AN INTRODUCTORY REVIEW OF OUR PRESENT
UNDERSTANDING OF THE STRUCTURE
AND COMPOSITION OF URANUS' ATMOSPHERE

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Measurements of the gross properties of Uranus are enough to show that it is a planet with quite unique characteristics. The best estimates of its radius (24900 km; Danielson, Tomasko and Savage, 1972) and of its mass (14.54 Earth masses; Klepczynski, Seidelmann and Duncombe, 1970) imply an interior structure and overall composition that set it clearly apart from Jupiter and Saturn (Hubbard and MacFarlane, 1980).

The best estimates of the maximum outflow of internally generated heat (< 250 ergs cm^{-2} sec^{-1}; cf. Wallace, 1980) and its peculiar axial orientation (98° obliquity; Dunham, 1971) set it apart from its otherwise superficially similar sister planet, Neptune, when considering problems of atmospheric structure.

In this review, I will attempt to summarize the enormous progress that I believe has been made during the past decade (the average number of research papers regarding Uranus' atmosphere has increased from an average of one per year in the late 1960's to an average of ∿ 13 papers per year in 1980) in understanding the planet's spectrum in terms of the probable chemical and physical nature of its atmosphere.

Essentially, all the work which has been done so far is *exploratory* in nature and I cannot report that a concensus on the/mean structure and composition of the planet's atmosphere has yet been achieved; there are, moreover, several important areas that need to be further explored before such a concensus can be expected. I am thinking particularly of questions concerning the time dependence of atmospheric structure which might occur as a result of the extreme seasonal characteristics of Uranus. On Uranus, unlike other planets, the polar regions receive an average of $\pi/2$ more insolation than the equatorial regions. It is, nevertheless, possible to identify the general domain of the mean structure and composition and, perhaps more significantly, identify some of the critical observations on which future advances may depend.

I begin by presenting a thumbnail sketch of our current view of the atmosphere in the context of a comparison with Neptune's atmosphere which, in the past, has often been assumed to have similar properties. This similarity of the two planets is now, I believe, very much in question.

1. A Thumbnail Sketch

So far as we know, the primary atmospheric constituents of the visible atmosphere (H$_2$ and He) represent only 11 percent of the planet's mass (Hubbard and Macfarlane, 1980) and, *if* an interface between this atmosphere and the ice-rock mixture that makes up the bulk of the planet, in fact exists, is about 7800 km deep with a base pressure near 221,000 bars at a temperature of 2500°K.

Of the sensible atmosphere itself, our observations have probed, albeit crudely in many cases, the region from $\sim$ 10 μ bars to near the 100 bar pressure level. Above 10 μ bars, we are in the realm of aeronomical conjecture which I shall not review although some exploratory work has been published by McElroy (1973) and by Capone et al (1977). 100 bars is about the deepest level that it has been possible to probe with microwave radiometry (21 cm observations; Briggs, 1973).

The Uranian stratosphere (10 μ bar - 0.05 bar) is surprisingly cold ($\sim$ 95°K) while that of Neptune has a temperature ($\sim$140°K) and emission properties that are more in concert with our experience at Jupiter and Saturn. This may imply small but significantly different tropopausal structures on the two planets, in spite of their almost identical effective temperatures, since it is the tropopause temperature which probably control the stratosphere methane content and, thereby, its thermal balance with solar insolation. The meaning of "significant" can be inferred by noting that only a 3°K change in the assumed effective temperature could lead to a factor of two in the inferred stratospheric temperature (Wallace, 1975) on account of the sensitivity of the vapor pressure of CH$_4$ on temperature. Evidence that such differences do exist in the tropopausal region ($\sim$ 50 m-bar level) is evidenced by the presence of cloud and "weather" at this level on Neptune (Joyce, Pilcher, Cruikshank and Morrison, 1977) but not on Uranus.

Between 0.1 and 10.0 bar, where the bulk atmosphere is in most effective radiative contact with space, the controlling thermal opacity (collisionally induced translational transitions in H$_2$ - He) and the "effective" temperature are essentially identical on the two planets. As a consequence, the structures in this region should be very similar; a fact to which the visible and near infrared spectrum atests. In this region, the scale height is about 40 km and the lapse is near 0.8°K km^{-1}; methane condenses in this region, solar heating has its peak value, and there are

indications of a system of layered clouds.

