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Intrinsic Luminosities of the Jovian Planets

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We review available data and theories on the size and nature of interior power sources in the Jovian planets. Broad band infrared measurements indicate that Jupiter and Saturn have interior heat fluxes about 150 and 50 times larger, respectively, than the terrestrial value. While Neptune has a modest heat flux (~5 times terrestrial), it is clearly detected by earth-based measurements. Only Uranus seems to lack a detectable interior heat flow. Various models, ranging from simple cooling to gravitational layering to radioactivity, are discussed. Current evidence seems to favor a cooling model in which the escape of heat is regulated by the atmosphere. This model seems capable of explaining phenomena such as the uniformity of effective temperature over Jupiter's surface and the different emission rates of Uranus and Neptune. In such a model the heat radiated from the atmosphere may derive from depletion of a thermal reservoir in the interior, or it may derive from separation of chemical elements during formation of a core. Calculations indicate that in the earlier stages of cooling, Jupiter and Saturn may have more homogeneous abundances of hydrogen and helium and radiate energy derived from simple cooling. At a subsequent phase (which may be later than the present time), hydrogen and helium will separate and supply gravitational energy. Either model is consistent with a hot, high-luminosity origin for the Jovian planets.

1. Historical Background; Definitions

The subject of the possible existence and nature of intrinsic luminosity sources in the Jovian planets has a history which extends back at least to 1923, when *Jeffreys* [1923] considered the question of whether Jupiter could have a hot interior. His conclusion was negative and was based upon the following considerations. Noting that Jupiter has an extensive atmosphere with some layers near a temperature of 300°K, Jeffreys calculated the cooling time for a blackbody the size and mass of Jupiter, radiating with an effective temperature of 300°K. The cooling time was found to be short in comparison with the age of the solar system.

Soon afterward, Jupiter, Saturn, and Uranus were investigated in a pioneering set of measurements made by *Menzel et al.* [1926] in the terrestrial infrared window of 8–14 μm. In this wavelength interval the brightness temperature of Jupiter was found to be ~130° ± 10°K (mean of two measurements) and for Saturn, ~127°. Uranus was undetected. These measurements could be interpreted as suggesting that Jupiter and Saturn possess internal power sources (see below) and thus spurred a further discussion of the question from a theoretical point of view by *Jeffreys* [1924], who basically stood by his earlier analysis after considering the unlikely possibility of radioactive heating in the outer envelopes of the Jovian planets.

Further progress was impossible in the absence of a better understanding of the composition of the Jovian planets, the opacity sources in their atmospheres, and the details of their energy balance with sunlight. However, *Öpik* [1962] published a comprehensive review of the physics of Jupiter in which he accepted the measurements of Menzel et al. as implying a net heat flux from Jupiter of approximately 10^4 erg/cm^2 s. The issue was clarified by *Low* [1966], who reported the results of further infrared measurements in the 17.5- to 25-μm atmospheric window. The infrared power from Jupiter in this window alone was in excess of the total power received from the sun, and thus an internal power source was strongly indicated.

In order to proceed with the discussion, we will now define several standard quantities which are helpful in discussing the energy balance of Jovian planets. The effective temperature T_e of the planet is defined as the temperature of a blackbody emitter of the same size as the planet which produces the same integrated infrared power. Here 'infrared' is defined as the region of the spectrum which excludes a significant contribution of scattered sunlight to the total power and in practice for the Jovian planets would include the wavelength band from approximately 8 μm to approximately 300 μm.

