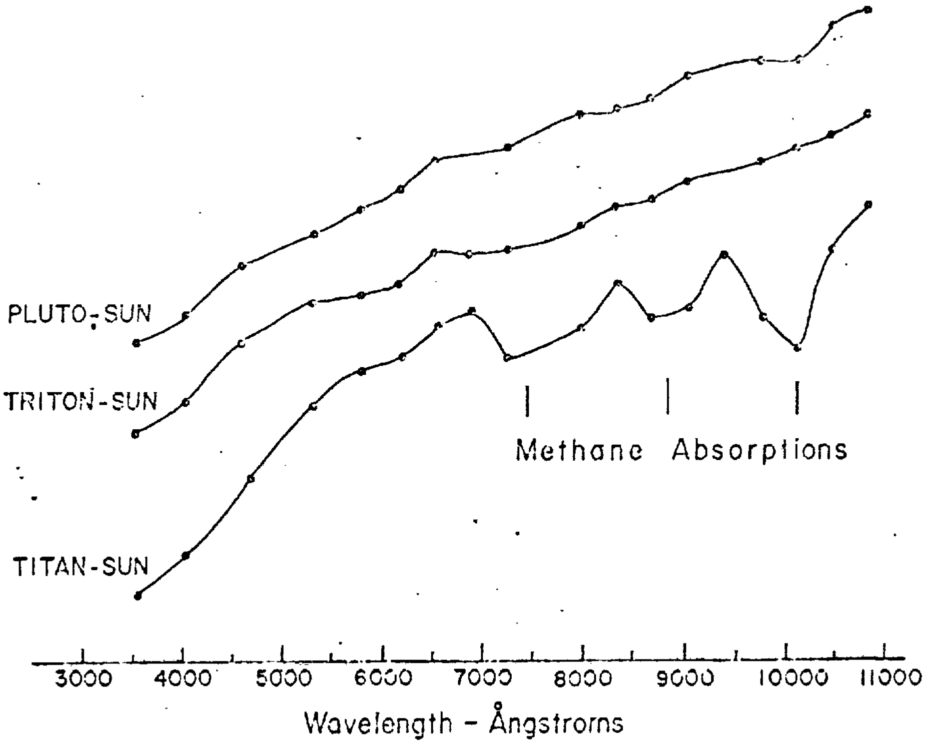
Now, a word about atmospheric models. A family of hydrogen greenhouse models for Titan has been developed by Pollack (1973). In his plots of wavelength against brightness temperature, a decrease in the brightness temperature near 16.7μm is predicted on the basis of the absorptivity of hydrogen. We have measured a point in the wing of this absorption (c.f. Figure 2-4) and we do not see any indication of this dip. Low and Rieke (1974) have obtained essentially an identical result. The absence of any indication of hydrogen absorption argues against a thick hydrogen greenhouse, if the atmosphere is completely clear (no clouds).

Carl Sagan has stressed that a lot of hydrogen could be hidden underneath a thick layer of clouds but, as we have seen, these clouds, if present, must be very thick and very dark at five microns.

The alternative model suggested by Danielson et al (1973) predicts that the flux should be rising toward wavelengths greater than 20μm because they are summing the contributions from the high-altitude dust layer and the surface. Now, in fact, we see a slight decline and a rather flat spectrum in this region, in mild disagreement with this particular model. Slight changes in the two emissivities and the temperatures might reconcile the predictions with the observations. We are not really in a position to make a definite statement in this case. This is the same conclusion reached by Low and Rieke (1974) who suggest that, perhaps, the answer is that Titan simply has a methane atmosphere with little, if any, hydrogen and a small methane-induced greenhouse effect. Titan may thus be a much less fantastic place than it seemed just last year.

D. PLUTO AND TRITON

Figure 2-6 shows some data in the 3,000-to-11,000-angstrom region; very low resolution spectroscopy obtained with the 200-inch telescope and a multichannel spectrometer just to see if there's any indication of methane absorption, i.e., atmospheres