   At pressures greater than a few tens of bars ($\sim$ 30 bar; cf.
Wallace, 1980) the thermal structure is very sensitive to the actual cloud
structures that are present (they control the deposition of solar heat)
and the internal heat flux. Since it seems that Neptune's internal heat
flow ($\sim$ 300 ergs cm^{-2} sec^{-1}) is at least two times that of Uranus (and
perhaps much more) then it seems to me quite possible that the two planets
might exhibit different structures at these levels. On the other hand,
the microwave spectra (1 - 21 cm) which are thought to probe these regions
on both planets are very similar (cf., Morrison and Cruikshank, 1973)
and, even though the shape of either spectrum has yet to have a satisfac-
tory explanation (Gulkis, Janssen, and Olsen, 1978), this probably means
similar atmosphere structures at these depths (10 - 100 bar).

   Before moving into a more detailed discussion and since this
paper is in the nature of an introductory review, I would now briefly like
to note a few of the speculations that have crept into the research liter-
ature and which are now known to be definitely incorrect. This should be
helpful to new readers of the literature and also helps to salve my own
conscience, since I helped perpetuate some of them. The idea that extended
wings in collisionally induced dipole transitions in H_2 provide substan-
tial opacity throughout the near infrared (Belton, McElroy, and Price,
1971) is no longer necessary or useful; the idea that simultaneous trans-
itions in a $CH_4 - H_2$ mixture have a role in producing the near infrared
spectrum (Danielson, 1974) has been disapproved by new and extensive
laboratory spectroscopy by Fink, Benner and Dick (1977) and by Giver
(1978); the idea that no detectable aerosols exist in the Uranus atmosphere
(Belton et al, 1971) has been disproved by proper treatment of radiative
transport in the H_2 quadropole lines and observations of the (3 - 0) S(0)
collisionally induced feature of H_2 at 8250Å (Trafton, 1976; Belton and
Spinrad, 1973); confusion in the literature on the value of the transition
movements of lines in the (4 - 0) band of H_2 (cf., Wallace, 1980) has now
been cleared up with further laboratory work by Brault and Smith (1980)
and the measured values are close to the theoretically computed value
(Dalgarno and Allison, 1969). Thus, Trafton's (1976) work in interpreting
the H_2 spectrum of Uranus remains valid; finally, speculations that have
surfaced from time to time regarding the presence, in large quantities, of
a spectroscopically inert gas other than He (eg., from the studies of sharp
CH_4 lines near 6819Å) all appear now to be without any real basis.

2. A Stroll through Uranus' Spectrum

   As an introduction to a discussion on structure, let me now
briefly review the character of the Uranian spectrum from whence the major
part of our knowledge comes. This emphasis, of course, is not meant to

deny the exceedingly important contributions from photometry (albedo; Younkin, 1970); from occultation measurements (stratospheric temperatures; Dunham, Elliot and Gierasch, 1980); from polarimetry (eg., Michalsky and Stokes, 1977; presence of upper atmospheric aerosols); from imagery (dimensions; limb brightening/darkening; Danielson et al, 1972; Sinton, 1972); and from center-to-limb observations (atmospheric inhomogeniety; CH_4 saturation; Price and Franz, 1979; Pilcher et al., 1979).

In the ultraviolet, the shortest wavelengths at which, to my knowledge, the planet has been observed is 1800Å by the ANS satellite (Savage, Cochran and Wesselius, 1980). The planetary spectrum between 1800Å - 4200Å, which is superposed on the reflected solar spectrum, is dominated by the effects of rotational Raman transitions in H_2 (Belton, Wallace and Price, 1973) and a diffuse absorption continuum whose origin is, at present, undetermined. At one time, I considered that observations of the Raman effect would impose significant boundary conditions on the distribution and amount of aerosols in the visible atmosphere, but this has not turned out to be the case and almost any of the many models considered so far for the Uranus atmosphere will satisfy the observations. The Raman transitions do, however, make a significant statement about the ortho/para ratio of H_2 in the atmosphere.

The underlying absorption may well be the same "Axel" dust that exists in the upper atmospheres of Jupiter and Saturn - a photochemical detrius - but this is ad hoc and some of the absorption may be associated with one of the atmospheric cloud layers.

