Internal Heating in Uranus: Observations, Implications, Explanations

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1 Introduction

Uranus and Neptune are very similar planets in many ways, from the blue-green clouds which cover both, to their comparable masses, rotation periods, bulk compositions, and even magnetic fields. Both worlds are composed largely of rock and ice (high Z) materials, and are less than than 20% H and He by mass, in contrast with the largely gaseous Jupiter and Saturn. Models for their internal and atmospheric structures also show many similarities (Hubbard et al. 1991; Podolak et al. 1990). But despite all this, there are striking differences between the two worlds.

One of the most notable of these lies in their planetary energy balances. Both are heated by the sun, with Uranus receiving about 2.4 times as much energy by virtue of its smaller orbit. Yet the cloud-top temperatures of the two planets are virtually identical, at 59 K (Lunine 1993). This surprising result arises because while Neptune, like Jupiter and Saturn, has a substantial internal heat source which warms it considerably above what would otherwise be its equilibrium temperature, Uranus does not. Alone among the four giant planets, Uranus has no convincingly detected internal heat source, and its temperature is roughly equal to that expected from insolation alone.

The mystery of why Uranus has this small or nonexistent internal heat source has endured since the disparity was first discovered. While the Voyager 2 fly-by in 1986 provided data unobtainable via Earth-based observations, the spacecraft's sensors were of course only able to probe the outer atmospheric layers of the planet. It has thus fallen to computer modeling and theoretical inquiries to investigate the planet's deep interior based on these and other observations of its upper reaches.

Initially, numerous hypotheses were advanced to explain the discrepancy in thermal flows, including that Neptune's heat source was derived from tidal decay of Triton's orbit rather than from any internal process, that the large rotational axis tilt of Uranus effects that planet's energy balance in some manner, and that the greater solar flux at Uranus might have caused it to evolve in a different direction than Neptune, even if the two started with otherwise identical initial conditions (Hubbard 1978). Increasingly sophisticated models have been developed since those first early investigations. Today it seems most plausible that stable stratification of the interior of Uranus prevents convective transport of energy and thus greatly limits the escape of internal heat. Molecular composition gradients and the unusual obliquity of Uranus' rotation axis may both play important roles in the maintenance of these stable layers.

2 Observational Constraints

2.1 Bulk Properties

Although ground-based observations have placed constraints on the physical properties of the ice giants for some time, and continue to be valuable today, the Voyager 2 fly-bys of the outer planets provided close-up measurements which in many cases are still unsurpassed today (Stone & Miner 1986).

Uranus and Neptune are in many aspects very similar planets, making the disparities in their heat sources all the more puzzling. They differ in mass by only 18% (Uranus is $14.5 M_\oplus$, Neptune $17.1 M_\oplus$) and in radius by only 4% ($4.01 R_\oplus, 3.88 R_\oplus$, respectively). Similar, too, are their rotation periods, at 17.3 and 16.1

hours respectively, based on measurements of the planets' magnetic fields, assumed to be anchored in the deep interior. These similarities, plus the outward likenesses of their blue-green atmospheres, led to early speculation that the interiors of the planets are likewise similar (Hubbard et al. 1991).

Podolak et al. (1990) used Voyager measurements of the first few moments of the gravitational potentials of the planets to model their interior mass distributions. They found that the density profiles for the two worlds are very similar in shape, although Neptune is more dense throughout by a factor of ~ 1.2 and has a somewhat larger core. Podolak et al. note that modeling efforts by several other researchers return consistent results. However, while these models pin down the density distributions of the ice giants, their compositions remain uncertain. This arises because the density for "ice" is equal to that of roughly 3 parts "rock" and "gas", where "ice", "rock", and "gas" refer to appropriate mixtures of frozen volatiles, heavy elements, and H & He respectively. Thus at any point within Uranus, one could remove some amount of ice and replace it with 3 parts rock and one part gas, leaving the density profile unchanged. This inability to constrain the composition of these worlds introduces a fundamental uncertainty into all attempts to model their interiors. Current belief is that rocky cores make up the inner 5-10% of these planets, while the outer 10-15% is a H and He rich atmosphere, the remaining bulk (about 80% of each planet by mass) being the icy mantle(Podolak et al. 1990, 1991).

Uranus's curious lack of internal heating was first identified in the 1970s via observations in the far infrared (e.g. Loewenstein et al. 1977). These observations established that its effective temperature is extremely close to that predicted solely based on equilibrium with incident solar energy, about 58 K. Similar observations established that Neptune radiates about twice as much energy as it receives from the sun. (Hubbard 1978)