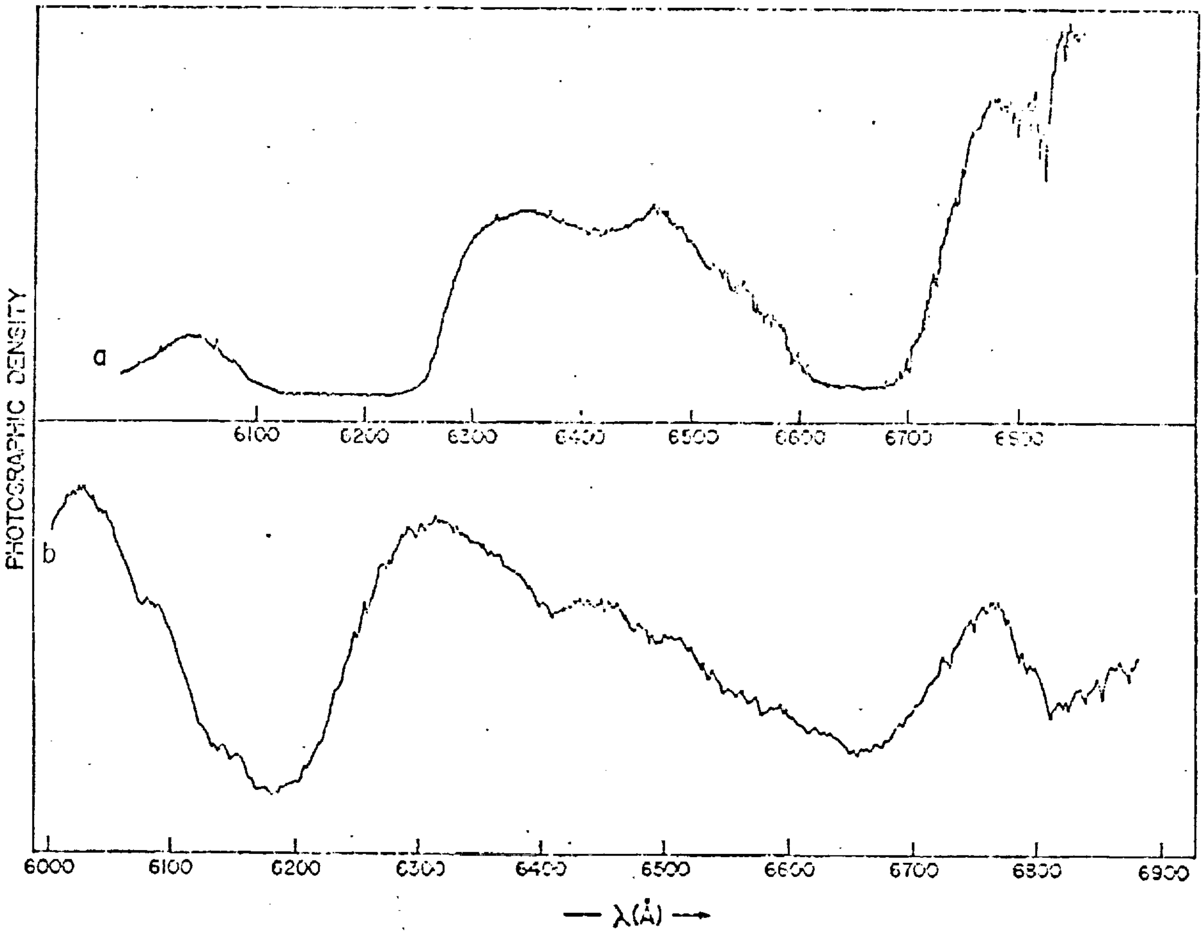
Low-resolution spectrophotometry of Titan, Triton and Pluto (200-in. telescope plus Oke multichannel spectrophotometer). Note the absence of methane on Pluto and Triton and the redder color (steeper slope at short wavelengths) of Titan. (The vertical scale is displaced for each object; these are only *relative* observations.)

FIGURE 2-6 - Low Resolution Spectrophotometry of Titan, Triton and Pluto on Triton and Pluto. Titan is shown for comparison. We don't see any absorptions at this kind of resolution with the data available thus far. These two objects would have to have some kind of greenhouse effect in order to get the temperatures up high enough to maintain methane atmospheres, and it appears that unlike Titan, they do not exhibit this phenomenon.

E. URANUS AND NEPTUNE

Even though Uranus and Neptune are very far from the Sun, radio observations at longer and longer wavelengths indicate higher and higher temperatures just as in the case of Jupiter and Saturn and so we should not, a priori, exclude the possibility that these planets have some interesting chemistry going on in their lower atmospheres in spite of their remoteness. This increases their attractiveness as targets for atmospheric probes.

The atmospheres of these two planets are very different from those of Jupiter and Saturn, and this difference has been emphasized by some new results that we obtained just last summer. What we found is that if we take the spectrum of Uranus after dividing out the solar spectrum and try to match the atmospheric absorptions with laboratory spectra of different amounts of methange, we can't do it with the pathlengths that are available to us (Figure 2-7). The maximum attained in the laboratory by Dr. D. A. Ramsay of the Canadian NRC is a five kilometer path at a pressure of two atmospheres, so the total amount of methane is ten kilometer amagats. There must be more methane than that in the optical path into and out of the atmosphere of Uranus (Owen et al, 1974). This was quite a surprise to us because we had looked at some weak bands in the spectra of these planets at longer wavelengths some time ago and thought that we had about the right amount of methane (Owen, 1967). These new results indicate that the methane-hydrogen mixing ratio on these two planets is very much higher than it is on Jupiter and Saturn; not just by a factor of ten as we had thought before.