From 4200Å out to nearly 5μ, the spectrum is dominated by a complex progression of CH_4 bands. Recent and extensive laboratory work by Lutz, Owen, and Cess (1976), by Fink, Benner, and Dick (1977), by Giver (1978), and by Silvaggio (1977); and some measurements at low temperatures (in the stronger bands) have enabled the first quantitative attempts of explaining the planetary spectrum in terms of the complex coupling between the abundance of CH_4 and atmospheric structure (Wallace, 1980). The so-called "blue" bands near 4800Å are found to place the most significant constraints on the deep CH_4/H_2 mixing ratio since they are weak enough for the radiation field to probe below the level of CH_4 saturation; the stronger bands near 1μ put strong constraints on the abundance of upper atmospheric aerosols <u>and</u> the He/H_2 ratio but not on the abundance of CH_4; finally, but in a less constructive way, the weak interband absorption in CH_4 severely limits the interpretation of the (3 - 0) collisionally induced dipole absorption of H_2 near 8250Å which is very important for constraining cloud structure (Trafton, 1976) and measurements in the laboratory at low temperature are urgently needed.

Superposed in the CH_4 spectrum in this region is the relatively sparce spectrum of H_2 and HD. HD <u>has</u>, I think, been detected (Trafton and Ramsey, 1980; Trauger et al, 1977) <u>in</u> the (5 - 0) band and the mixing ratio with H_2 is close to $4 \cdot 8 \times 10^{-5}$, similar to Jupiter and Saturn. This result evidently must be taken into consideration in condensation scenarios for the planet (Hubbard and MacFarlane, 1981) for enhancements of a factor of two or more in Uranus and Neptune are expected. Perhaps on Uranus, D is still "trapped" in a partially solid ice ball? Observations of HD in Neptune are obviously of great interest.

The observed H_2 spectrum consists of six lines of the quadrupole spectrum (5 - 0, 4 - 0, and 3 - 0 bands) and one line of the pressure induced dipole spectrum (S(0) in the 3 - 0 band). The relative strengths of lines from odd and even rotational levels indicate that the H_2 rotational populations are close to thermal equilibrium for the temperatures in Uranus' upper atmosphere. (This is also indicated by the Raman spectrum.)

The H_2 spectrum has turned out to be the crucial element in understanding cloud structure in the visible part of the atmosphere (cf., Trafton, 1976). The (3 - 0) quadrupole and dipole lines require a base cloud at a depth of $\sim$ 500 km - amagats of H_2 ($\sim$ 5 bar level); while the (4 - 0) lines require, in addition, a thin, tenuous, haze high in the atmosphere ($\tau \sim 0.3$ at 6400Å). The haze is ineffective if placed low in the atmosphere while its highest possible altitude is restricted by the observed albedo in the bottom of strong CH_4 bands. The 1 bar level appears to be appropriate for this haze. Uncertainties in the observed strength of the (4 - 0) lines (Smith, Macy, and Pilcher, 1980) lead to considerable uncertainties in the properties of this elevated haze layer, although Wallace (1980) finds it an essential component in balancing the predicted strength of the CH_4 "blue" band spectrum with the (3 - 0) dipole feature.

It might be expected that at 5μ, both Uranus and Neptune should easily be detected in reflected sunlight for molecular and aerosol scattering represents the only known and unexpected opacity. The planet has been detected (Gillett and Rieke, 1977; Macy, Sinton, and Beichman, 1980), but with the very low albedo of $\sim$ 0.01. Macy et al suspect CH_3D and PH_3 as being the source of this absorption and spectra in this region are urgently needed.

Beyond 5μ is the undisputed domain of thermal radiation and the observed spectrum is dominated by collisionally induced rotational and translational transitions in H_2. Stratospheric emissions of stratospheric hydrocarbons at 7.8 and 12 μ have not yet been observed on Uranus and new efforts are clearly needed since I am not aware of any work since that of Gillett and Rieke (1977) or Macy and Sinton (1977). The stratosphere is

not a total unknown as a result of successful observations of a grazing
occultation of SAO 158687 by the planet from the Kuiper Airborne Obser-
vatory in 1977 (Dunham, Eliott and Gierasch, 1980) for a reasonable mix-
ture of H_2 and these observations indicate a temperature of $\sim$ 95° K at
the 10µ bar level considerably cooler than is the case for the other giant
planets.