2.2 Thermal Structure

The 1986 Voyager 2 flyby of Uranus provided more refined data than could be obtained via Earth-based observations. Pearl et al. (1990) obtained via careful analysis of the Voyager IRIS instrument data a ratio of total thermal radiation to absorbed solar energy (E/I)of 1.06 ± 0.08, or in other words a maximum internal energy source of 14% the magnitude of total absorbed solar energy, with a confidence of one standard deviation. This stands to this day as the tightest upper limit on the internal hear source. Using an effective temperature of $T_e = 59$ K, this implies an internal heat flux of $F_{int} = (1 - I/E)\sigma T_e^4 = 34 \pm 38$ erg cm^{-2} s^{-1}, where σ is the usual Stefan-Boltzmann constant (Allison et al. 1991). For comparison, the Earth's heat flux has been measured as 75 erg cm^{-2} s^{-1} (de Pater & Lissaur 2000), and Neptune's is 433 ± 46 erg cm^{-2} s^{-1}, and Jupiter and Saturn's are several times larger than even that. (Guillot et al. 1994). It is interesting to note that if Neptune were moved to orbit the sun at the distance of Uranus, the ratio of its emitted to absorbed energy would be ~ 1.7, in sharp contrast to Uranus's 1.06 ± 0.08 (Podolak et al. 1990). The difference between the two energy balances is striking, especially in light of how similar the worlds are in other aspects, and thus bears further investigation.

Observations of the detailed thermal profile in the upper atmosphere can provide indirect information on any heat sources operating deeper in the planet; these observations and their implications will be discussed shortly.

2.3 Other Aspects

Two other well-known aspects of Uranus bear commenting on here. One of the most unusual facts about the planet is that its rotation axis is inclined some 98 degrees relative to its ecliptic. Thus as it moves in its orbit, first one pole and then the other is pointed nearly directly at the sun, for decades at a time. Because of this, the poles receive *more* solar energy than the equator, averaged over a full Uranian year, by a factor of about $\pi/2$. It is tempting to assume that there may be some link between this unusual situation and the anomalously low internal heat, although a physical mechanism for this is not immediately apparent.

The second noteworthy fact is the planet's nearly featureless external appearance. Internal heat sources on Jupiter, Saturn, and Neptune are believed to provide most of the energy driving the often colorful atmospheric circulation patterns on those worlds. Thus, the low internal flux of Uranus may well provide a compelling explanation for the planet's homogeneous appearance.

3 Planetary Internal Energy Sources

3.1 Heat of Formation

Sources of internal heat in the other giant planets are believed to be fairly well understood. The dominant source is thought to be trapped heat of formation, ultimately derived from the gravitational potential energy freed during the initial condensation of the planets from planetesimals and the solar nebula. It was initially considered plausible that perhaps the current disparity between Uranus and Neptune reflects further disparities in their past histories, that Uranus could have formed with inherently less internal heat, leaving it correspondingly less energy to radiate away today. For instance, if the formation of Uranus took longer than that of the other planets, released gravitational potential energy could be radiated away during the formation period rather than become trapped in the interior of the planet.

If, following Podolak et al. (1991), we assume that planetary luminosity is dominated by cooling at constant radius,

$$L = 4\pi R_u^2 \sigma (T_e^4 - T_\odot^4)$$

where T_e is the current effective temperature and $T_\odot$ is what the effective temperature would be if there were only solar heating ($\sim$ 58 K). Numerical solutions of this equation, using current models for the interior of the planet, yield

$$L_{now} = 7 \times 10^{22} \left[\frac{T_{e,i}}{T_\odot} - 1\right] \text{ erg s}^{-1}$$

where $T_{e,i}$ is the planet's initial effective temperature. To obtain the correct current luminosity using this equation requires $T_{e,i} = 1.08 T_\odot = 62$ K. Given that there is no known mechanism why the initial temperature should be even similar in order of magnitude to $T_\odot$, much less tuned so precisely, this requirement seems rather improbable.

Consideration of the formation process helps to further dismiss the possibility that Uranus may have formed cool. If Uranus accreted on a time scale τ_a, then a rough estimate for T_e can be obtained via

$$4\pi R_u^2 \sigma T_{e,i}^4 = \left[G\frac{M^2}{R_u} - E_{thermal}\right] \tau_a^{-1}$$

If we assume $T_a > 1$ Myr, then this yields

$$T_{e,i} = 350 \text{ K} \left[\frac{100 \text{ Myr}}{\tau_a}\right]^{1/4}$$

Even assuming that Uranus accreted extremely slowly (over more than a billion years) results in $T_{e,i} \simeq 200K$, far above the 62 K required above. (Podolak et al. 1991) Thus we cannot assume Uranus's low internal heat is due to cool formation without requiring an untenably long time scale of formation which is inconsistent with our knowledge of the formation of the solar system.

3.2 Helium Rain-out

An additional source of heat can come from the "rain-out" of helium from the atmosphere onto the core. This will take place if temperatures and pressures produce the metallic phase of hydrogen, in which helium becomes immiscible. It will then separate from the rest of the atmosphere and descend towards the core, releasing energy both from the phase transition and during its subsequent descent towards the core. The transition to metallic hydrogen is believed to occur at a pressure of roughly 2 megabars. (Fegley et al. 1991) This process is invoked for Jupiter and Saturn, whose internal energies sources are too large to be explained purely by gravitational contraction, particularly in the case of Saturn. It also helps to explain the depletion of He in their atmospheres ($Y = 0.18, 0.06$, respectively, compared with a solar abundance of ~ 0.27) (Bergstralh & Miner 1991). However, it is not believed that metallic hydrogen exists in any large amount within the ice giants–the pressures within these smaller worlds do not reach high enough levels to induce the phase transition to metallicity in H. Current models of the interior pressures and temperatures, as well as the assumed saturation curve for He in H_2 under these conditions, predict that He is well under its saturation point in the interiors of Uranus and Neptune. Thus helium differentiation should not yet have begun. This is consistent with both the low value for Uranus's internal heat source, and with its near-solar measured He abundance of 0.262. (Fegley et al. 1991; Bergstralh & Miner 1991).