In first approximation, the photon power observed as a function of wavelength is a superposition of two Planck distributions. The bluer component is reflected sunlight and is essentially a diluted version of the solar blackbody emission curve at a temperature of ~6000°K. Let the total photon power incident on the planet per unit of time be J. Then the Bond albedo A represents that fraction of J which is scattered into space by the planet without being absorbed by its atmosphere. Thus AJ represents the integrated photon power in the bluer Planck distribution, and $(1 - A)J$ represents the photon power which is absorbed by the planet's atmosphere and which in a steady state must reappear in the redder Planck distribution. The equilibrium effective temperature T_S is then given by

$$4\pi R^2 \sigma T_S^4 = (1 - A)J \quad (1)$$

where R is the planet's radius and σ is the Stefan-Boltzmann constant. In other words, the effective temperature of the planet is T_S if it is in equilibrium with sunlight and has no internal power sources. The net internal power, Q, is then given by

$$Q = 4\pi R^2 \sigma (T_e^4 - T_S^4) \quad (2)$$

where Q is in units of ergs per second. Thus in order to determine Q, it is necessary to know A in addition to T_e.

Some of the difficulties involved in establishing Q can be appreciated by considering Figure 1. Here we have plotted the emitted photon power per unit wavelength interval as a function of wavelength for Jupiter, under the approximation that the power can be represented as a superposition of two Planck distributions. The left-hand peak represents scattered solar photons at an effective temperature of 6000°K and has an integrated power equal to AJ. The right-hand peak (solid curve)

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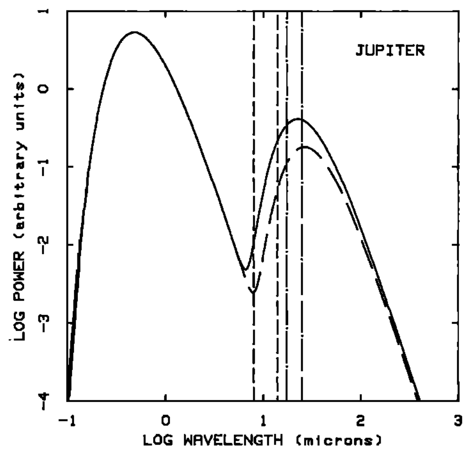

Fig. 1. Schematic photon emission spectrum for Jupiter. Terrestrial atmospheric transmission windows at 8–14 μm (vertical dashed lines) and 17.5–25 μm (vertical dot-dashed lines) are shown. Relative intrinsic luminosity is the difference between the solid and dashed emission curves.

has $T_e = 129$°K and assumes $A = 0.35$. For this value of A, (1) gives $T_S = 109$°K, and the dashed right-hand curve corresponds to a Planck distribution with this temperature. Clearly the integral between the dashed and the solid curve gives the net internal power, Q. The vertical lines show the atmospheric windows at 8–14 μm and 17.5–25 μm. If the distributions were precisely planckian, a measurement of a local effective temperature in a single wavelength interval (brightness temperature) would suffice to define Q, but the actual power distribution in Jovian planets is significantly nonplanckian, and broadband measurements are needed. As Figure 1 shows, the most important wavelength band for this measurement is approximately 15–50 μm.

The problem of determining the value of Q is even more severe for Saturn, Uranus, and Neptune (Figures 2, 3, 4). Because of the generally lower temperatures at these distances from the sun, the peak of the infrared Planck distribution lies beyond 25 μm, and measurements in the 8 to 14-μm band are of little value in constraining the value of Q.

In summary, it appears that the measurements of Menzel et al. and many of the conclusions drawn from them by early investigators were, in general, qualitatively correct, i.e., Jupiter and Saturn do indeed possess significant internal power sources, while Uranus apparently does not. However, quantitative work on this subject has had to await more comprehensive measurements of the infrared flux at wavelengths inaccessible to observers near the earth's surface.