Between 10 and 30µ where opacity due to the S(0) and S(1) lines
in H_2 (collisionally induced dipole rotational transitions) should allow
probing of the upper troposphere and possibly the lower stratosphere,
the observations are broad band radiometric measurements and are too crude
to establish whether an inversion definitely exists in the 0.01 bar
region (cf., Courtin, Goutier, and Lacombe, 1978), but they suffice to
demonstrate the reasonableness of radiative-convective model atmospheres
(Wallace, 1980).
From 30µ to a few mm, the spectrum provides what is perhaps its
most important constraint on atmospheric structure. This is because the
bulk of the planetary thermal radiation emerges from the atmosphere in
this spectral region where the opacity is controlled by collisionally
induced dipole absorption between translational states of H_2 and He.
Deep in the atmosphere, CH_4 also plays an important role in the magnitude
of this opacity (Wallace, 1980) but in the region of the visible atmos-
phere, the abundance of CH_4 is depleted by condensation and is, therefore,
not a factor in determining structure (Trafton, 1972). The various
measurements show that the effective temperature is within 2 degrees of
58°K (Courtin et al, 1978; Stier et al., 1978) which restricts the inter-
nal outflow of internal heat to less than 250 ergs cm^{-2} sec^{-1}. Theore-
tical estimates of the internal heat flow range from 100 erg cm^{-2} sec^{-1}
to 10 ergs cm^{-2} sec^{-1} (Danielson, 1975) and could possibly be lower.

H_2 - He opacity controls the spectrum to about 1 cm wavelength
at which point the spectrum becomes exceedingly interesting and problem-
atical. In the region between 1 - 21 cm, the spectrum was anticipated
to show brightness temperatures near 150°K and a shape that reflected the
powerful absorption associated with inversion transitions in NH_3. A
"flat" spectrum was expected because of the high pressure ($\sim 10^3$ bar) at
which the spectrum would be formed and as a result of the vapor pressure
characteristics of NH_3 which cause a rapid increase in opacity over a
limited vertical extent in the atmosphere. It was, therefore, a great
surprise (albeit delayed) when Gulkis (1975) pointed out the fact that the
spectrum is unexpectedly hot at 2 - 10 cm; a surprise that was compounded
when Klein and Turanago (1978) found the micro wave spectrum to be (at
least at the present time) changing with time. Even at the present time,
the shape of the Uranus microwave spectrum from 2 - 21 cm, which is
shared by Neptune, has defied adequate explanation.

3. Structure and Composition

a. General Considerations

In a deep, cold, atmosphere like that which exists on Uranus, both the scattering of radiation and compositional inhomogeniety are of first order importance in the process of spectral line and band formation. As a result, we have learned by experience that the compositional problem and the structural problem are inextricably mixed. Most of the work to date has been of an exploratory nature; attempts to understand in the widest sense the complex interactions between assumed composition, cloud structure, and thermal structure. With the work of Danielson and his associates (1975, 1977), Trafton (1976), Courtin, Gautier and Lacombe (1978), and Wallace (1980), we have, I believe, arrived in the correct domain of structure and composition but, as yet, still lack a firm quantitative understanding.

Schematically, there are two approaches available for probing the atmospheric structure: "inverting" the observed spectral data on the basis of a set of rather restrictive and ad hoc assumptions (composition, behavior of the structure near upper and lower boundaries of the region probed) and the equation of radiative transfer; and, secondly, constructing sets of highly parameterized but physically consistent and reasonable radiative-convective models and comparing the predicted spectrum with observations. The inversion method has been applied by Courtin et al (1978) and serves to give a crude idea of the general domain of possible models. The inversion method is, I believe, unsuitable for more refined work at the present time because of the very poor quality of the 10 - 300 μ data that must be used (but see G. Orton's contribution to this colloquium).

The "modelling" method is technically more stable and forgiving and, in my view, is much more informative as it clearly exposes the influences of the physical processes that are at work and also help to identify whatever shortcomings exist in the observational data. This is the technique used by Danielson and his associates (1975, 1977), by Trafton (1976), by Macy (1979), and most recently by Wallace (1980). The remainder of this review is concerned with this latter approach.

In creating a model, the following steps are normally employed:

(A) Assumptions regarding composition and internal heat flow

(B) First guess at a thermal structure (i.e., the dependence of

temperature on pressure throughout the atmosphere)

(C)   Imposition of cloud characteristics

(D)   Calculation of solar heat deposition

(E)   Correction of initial thermal structure by iteration on
      step (B) to achieve a constant net energy flux condition
      throughout the atmosphere.