3.3 Radioactive Decay

The decay of radioactive elements is believed to be the primary source of internal heating for terrestrial planets including the Earth, and is likewise thought to play a considerable role in the energy balance of the ice giants due to their large amount of high Z material. The core of Uranus may plausibly contain up to 5 $M_\oplus$ of rock of composition roughly that of carbonaceous chondrites. Heat production in these materials has been well studied in terrestrial laboratories. 5 $M_\oplus$ of rocky material could produce at most 2×10^{21} erg s^{-1}, corresponding to a flux of 30 erg cm^{-2} s^{-1} at the surface. This value is already very near the best-fit measurement of 34 erg cm^{-2} s^{-1} and indeed is nearly half of the observed upper bound. (Podolak et al. 1991) This suggests that the Uranian heat source may well lie towards the top of the current error range.

3.4 Tidal Heating

One mechanism which was initially proposed to explain the disparity between Uranus and Neptune was that the latter might be deriving heat from the decay of the orbit of its moon Triton rather than from any internal process. Uranus, lacking any large satellite much less one in such an unusual orbit, would show no such heating. However, it has been shown that for this to be the primary energy source for Neptune would imply a decay time for Triton's orbit of much less than the age of the solar system, and thus this explanation seems extremely unlikely. (Hubbard 1978) More generally, tidal effects do not seem to play any significant role in heating any of the giant planets, and are indeed negligible compared to radioactive heating (Podolak et al. 1991).

4 Derived Constraints

Voyager and Earth-based observations of Uranus have provided an upper bound on the planet's internal flux, but they have not been successful in determining a lower bound. Indeed, an internal flux of precisely zero is not ruled out by the Voyager IRIS results. However, it is possible to derive tighter (i.e. nonzero) lower bounds on the flux based on the implications of other measurements. We have already encountered one such indirect bound above: Measurements of Uranus' composition indicate it contains ~ 5 $M_\oplus$ of rock, implying a flux of about 30 erg cm^{-2} s^{-1}. Similar indirect lower bounds can be derived based on measurements of the planet's magnetic field and atmospheric temperature profile.

4.1 Magnetic Field

The Voyager fly-by of Uranus supplied a wealth of data on its magnetosphere; Ness et al. (1991) provides an overview and further references. The primary results are a dipole moment about 50 times that of Earth, an equatorial surface field of 0.23 gauss, and most strikingly an angle of 59 degrees between the rotational and magnetic axes and an offset of 0.3 R_U between their centers. The field is supposed to originate via the action of a magnetohydrodynamic dynamo within the planet's interior. Although it was initially supposed that the odd configuration might be due to Voyager encountering the planet during a field reversal, the very similar result obtained a few years later at Neptune discredits this hypothesis (Bergstralh & Miner 1991). The details of the dynamo mechanism which must be invoked to generate this odd field are beyond the scope of this paper. However, whatever its detailed nature, this dynamo must be driven by the convective motion of materials within the planet.

Thus one can investigate what internal heat flux is necessary to induce convection sufficient to drive the planetary dynamo and produce the magnetic field. The details of planetary dynamos are sufficiently uncertain that this will be a rough bound at best, but the effort is still worthwhile. The convective velocity will be

$$v_{conv} = 0.1 \left(\frac{F_{conv}}{\rho} \right)^{1/3}$$

assuming a mixing length comparable to the pressure scale height H. Note that v_{conv} has only a low dependence on F_{conv}; thus any constraints on v_{conv} can at best lead to even rougher constraints on F_{conv}. That said, in order for a dynamo to sustain a magnetic field, the magnetic Reynolds number R_m must be large.

$$R_m = \frac{v_{conv} H}{c^2/4\pi\varsigma} > 10$$

where ς is the electrical conductivity in cgs units. For $H = 10^9$ cm, these immediately provide

$$F_{conv} > 10^{-3} \left(\frac{c^2/4\pi\varsigma}{1} 0^{-6} \text{ cm}^2 \text{ s}^{-1} \right)^3 \rho$$

Values for the interior of Uranus are $\rho = 1$ g cm^{-3} and $\lambda = c^2/4\pi\varsigma$ =anywhere from 10^4 cm^2 s$^-1$ to 3×10^6 cm^2 s$^-1$; the high uncertainty in the latter parameter results from our lack of knowledge of the properties of materials at temperatures and pressures typical of giant planet interiors. These numbers imply that F_{conv} is plausibly comparable to 10 erg cm^{-2} s^{-1} or less, although this is by no means certain. Thus it seems that the necessity of having sufficient flux to generate the planetary magnetic field provides only a weak constraint on the minimum value for that flux.