-(*a*) Density tracing of the 10.1 km amagat spectrum of methane, without the wavelength comparison lines, taken with the 33-m NRCC White cell. The rotational structure longward of 6800 has been tentatively identified as $5\nu_3$ by Owen (1966). (*b*) Intensity spectrum of Uranus divided by the lunar spectrum in the same spectral region as in fig. 2*a*. Note the slight difference in scales, and that the ordinate labeling of "photographic density" applies only to fig. 2*a*.

FIGURE 2-7

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We have made a preliminary attempt to try to compare the two planets at even shorter wavelengths (Encrenaz et al, 1974). This study indicates that there is even more methane on Neptune than on Uranus. The increase seems to be on the order of twenty-five percent or so. The mere fact that one is seeing methane bands down to these very short wavelengths (the shortest is found at 4410 angstroms) is an indication that really immense amounts of this gas must be present.

Model atmospheres for Uranus and Neptune have been suggested by Lewis and Prinn (1973) and revised by Weidenschilling and Lewis (1973). What we are saying implies that the level of methane condensation has to be lowered quite a bit and that condensation is going to occur even lower in the atmosphere than was indicated before. It looks to us as if one is seeing beneath the condensation level in these short wavelength spectra just as one is on Jupiter in the case of ammonia and that the methane abundances are very large indeed. How can this be reconciled with the Rayleigh scattering that should occur in such deep atmospheres? This is one of many questions yet to be resolved.

F. CONCLUSIONS

Let me close by just summarizing the abundance situation as we see it at the moment (Figure 2-8). I am not including here the very exciting new work on ethane and acetylene and so on, these are just the major atmospheric constituents. What we find, in compiling these various numbers and then trying to deduce the hydrogen-to-carbon ratio, is that in the case of Jupiter and Saturn we seem to have roughly solar abundances as far as hydrogen and methane are concerned at least; whereas, for Uranus and Neptune these ratios are way, way down. We simply don't know the exact numbers because we don't have long enough pathlengths to determine them. We don't have any of the methane bands quantitatively analyzed so that we cannot calculate these numbers either.

Figure 2-8

ABUNDANCES IN THE OUTER SOLAR SYSTEM

OBJECT	H_2 (km atm)	NH_3 (m atm)	CH_4 (m atm)	H/C
JUPITER	75 ± 15	12 ± 5	50 ± 15	3000 ± 300
SATURN	75 ± 20	2 ± 1	60 ± 12	2500 ± 400
URANUS	450 ± 100	< 2.5	$>10 \times 10^3$	< 100
NEPTUNE	450 ± 100	---	$>10 \times 10^3$	< 100
PLUTO	---	< 10	< 2?	---
TITAN	5 ± 2.5	< 2.5	200 to 1600	6 to 50
TRITON	---	---	< 2?	---
			SUN	2700 ± 300

Model dependent upper limits are given for the other objects. The hydrogen and methane abundances for Titan deduced by Trafton (1973 a,b) lead to a very low ratio for H/C. There now seems to be the possibility that the ratio is even lower, if the hydrogen observations can't be confirmed.

MR. RASOOL: Those are in kilometers and the others are in meters?

MR. OWEN: That is right; the hydrogen values are in kilometers, the others are in meters.

Incidentally, the ammonia on Jupiter also seems to have the solar ratio and this is what convinces us that we are looking beneath the level where the abundance is set by the saturation vapor pressure, whereas, on Saturn this is obviously not the case.

You may now feel in the midst of total confusion because I have tried to cover a lot of material in a very short time. But some of this confusion is real; there is a large amount of basic information we simply don't have, other sets of data seem to be in conflict with one another, and there are glimmerings of very intriguing problems we are only beginning to solve. That is the point from which we want to go forward and produce the atmospheric probes which are the main subject of this conference so we can finally obtain some really reliable results.

MR. RASOOL: Thanks, Toby, for a very scholarly lecture in which you included some of the very recent results which shows immediately how the science is moving on a daily basis. A year ago when we had a Titan workshop here we thought everything was under control. We had some estimates of the hydrogen pressures going up to 700 millibars. Today we see entirely different things. That will give you an idea how fast this science is moving; the amount of data we get in all the spectral bands is restricted because the ground-based telescope is the only tool we have at the present time, the only means of deducing the abundances except for Jupiter, of course, where we have some new results.

Now, this presentation assumed that all of you know that outer planets are giant bodies with high gravity and made mainly of hydrogen and helium. The helium was absent in the last table because we cannot observe helium from groundbased telescopes. So I am just adding the helium part; we don't know how much there is on the outer planets. That is one very important question we have to answer. The problem you are going to have in the next ten years is to be able to design probes to survive the uncertainty, and also design payloads for the probes which clarify the uncertainties.

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