2. CURRENT STATUS OF IR FLUX MEASUREMENTS OF THE MAJOR PLANETS

Jupiter

Despite the abundance of good observational data on Jupiter, there is some disagreement about the size of the internal power source. *Armstrong et al.* [1972] carried out medium-band observations of Jupiter at wavelengths of 30–45 μm, 45–80 μm, 65–110 μm, 125–300 μm, and 350 μm using an airborne telescope at 15,000-m altitude and concluded that $T_e = 134 \pm 4$°K. The infrared radiometer experiment on board Pioneers 10 and 11 [*Ingersoll et al.,* 1976] made observations of Jupiter from space at wavelengths of ~10–30 μm and ~35–55 μm, covering a large fraction of the infrared thermal emission from Jupiter. The result from this effort was $T_e = 125 \pm 3$°K, although *Low* [1976] indicated that a suitable combination of earth-based and spacecraft data might give $T_e = 129 \pm 4$°K, and this compromise value has been adopted here.

Accurate determination of the other critical parameter, A, does require spacecraft data on the component of visual scattered light, and a result is now available from analysis of the Pioneer 10 flyby data [*Tomasko et al.,* 1978]: $A = 0.35$. With this result, we obtain the values presented for Jupiter in Table 1.

Saturn

No spacecraft data on Saturn's IR flux exist at this writing, although results from Pioneer 11 may become available in late 1979. The existence of a possible Saturnian internal power source was reported by *Low* [1966], and more recent investigations include those of *Rieke* [1975] and *Loewenstein et al.* [1977*a*]. The largest problem in determining Q for Saturn is the elimination of the infrared flux from the ring particles, which contribute in a non-negligible way to the infrared brightness in the 40- to 100-μm region of principal interest. Rieke attempted to eliminate the ring contribution by making spatially resolved observations of the planet and rings at 5, 12, 22.5, and 33.5 μm. These measurements were then used to predict the behavior of the rings at wavelengths beyond 40 μm, and this component was then removed from the data of *Armstrong et al.* [1972]. The predicted effective temperature is then $T_e = 95 \pm 6$°K. Similar results were obtained by *Loewenstein et al.* [1977*a*], who obtained $T_e \simeq 99 \pm 10$°K with the uncertainty due to the contribution of the rings included in the error bars. The value of A for Saturn is as yet not directly measured but may be assumed to be ~0.4 by analogy with Jupiter, leading to a value $T_S \simeq 79 \pm 4$°K.

Uranus

Since the bulk of Uranus' infrared peak lies redward of 25 μm, special observing techniques have been needed to investigate its energy balance. The results of several investigations are apparently consistent: Uranus has little or no internal power. Recent observations from the Kuiper Airborne Observatory which span the wavelength range from ~30 to ~400 μm yield $T_e = 58 \pm 2$°K [*Loewenstein et al.,* 1977*a*], thus confirming a similar earlier result by *Fazio et al.* [1976]. The major uncertainty in assigning a limit to Q is the value of A, which is known only from theory. Assuming $A = 0.37$, we find $T_S = 57$°K.

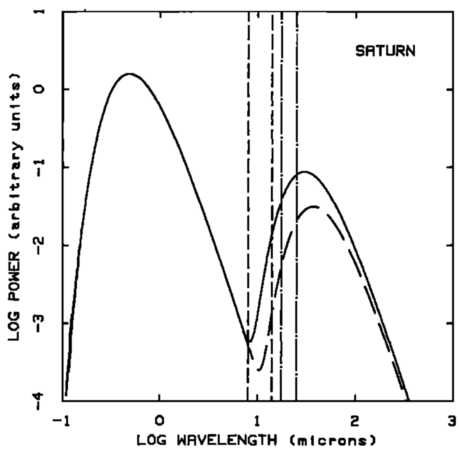

Fig. 2. Same as Figure 1 but for Saturn.

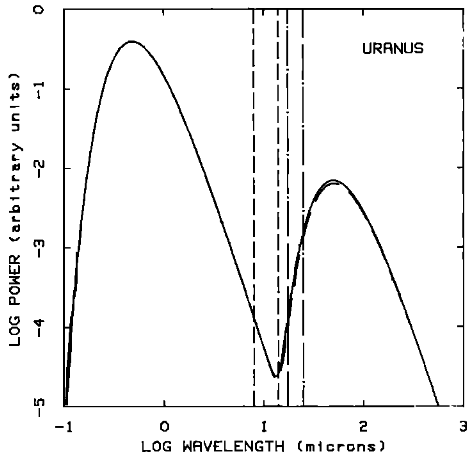

Fig. 3. Same as Figure 1 but for Uranus. Note that Uranus has no detectable intrinsic luminosity.