4.2 Atmospheric Temperature Profile

The only directly observable portion of a gas planet is its atmosphere. A range of wavelengths have been used to probe the atmosphere of Uranus at varying depths. These observations have returned a wealth of information on the thermal structure, density profile, and molecular composition of the atmosphere, although many details still remain uncertain. As the energy input into an atmosphere will have substantial effects upon its structure, models of the atmosphere of Uranus can provide us with constraints on heat flows operating at much lower depths.

4.2.1 Observed Properties of the Uranian Atmosphere

Voyager radio science results provide temperatures for the 0.3 to 2.3 bar range, while other Voyager instruments provide measurements in the 0.01 to 1 bar and the millibar and above regions. Ground based stellar occultation observations provides estimated temperatures in the microbar level, while ground-based thermal IR brightness temperatures can be used as checks against the Voyager data. All of these measurements can be combined to produce an atmospheric temperature profile against which model atmospheres may be compared. In broad outline, it is as follows: the atmospheric temperature drops from about 160 K at 10 bars, to 100 K at 1 bar to a $\sim$ 50 K minimum near 100 mbars, above which it gradually rises again as one enters the relatively hot (100-200 K) stratosphere. Methane and other condensible species of molecules form clouds at various levels within the atmosphere, releasing latent heat and influencing the adiabatic lapse rate as they do (Conrath et al. 1991).

Another notable fact of these observations is that there is very little latitudinal variation in temperature. Given the obliquity of Uranus' rotation axis, the poles receive $\pi/2$ more energy over the course of one year than the equator does. If the planet were a black body in equilibrium with this received flux, there would be an equator-to-pole gradient of $\Delta T = 0.12 T_e = 7$ K. However, observations indicate that at altitudes ($0.5 < P < 1$ bar), there is almost no temperature gradient whatsoever, while at millibar altitudes the equator is about 1.5 K *warmer* than the poles. Thus interior processes on Uranus must act to redistribute energy and counteract the imbalance in the received solar radiation (Bergstralh & Miner 1991).

4.2.2 A Recent Model of the Uranian Atmosphere

Many model atmospheres have been calculated for Uranus over the years; the most recent and most detailed is that of Marley & McKay (1999). These researchers constructed a radiative-convective equilibrium model both to investigate the role of hazes in the upper atmosphere and to attempt to provide a lower bound on the internal energy source. They found that internal heat fluxes ≤ 60 erg cm^{-2} s^{-1} are not consistent with the observed temperature profile in the atmosphere. We briefly review here the details of their model before considering its implications.

Their model consists of several dozen homogeneous layers extending from the 20 bar level upwards to 2 microbars, spaced evenly in log P. It incorporates both radiative transfer of energy and molecular absorption for nearly a hundred different frequency bands; convection is introduced by appropriately adjusting the temperature distribution to match that of an adiabat when the Schwarzschild convective instability criterion is met. Various extinction and scattering factors for each layer are averaged together, including contributions from numerous molecules, particulate hazes, dust, and clouds, These averages are used to calculate the radiative fluxes both upwards and downwards. Energy enters the system via the solar flux from above and internal heating from below, and leaves as thermal infrared from the upper atmosphere. The model is iterated, adjusting the temperature at each layer, until it converges to thermal equilibrium, determined by the net flux at each layer vanishing. This resulting model can then be compared to the observed temperature profile described above.

Marley & McKay (1999) found that the resulting temperature profile in the troposphere of their model was indeed dependent upon the magnitude of the internal heat source. Models with a heat source less than 60 erg cm^{-2} s^{-1} produced colder temperatures throughout the troposphere than are allowed by observations. Indeed, their best-fitting model incorporated a flux of 80 erg cm^{-2} s^{-1}, which is slightly *above* the 1σ error level for the Voyager results. Model differences tended to increase with atmospheric depth, and by the 2 bar level, models using lower internal heat sources fell substantially outside the 100.9 ± 1 K temperature measurement from Voyager.

Marley et al. also find that in order to obtain a good temperature fit through regions of methane cloud condensation, one must use a mixture of the wet and dry adiabatic lapse rate. In a model using only the wet adiabat, an relatively quite large internal energy source of 120 erg cm^{-2} s^{-1} was required to match temperatures at the 2 bar level, but this resulted in much too warm an atmosphere above that. By using a mean of the wet and dry adiabats, they were able to match the observed temperature lapse rate both above and below the clouds with the aforementioned energy sources in the $60 - 80$ erg cm^{-2} s^{-1} range. These models resulted in planetary effective temperatures of ~ 56 K, cooler than Voyager's measured 59 K. Marley asserts that this discrepancy relates to the cooler-than-expected stratospheres found in all current models of the Uranian atmosphere and that therefore the effective temperature discrepancy does not invalidate the models' implications for the internal heat flow. Based on their calculations, it seems likely that the Uranian internal energy source is at, near, or perhaps even slightly above the Voyager upper limit. (Marley & McKay 1999)