In step (A), the molecules and atoms we expect to be important
for the visible atmosphere are a subset of those seen on Jupiter, but
primarily H_2, He, CH_4 and NH_3. Prinn and Lewis (1973) have noted that
H_2S may be an important molecule in the lower regions of the visible
atmosphere and that it could be substantially enhanced (relative to NH_3)
over solar proportions as a result of some possible scenarios for the
planet's origin. An He/H_2 ratio near 0.18 (e.g. Wallace, 1980) is used in all
the modern models, and only the (very significant) effects of CH_4 conden-
sation need be considered in structural models of the visible atmosphere.
The CH_4/H_2 mixing ratio is taken as a free parameter in most models and
the most satisfactory models have it enhanced some 40 times over the
solar value ($\sim 7 \times 10^{-4}$). NH_3 and H_2S may have significant effects on
the microwave spectrum but are apparently unimportant in structure cal-
culations. Hunten (1981) has considered the effects of H_2O on the
structure but these are all confined to depths below 100 bars which are
currently outside the limits of the observable atmosphere.

Limits exist for line of sight abundances of NH_3 and H_2S (Fink
and Larson, 1979) but a proper interpretation of these limits in terms
of deep mixing ratios has not been attempted and would be, I think, an
exceedingly difficult task.

In step (C), two approaches have been used. In the first, a
minimum of clouds and hazes are placed in the model atmosphere where needed
in order to get a satisfactory rendition of the observed spectrum. Wallace
(1980) who employs variations on Trafton's (1976) cloud models uses this
approach as does Macy (1979). When a satisfactory physical structure is
achieved, the models are then examined to see if the assumed cloud layers
can be identified with potential condensates in the atmosphere. In these
models, CH_4 forms a high haze near 1 bar with a thick cloud base of H_2S
or NH_3 near the 5 bar level. In the second method, clouds are presumed
a priori to occur where an assumed chemical component is predicted to con-
dense. The models of Danielson (1975) are of this type and are essentially
single CH_4 cloud models.

In step (D), great advances have been made by Macy (1979) and Wallace (1980) through the use of laboratory spectra of CH_4 (Fink et al, 1977; Giver, 1978) in computing solar heat deposition as a function of depth in the atmosphere. The heating (in terms of ergs/gm/sec) peaks just above the 1 bar level, but its influence on structure may extend well below the 10 bar level depending on the precise nature of the lower cloud (cf., Wallace, 1980) and the magnitude of the internal heat flow.

Danielson (1975) was the first to explore the influence of heat deposition on structure with the help of a highly parameterized heating function. He was able to show that deep radiative structures might be possible for Uranus but I believe that models are now mainly of historical interest for they are all too cold and fail to give a reasonable account of the microwave spectrum between 0.1 and 1 cm.

Step (E), which is the heart of the modelling method, involves the calculation of thermal opacity. Now usually based on the work of Birnbaum, (1978) and numerical tests of the local buoyant stability of the atmosphere. The latter are dependent on the assumed composition through the specific heat of the atmospheric mixture. Both the assumed proportion of CH_4 and the ability of H_2 to convert between its ortho and para varieties is important in the calculation of specific heat. At the low temperatures in the Uranus visible atmosphere so called "equilibrium" H_2 (in which transitions between ortho and para states are assumed unhindered) and "normal" H_2 have very different specific heats, and the kind of H_2 which is assumed leads to quite different stability conditions. Wallace (1980) has made a major point of including this problem in his calculations and carries three assumptions as to the state of H_2: (i) "normal" H_2 in which the ortho-para ratio is effectively assumed to be that imposed at high temperature deep in the atmosphere, (iii) "equilibrium" H_2 in which ortho-para conversion is unhindered by quantum mechanical restriction at any temperature, and (iii) "intermediate" H_2, first postulated by Trafton (1967), in which the ortho-para ratio responds (presumably on a very long time scale) to conversion at the mean local temperature but does not respond on the short time scales of local convective processes in the atmosphere. Thus, "intermediate" hydrogen reflects a population of rotational states similar to "equilibrium" H_2 but has a specific heat similar to "normal" hydrogen. I think that in this application to Uranus Wallace has convincingly shown that it is to this "intermediate" case that H_2 prefers to conform in the atmosphere of the outer planets.