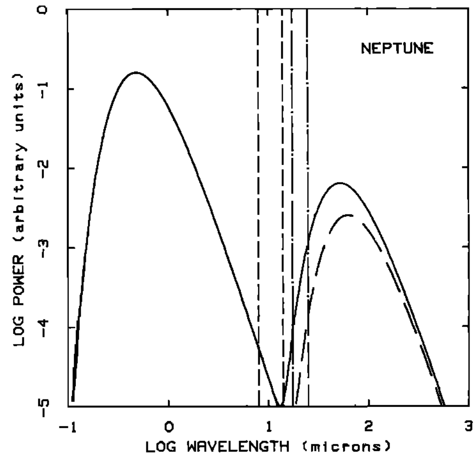

Fig. 4. Same as Figure 1 but for Neptune.

Neptune

The original supposition that Neptune may have an internal power source, while Uranus does not, is due to *Murphy and Trafton* [1974]. The latter work is based upon observations shortward of 35 μm (cf. Figure 4) and therefore could not alone confirm the hypothesis. More recent observations have been carried out from the Kuiper Airborne Observatory by *Loewenstein et al.* [1977*b*] in the wavelength bands 53–170 μm and 25–39 μm. The resulting effective temperature was found to be $T_e = 55.5 \pm 2.3$°K. Using an estimated $A = 0.33$ from *Murphy and Trafton* [1974], one then finds $T_S = 46$°K, and an internal power source is clearly demonstrated.

3. MODELS FOR POWER SOURCES

Introduction

It is convenient to classify models for the interior power sources into three rough categories: thermal models, gravitational models, and miscellaneous models. This division is useful because the first two types appear to be the most likely, and present information is not sufficient to strongly favor one over the other. Among the miscellaneous models, we have relatively bizarre possibilities for energy sources such as nuclear fusion, nuclear fission, meteorite infall, and secular albedo change. These concepts can be rather quickly eliminated. Nuclear fusion would require interior temperatures in excess of $\sim 10^5$ °K [*Grossman and Graboske,* 1973; *Suchkov,* 1976] and could probably not proceed in a stable manner. Nuclear fission as originally suggested by *Jeffreys* [1924] also seems implausible, for using typical abundances of radioactive isotopes of uranium, thorium, and potassium, we find that Jupiter would have to be essentially pure granite to account for its observed heat flux by this mechanism. The current rate of contribution of energy by meteorite infall is likewise inadequate by many orders of magnitude [*Humes,* 1976].

We may entertain the possibility that the albedo of the Jovian planets has recently changed to a larger value, so that the excess luminosity can be attributed to stored sunlight from an earlier epoch. In this case, however, it would be difficult for the effective temperature to exceed T_S given by (1) with A set equal to zero.

How can we deal with Jeffreys' suggestion that the Jovian planets should have cooled to very low temperatures over the age of the solar system? The point here is that an effective temperature of 300°K implies an emission rate roughly 30 times greater than for the actual effective temperature of $\sim$130°K for Jupiter. Table 1 shows that the required power source must produce $\sim 3 \times 10^{11}$ erg/g on the average for Jupiter or Saturn over the age of the solar system and about an order of magnitude less for Neptune. Assuming atomic hydrogen composition, this corresponds to an average temperature of $\sim$4000°K. This is an altogether reasonable internal temperature for a Jovian planet, but the key point for any model to address is the mechanism for maintaining such an internal temperature for the age of the solar system and at the same time maintaining an effective photospheric temperature of $\sim$100°K.