5 Models of the Deep Atmosphere and Interior

The model just considered was one of the upper atmosphere. On a giant planet like Uranus, the upper atmosphere smoothly transitions into the deep atmosphere where pressures reach tens and hundreds of kilobars before one descends into the icy mantle and core of the planet where pressures soar to megabars and temperatures to thousands of degrees. here in the core is where the latent heat of Uranus's formation remains. We established above that a "cool formation" of Uranus is not particularly plausible, and thus we must assume that there was indeed considerable heat in the planet's core originally. Given the low present luminosity, we must question whether some process is inhibiting the transport of heat out of the interior, trapping the heat of formation in the planet's core on a semi-permanent basis.

The most efficient mechanism for the transport of internal energy outward from the interior of a planet is convection. Radiative transport through solid bodies, even icy ones, is effectively nil, so radiative transport in the core and mantle can be neglected. While it has long been assumed that radiative transport is ineffective in the atmosphere as well, Guillot et al. (1994) calculate that there may well be radiative windows at certain levels; the effects of this will be discussed below. The exact thermal conductivity inside giant planets is unknown, due again to our inexact at best knowledge of the properties of matter at such extreme conditions. In regions of metallic H the thermal conductivity may be high, but there is expected to be little to no metallic H inside of Uranus (Fegley et al. 1991). However, others have argued that even metallic H will not be sufficiently conductive to transport much energy, and thermal conductivity through other components of the interior will surely be even less (Guillot et al. 1994). Convective transport, if it occurs, will completely dominate the other two modes of energy transport, very efficiently transporting energy and leading to an adiabatic temperature profile for the planet.

5.1 Evolution of Identical Models for the Ice Giants

It is conceivable that the differences between Uranus and Neptune may arise in a simple manner due to fact that the former receives 2.4 times more solar energy. Hubbard (1978) calculated the thermal evolution of the two planets, starting with similar initial temperatures and using plausible models for the interiors of the planets. He found that while the two initially cooled at the same rate, after sufficient time the greater energy flux onto Uranus tended to suppress the escape of interior energy. A group of researchers in Russia led by Gudkova obtained similar results, as discussed in Podolak et al. (1991)[1]. Indeed, in their model, the cooling curves for the two planets cross at about 58 K, very close to the observed temperatures! However, the time required to reach this crossing point tends to be somewhat larger than the current age of the solar system. This discrepancy may be resolved by assuming that Neptune is in fact younger than Uranus (i.e. formed at a later point in time) but this is contradicted by current planet formation theories. However, the exact results of the modeling depend strongly upon the assumptions made about material properties and energy transport in the interior of the ice planets; many of these values are currently poorly constrained leading to considerable uncertainty in the model results. Podolak et al. dismiss these models due to the too long time scale predicted and the strong dependences on poorly characterized parameters. However, Hubbard et al. (1991) argues that the strong similarites in interior compositions, densities, and so on, are strongly in favor of this sort of evolutionary divergence being the primary explanation for the low internal heat flow on Uranus. However, very little work has been published in support of this proposition since the late 1970s and early 1980s; attention seems to have shifted towards the stable stratification model which is discussed below.

5.2 Possible Initial Sub-adiabaticity

Although we have established that Uranus must have formed with a hot interior, if the outer regions were heated more during formation than the inner regions (perhaps by energy released from the accretion of material, or more violently through giant impacts) the planet could have formed with a subadiabatic temperature profile. This would suppress convection. Realistic models of planetary formation indicate that in fact it is likely such is the case immediately following the formation of the planet. However, the subadiabaticity is small, and since the outer layers will cool more rapidly than the interior, this state will not persist long. A decrease in T_e of only 10-20% will cause convection to increase from essentially nothing to include more than half of the planet's mass (Podolak et al. 1991). As a sub-adiabatic profile cannot persist long, it cannot be invoked to explain the inhibition of convection today.

5.3 Stable Stratification

5.3.1 Basic Concepts

Voyager measurements of the thermal structure of Uranus can shed light on the nature of convection within the planet because the observed temperature lapse rate carries strong implications about internal energy transport. At the low temperatures found there, there are large differences between different kinds of adiabats (e.g. wet and dry), due to latent heat stored in or released by conversions of the ortho and para forms of hydrogen, and in methane and the other molecular species. The Voyager temperature profile confirms the suggestion based on earlier ground-based work that temperature gradients in the deep atmosphere (1-2 bars pressure and below) are large. At these levels, both the condensation of volatiles and ortho-para hydrogen conversion were expected to reduce the gradient by increasing the effective heat capacity. Neither one of these processes appears to be at work, however. Indeed, the observed lapse rate is very similar to that of a "frozen adiabat", an adiabat calculated assuming that the ortho and para fractions of hydrogen are "frozen" somehow and prevented from equilibrating along the adiabat (Gierasch & Conrath 1987). This "frozen adiabat" produces a steeper temperature gradient, such that larger interior temperatures are reached more quickly. Conversely, it allows a higher internal central temperature for a given surface temperature than does an equilibrium adiabat, precisely what is needed for inhibiting the release of internal heat from Uranus.