(b) Wallace's (1980) Models

The essential ingredients of the successful model, chosen to give the widest satisfaction to the complete set of observations, rather

than precise agreement to any particular observation, are as follows:

(i)   a Trafton (1976) type cloud and haze structure consisting
      of a diffuse, highly reflective, but optically thin haze of
      probably CH_4, near 1 bar which is separated from a thick
      (in visual wavelengths) cloud base near the 5 bar level.
      This lower cloud takes on an albedo to sunlight of 0.98
      (and is probably H_2S or NH_3).

(ii) a ubiquitous, lightly absorbing haze (photochemical
      "detrius"?)

(iii) "intermediate" hydrogen

(iv) a mixing ratio for methane of 0.03 relative to H_2.

    The best models (shown in Fig. 17 of Wallace, (1980) represent,
in my view, the best approximation to the mean atmospheric structure on
Uranus between the 0.1 and 30 bar level available at this time. Below
30 bars, the structure is uncertain and depends partly on what is assumed
about the magnitude of the internal heat flux and partly on the optical
properties of the base cloud at 5 bars. Above 0.1 bars, the structure
is similarly uncertain depending on the precise nature and mechanisms
of any tropopausal "cold trap", on the particular nature of the photo-
chemistry, and on whatever energy transport and disipation mechanisms
exist in that region.

    Wallace's comparison of his models with observational data is
instructive: The models predict Bond albedos and effective temperature
and since all of them give an adequate account of these quantities
(Bond albedo between 0.315 and 0.361; effective temperatures between
56.9 and 60°K) it turns out that these parameters do not help
discriminate between the models but merely represent an overall
check of their validity.

    The predicted IR spectrum between 10 and 300μ turns out to be
a poor discriminator between models, primarily because of the very poor
quality and the inconsistency in the data set.

    It is the microwave spectrum between 1 - 10 mm and in the visual
and near infrared spectrum that the most leverage to discriminate between
the various models is found. The mm observations rule out all "equili-
brium" H_2 models and those "intermediate" H_2 models with too much CH_4.
The CH_4/H_2 ratio is restricted to less than 0.1.

In the visible and near infrared reflection spectrum, the CH_4 "blue" bands put a lower limit on the amount of methane and require $CH_4/H_2 > 0.01$; while a combination of the H_2 spectrum and the strong CH_4 bands near .8μ set the character of the cloud structure as explained previously.

The models place little constraint on the internal heat flux although the comparison with the microwave spectrum seems to prefer the models with higher internal heat flow.

However, this is barely a significant result, if at all.

4. Unsolved Problems, Speculation, and Future Observations

The outstanding contemporary problems in structure and composition that I believe need to be addressed in the immediate future are as follows:

(i) Why does Neptune have so much more cloud activity in the upper troposphere then Uranus?

(ii) What seasonal variations occur in the Uranus atmosphere; particularly near the tropopausal minimum?

(iii) What is the explanation of the shape and variability of Uranus' microwave spectrum between 1 and 21 cm?

(iv) What is the explanation of the apparently low atmospheric deuterium and nitrogen abundances?

The first three problems are probably related and will require high quality observations in the 5 - 30 μ region over an extended time base together with more occultations and observations particularly from Voyager. Problems (iii) and (iv) may also be interrelated. The microwave spectrum at wavelengths longer than 2 cm seems to demand either a local or overall depletion of NH_3 by a factor of 100 relative to solar abundance depending on the particular hypothesis that is made regarding the deep atmospheric structure. Excluding what seems to be clearly unacceptable hypotheses involving ionospheric emission and magnetospheric emission, the following ideas have been proposed as possible explanations of the shape of the microwave spectrum:

(a) depletion of NH_3 coupled with a deep, roughly isothermal region below 30 bars ($\sim 250°K$)

(b) a "surface" near the 280°K level (plus a depletion of NH_3).

(c) chemical removal of NH_3 at the 150°K level by a super abundance of H_2S.

Idea (a) seems unacceptable because it does not provide a basis for an explanation of Neptune's microwave spectrum that has similar properties (Morrison and Cruikshank, 1973). Idea (b) might be acceptable if the equation of state of cosmic ices can accommodate an ice ball as large as Uranus and still meet the constraints of the mean density, as well as accommodate Neptune's large internal heat flow. In the context of this idea, the low N and D abundances would be explained by keeping these atoms largely trapped within the "ice ball." Idea (c) may work for both planets but leaves the deuterium problem unresolved. This idea also presents an untested hypothesis regarding the sulphur content of the atmosphere. Observations of HD on Neptune are needed as are more sensitive attempts to detect H_2S.

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