Adiabatic Cooling Models

Cooling models for Jupiter and Jupiter-like planets are ultimately based upon the pioneering work of *DeMarcus* [1958], who carried out an analysis of low-temperature Jovian planet models and elucidated the importance of hydrogen in the composition of such objects.

TABLE 1. Energy Flow Parameters for the Jovian Planets

Planet	T_e °K	A	T_S, °K	Net Average Surface Heat Flux $Q/4\pi R^2$, erg/cm²/s	Luminosity/Mass, erg/g·s
Jupiter	129 ± 4	0.35	109.4	7600	2.4×10^{-6}
Saturn	97 ± 7	0.4	79 ± 4	2800	2.2×10^{-6}
Uranus	58 ± 2	0.37	57	<180	$<2 \times 10^{-7}$
Neptune	55.5 ± 2	0.33	46	285	2×10^{-7}

See text for a discussion of adopted values.

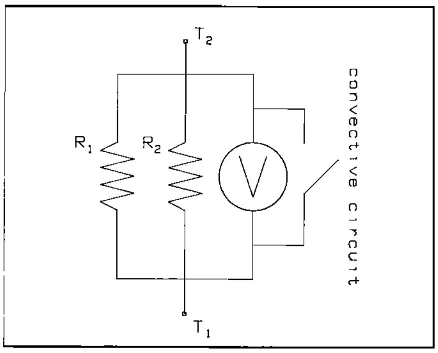

Fig. 5. A schematic 'circuit element' for energy transport in a liquid planetary interior.

Hubbard [1968] proposed that the thermal structure of Jupiter would tend to follow an adiabat because of the relatively low thermal conductivity of dense hydrogen, the relatively high internal temperature implied by the heat flow measurements, and the instability to convection produced by the heat flow. This circumstance would lead to a radically different cooling mechanism from that which governs terrestrial-type planets. Figure 5 illustrates the point with an analogous circuit diagram. In this diagram, temperature plays the role of voltage, and heat flow is analogous to electrical current. Thus the circuit element with terminals at 'voltages' T_1 and T_2 ($T_1 > T_2$) is analogous to a layer in a planet with a temperature gradient. Current then flows from T_1 to T_2 via 'resistances' R_1 and R_2. The latter represent energy transport by radiation and by electron conduction, respectively. If $T_2 - T_1$ becomes greater than a critical value (the adiabatic temperature gradient), then the switch closes and quickly reduces $T_2 - T_1$ to a value below the critical value $(T_2 - T_1)_{\rm crit}$. For Jupiter and Saturn, in practice, the resistances R_1 and R_2 are so large through most of the interior that most of the energy transport takes place through the 'convective circuit.' The resistance in the latter is so low (because of the high efficiency of convection in hot, liquid hydrogen) that the temperature gradient settles at a value only slightly above the adiabatic gradient [*Hubbard,* 1968; *Stevenson and Salpeter,* 1977].

We may think of the interior temperature distribution in Jupiter as being determined by a sequence of elementary circuits such as that of Figure 5, connected in series. The role of the atmosphere is then analogous to a final element where only resistance R_1 is present (Figure 6).

In the atmosphere, which we define as that region of the planet where the optical depth to infrared radiation is $\lesssim 1$, convective transport of energy becomes inefficient or ceases altogether, and the only available means of energy transport is infrared photons, which are impeded by the opacity of the atmosphere (schematically represented by R_1). Since the resistance in the convective branch of each elementary circuit is negligible, it is clear that for a given current flow, the entire voltage drop in the circuit of Figure 6 is governed by the atmosphere, provided only that the voltage drop is sufficient to close the convective subcircuits at all points.

The above properties are a noteworthy feature of this class of models for the Jovian planets' luminosity and differ quite remarkably from energy transport processes in terrestrial planets. In the latter, convection where it occurs is not particularly efficient, and thus the thermal evolution of the planet is governed by transport processes throughout its interior and not just in a thin surface layer.