What explanations are possible for the presence of a frozen adiabat? The simplest would be for convective overturning to be too rapid for the two states of hydrogen to reach equilibrium. However, both Voyager IRIS results and ground-based spectra indicate that the ortho and para hydrogen fractions *are* in equilibrium,

[1] I do not know Russian and thus was unable to read these results in the original.

at least for any specific level of the atmosphere. An alternative explanation is that convection must take place in a multitude of layers which are each much smaller than one scale height; Gierasch & Conrath (1987) suggests picturing a series of impermeable but heat conducting horizontal membranes placed throughout the atmosphere. This is not meant as a serious physical hypothesis for the cause of the layered convection, but rather a visualization aid for gaining intuition about its effects. Convection will take place in each narrow layer. The short overturning time will lead to a frozen hydrogen adiabat, while the fact that material is trapped in a single layer for times much longer than the overturning time will allow each layer individually to reach ortho-para equilibrium. Thus this many-layers model can reconcile these two otherwise contradictory observations about the deep atmosphere. Furthermore, while the temperature will decrease following an adiabat within each convective layer, it will drop effectively discontinuously at the interfaces between layers. Heat can be transported through these nonconvective regions only via thermal conduction, which is inefficient compared to convection, leading to larger gradients in T. Since the interface thickness is assumed to be much smaller than a mixing length, these gradients can be approximated as small discontinuities.

5.3.2 Mechanisms of stratification

There are a number of physically plausible mechanisms for the production of these layers. First, kinetic energy effects such as breaking waves or shear instability can cause local convective overturning in small regions of the atmosphere. Secondly, compositional gradients in an atmosphere can result in corresponding molecular weight gradients. If the molecular weight decreases with altitude, the buoyancy of warmer air masses will be reduced and thus convection will be inhibited and a stable layer will form. Numerous examples of such stably layered systems are known, ranging from the nonlinear breaking of waves in Earth's stratosphere to stratified layers of salt water in the oceans to semi-convection in stars resulting from molecular weight differences (Gierasch & Conrath 1987; Podolak et al. 1991).

A key point to realize about convection is that it can be efficiently driven by very small instabilities. A warm airmass will rise for *any* nonzero value of the buoyancy, even one which is extremely small. This implies that it is easy to start convection and even the slightest superadiabaticity will drive it, quickly reducing the gradient to an adiabatic one. The converse of this is that it is equally easy to *disrupt* convection. Gierasch and Conrath considered "stirring" in convective regions, by which is meant the tendency of local turbulence and wave motions to disrupt convection. The effect of this is to limit the size of a convective cell to some small value, which we will denote as lH, where H is the usual pressure scale height. First, they related the energy flux F to an energetic time constant t_E via

$$F = \frac{c_{pf} H}{k t_E} P$$

where c_{pf} is the specific heat assuming frozen ortho-para hydrogen ratio and the rest of the symbols have their usual meaning. It can then be shown, based on a hydrodynamic analysis of the convective layer considering both diffusion and turbulence, that

$$l^4 = R_i \frac{(1+\alpha)^3}{\alpha G^3} \frac{H}{g t_E}$$

where R_i, α, G are parameters of order unity describing the turbulence, strength of stirring, and general thermal structure, and $g = 880 \text{ cm s}^{-2}$ is the surface gravity. For $T_e = 58 \text{ K}, t_E = 1.3 \times 10^{10}$ s. Using appropriate values for the scale height (about 30 km) and the dimensionless factors, the above equation yields $l \simeq 1 \times 10^{-3}$. The mixing length for convection in the presence of stirring is thus only a small fraction of a scale height. Note in particular that l has only a weak dependence on the stirring factor α, so quite small amounts of stirring can easily limit the mixing length (Gierasch & Conrath 1987).

Likewise, extremely small molecular weight gradients are sufficient to inhibit convection. For the outer planets, the fractional buoyancy over one mixing length can be 10^{-7} or less, and thus a mere fraction of a gram cm^{-3} difference in density between the top and bottom of a region will completely damp out convection. The molecular weight of methane is substantially larger than the mean molecular weight of the mostly hydrogen upper Uranian atmosphere, and thus it can quite naturally become stratified. This density gradient will counteract the buoyancy of warmer airmasses after they have moved only a short distance, and thus places a tight constraint on the allowable mixing length. Latent heat effects from hydrogen ortho-para conversion also act to damp vertical motions. Taking both of these effects into consideration, it can be shown that the mixing length will be

$$l = \left(\frac{\epsilon^4}{G} \frac{t_H}{t_E} \right)^{1/6}$$

where t_H is the time scale for ortho-para equilibration and ϵ is a parameter related to the internal heat flux. For Uranus, $l \simeq 0.02$, giving a mixing length $lH = 400$ m, comparable to the result obtained above, and again we see that l is only weakly dependent on the various parameters.

The picture we have thus obtained is one of many relatively narrow convective layers, each with its own molecular weight and density, which varies in a "stair-step" function from layer to layer. There are further complications to this model resulting from additional ortho-para conversion effects, condensation of methane, and the tendency of gradual diffusion to reduce any molecular weight gradients, and these effects can be quite difficult to treat analytically, requiring numerous assumptions to allow exact solutions to be obtained. However, it seems clear that both molecular weight and stirring effects are capable of producing and maintaining a large number of narrow convective layers, with molecular weight gradients most likely playing a major role in the upper reaches of the atmosphere and stirring effects dominating at lower levels. While some of the details are uncertain, both of the physical processes at work and the values of the dimensionless parameters characterizing the conditions, the overall concept of stable stratification seems very solidly established. In fact, it is the only known possible explanation consistent with both the steep observed temperature lapse rate (the "frozen adiabat"), and the equilibrium ortho-para hydrogen ratios (Gierasch & Conrath 1987).

5.3.3 Application to the Deep Interior

Podolak et al. (1991) extended the stable stratification model to the deep interior (i.e. mantle) of the planet, in a general manner without calculating specifics. They stress that in order to adequately suppress the escape of internal energy, a small number of layers is not sufficient: If there are only a small number of boundary interfaces between layers, there will be only a small number of discontinuous jumps in temperature. Each jump will be a small fraction of a degree, and so the net effect will be minimal and the overall profile will still closely resemble an unfrozen, dry adiabat. Rather, there must be a very large number of separate layers, on the order of 10^6 or higher. They claim this high number is not implausible based on what is known of other stably stratified systems such as layers of varying salinity in Earth's oceans. Again, extremely small differences in mean molecular weight serve to efficiently limit buoyancy and stop convection after very short vertical distances. With such a model, it is found that if no more than the outer third of the planet's mass (half the radius) can convect freely, the rest being stably stratified, the observed heat flow can be reconciled with quite large central temperatures. This also meets the requirements for generation of the planetary magnetic field by allowing free convection in the outer regions. Indeed, the fact that the magnetic field is generated in a relatively thin layer in the outer portion of the interior does much to explain the unusual characteristics of the Uranian and Neptunian magnetic fields (e.g. large high-order moments, offset between the center and axis of the magnetic field and that of the planet.) (de Pater & Lissaur 2000).

Consideration of the formation of Uranus via accretion shows that the planet could reasonably form already containing compositional gradients, simply because of inhomogeneous accretion, perhaps related to the different capture mechanisms for gas and ice & rock. It has been suggested, by Al Cameron among others, that a giant impact may be responsible for the tilted inclination of Uranus. Such a giant impact would most likely completely stir up the interior of the planet to some extent. This is a possible mechanism for explaining the lack of compositional gradients in the outer portion of the interior which allows convection to take place there. However, this hypothesis is speculative at best, and conversely, the late accretion of large planetesimals might *increase* compositional gradients if the planetesimals do not mix well with material already accreted. In any case, it seems that Uranus' low internal heat flux may well be explained by the inhibition of convection via a tremendous number of thin, stable layers maintained by molecular weight gradients. (Podolak et al. 1991).

5.4 Meridional Transport of Energy

However satisfying the stable layer model may be, it does not address the question of the difference between Uranus and Neptune. The two planets have similar compositions, densities, and temperature profiles. Why should convection be any more inhibited in one than in the other? We must note that the relative difference in convection between the two worlds need not be that great in order to account for the disparity in luminosities: The inhibition of convection inside of 0.6 R_U on Uranus and 0.5 R_N on Neptune can account for the observed luminosities of both worlds (de Pater & Lissaur 2000). However, we must still ask if there is any identifiable factor responsible for the difference.

Friedson & Ingersoll (1987) constructed a model of the atmosphere of Uranus to investigate the role of meridional (that is, north-south) transport of energy on that planet, and to see what if any relationship exists between meridional transport and magnitude of internal heat source. As has been previously noted, Uranus is surprisingly uniform in temperature at all latitudes, especially in light of the unusual pattern in which energy is received from the sun. However, this planet-wide uniformity in effective temperature has been observed for all four giant planets, and has been explained in terms of meridional transport of energy from areas which receive more than the average to areas which receive less. This enables all areas to radiate equally into space at the same temperature despite differences in insolation.

Several important results were obtained. First, the internal energy source appears to be able to exist in two possible states, one in which the source has a uniform low value for all latitudes (the "terrestrial regime") and one in which the internal flux varies with latitude and potentially becomes much larger in some regions (the "Jovian regime"). Lower overall magnitudes for the internal energy source are related to models in which the planet spends a larger proportion of time in the terrestrial regime.

Secondly, for energy sources below a critical value of $E/I = 1.27$, the distribution of the solar flux plays a dominant role in determining the latitudinal structure of the internal source. Sources larger than this critical value (such as that found on Jupiter or Neptune) are capable of producing identical temperatures at all latitudes via energy transport in the deep interior; convection will be stronger in regions which receive less insolation, leading to a larger release of internal heat there. For energy sources weaker than the critical ratio (including Uranus'), variations in internal energy release with latitude cannot be sufficiently large to balance the different amounts of solar radiation. In this case, the meridional transport of energy must take place in the atmosphere rather than in the deep interior. Via their modeling, Friedson & Ingersoll established that large-scale motions in a relatively shallow layer of the atmosphere are capable of transporting sufficient energy to bring all latitudes into equilibrium.

Incidentally, the Friedson & Ingersoll models for varying magnitudes of the internal energy source produced a result in agreement with that of Marly & McKay discussed already: A source of magnitude $E/I = 1.10$ led to a slightly too cool atmosphere, while $E/I = 1.20$ led to too warm a result. This matches quite well with Marley et al.'s result that the energy source must be near or slightly above the Voyager bound of 1.14.

5.5 A Combination of Stratification and Insolation Effects?

Podolak et al. (1991) raise an interesting hypothesis based upon these results, combining the stratification idea with the differential solar heating proposition advocated by Hubbard et al. (1991). In the upper reaches of the atmosphere, meridional transport allows no more than a few K temperature gradient over the entire planet. Below a certain depth, the time constant for thermal adjustment will become longer than a Uranian year. Thus temperature variations at or below this level will be damped, and the sun can be considered to be effectively a globally averaged source. Podolak suggests

> The results of Ingersoll and Porco suggest the possibility that solar insolation affect the heat transport and therefor the interior temperature distribution to the extent that statically stable interior regions exist. Since every point in the atmosphere is effectively heated by the sun because of the long radiative time constant, the internal heat flux may be suppressed at all latitudes on Uranus. In contrast, since Neptune has an obliquity of about 29°, most of the solar insolation occurs at low latitudes. The interior heat flow of Neptune should be shunted towards higher latitudes, as apparently occurs for Jupiter...Thus, the interior temperature structure may be significantly different for Uranus than for Neptune. (Podolak et al. 1990)

In other words, the unusual obliquity of Uranus leads to, at deep levels at least, a more uniform insolation than is found on any other planet. This process may well act to maintain the statically stable layers in the interior of Uranus, while the insolation differences on Neptune leads to larger temperature gradients near the poles, and thus more convection there, working against the effects of stable stratification. As has been already noted, only on the order of a 10% difference in the amount of the planet which convects freely is enough to account for the difference in magnitude for the two planet's heat sources. Thus perhaps after all there is a role for Uranus's unusual obliquity in explaining its low internal heat.

6 Conclusions

Voyager measurements constrain the ratio of emitted to absorbed energy on Uranus to be 1.06 ± 0.08, much lower than that of any other giant planet. However, comparison of models with the observed atmospheric temperature profile indicates that the internal energy source must be near or slightly above the Voyager upper limit, corresponding to a surface energy flux of $60 - 80$ erg cm^{-2} s^{-1}. While this reduces the problem somewhat, such a flux is still much lower than that observed for any of the other giants. It has been suggested that the different amounts and distributions of solar radiation as recieved by Uranus and Neptune could lead to the disparity seen today. Models of the time evolution of the two planets do result in different thermal histories and predict their temperatures will cross at a point very close to the observed present effective temperatures. However, strong dependence upon assumed parameters and a tendancy to require ages greater than the established age of the solar system render these models somewhat questionable. (Hubbard 1978; Hubbard et al. 1991; Podolak et al. 1991)

An alternative explanation is that convection is inhibited within the bulk of Uranus, by some combination of molecular weight gradients and turbulent stirring effects. This leads to the formation of a large number of narrow layers, each convecting separately; this model can explain the otherwise contradictory observations of both a "frozen hydrogen adiabat" temperature profile simultaneously with ortho-para equilibrium at every individual level. The steeper adiabat acts to suppress the escape of heat from the deep interior, while the suppression of convection within much of the interior is consistent with the character of the Uranian magnetic field. Meridional transport of energy in the upper atmosphere serves to explain the similar effective temperatures observed at all latitudes. Despite the successes of the stratification model in explainig the observed properties of Uranus, it does not directly address the cause of the disparity between the two ice giants. It is conceivable that insolation effects due to Uranus' unusual obliquity may play some role in explaining the differences between that planet and Neptune. However, this is still speculative; some currently unknown mechanism may well be responsible for the differences in suppression of convection in the two. (Gierasch & Conrath 1987; Friedson & Ingersoll 1987; Podolak et al. 1990, 1991)

Given the great distances to Uranus, Earth-based measurements are possible for only some quantities. The stratification model makes predictions for certain elemental and molecular abundances in the atmosphere, and for differences in these between the two ice giants. Existing observations seem to confirm some of these predictions, but uncertainties in others are too great for confirmation or rejection of the stable stratification model (Lunine 1993). Precision measurements of atmospheric composition from the vicinity of Earth are extremely challenging even with modern methods. Deeper understanding of the interior and heat flow of Uranus will likely therefore have to wait for future spacecraft visits to the ever-enigmatic eighth planet.

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