There is another class of models for the Jovian planets which also predict an adiabatic temperature profile in the interior on the basis of considerations other than intrinsic luminosity. According to *Zharkov and Trubitsyn* [1969, 1972], molecular heat conduction is expected to be highly inefficient in the Jovian planets. From the equation of heat conduction, one can define a characteristic conduction time Δt and a characteristic conduction scale Δl, which are related by

$$\Delta t \sim (\Delta l)^2/\chi \tag{3}$$

where χ is the thermometric conductivity with dimensions of a diffusion coefficient. According to *Zharkov and Trubitsyn* [1978], χ has a typical value of $\sim 10^{-2}$–10^{-3} cm²/s in Jovian planet interiors, leading to $\Delta l \sim 10^2$ km for $\Delta t \sim 5 \times 10^9$ years. Since Δl is much smaller than the typical dimensions of a Jovian planet, Zharkov and Trubitsyn conclude that the temperature distribution in Jovian planets should be close to adiabatic as a result of adiabatic compression during primordial accumulation processes. *Peebles* [1964] noted even earlier that the current structure of Jupiter and Saturn was most consistent with a deep, adiabatic envelope.

A cooling calculation is performed for an adiabatic-convective model as follows. We shall assume that an atmosphere model is available which gives the internal temperature as a function of density ρ, effective temperature T_e, and surface gravity of the atmosphere g. In practice, this is carried out by prescribing the thermal flux (equivalent to T_e) and g, and then integrating the equations of radiative transfer and hydrostatic equilibrium simultaneously to obtain the temperature T, pressure P, and ρ as a function of depth [*Trafton,* 1967; *Graboske et al.,* 1975]. Convection is included as an energy transport mechanism via mixing-length theory. For the Jovian planets, it is found that the atmosphere becomes convectively unstable at pressures greater than ~ 1 bar and quickly approaches an adiabatic structure at greater depths due to the efficiency of convection. The temperature distribution in the convective part of the planet can then be expressed as

$$T = f(T_e, g, \rho) \tag{4}$$

where $f(\rho)$ for fixed T_e, g coincides with an adiabat.

Using (2), the equation for the luminosity of a planet derived from a change in its thermodynamic state is then

$$4\pi R^2 \sigma T_e^4 = -\int dm \left(\frac{dE}{dt} - \frac{P}{\rho^2}\frac{d\rho}{dt} \right) \tag{5}$$

where the integral is taken over all elements of mass dm of the planet, E is the internal energy per unit mass, and t is the time. In (5) we have temporarily neglected the effect of any luminosity derived from the sun. After substituting thermodynamic identities, (5) becomes

$$4\pi R^2 \sigma T_e^4 = -\int dm\, C_v \left[\frac{dT}{dt} - \left(\frac{\partial T}{\partial \rho}\right)_s \frac{d\rho}{dt} \right] \tag{6}$$

where C_v is the heat capacity at constant volume per unit mass, and $(\partial T/\partial \rho)_s$ is evaluated at constant entropy. We then use (4) for an adiabatic planet to obtain

$$4\pi R^2 \sigma T_e^4 = -\frac{dT_e}{dt}\int dm\, C_v \left(\frac{\partial f}{\partial T_e}\right)_{g,\rho} - \frac{dg}{dt}\int dm\, C_v \left(\frac{\partial f}{\partial g}\right)_{T_e,\rho} \tag{7}$$

According to model atmosphere calculations [*Graboske et al.,* 1975], f has only a very weak dependence on g, so that the second term on the right in (7) can generally be neglected.

A convenient fit to the model atmospheres of *Graboske et al.* [1975] is given by

$$f = 66.8g^{-1/6}T_e^{1.243}\rho^{\gamma} \tag{8}$$

[*Hubbard,* 1977], where f and T_e are in degrees Kelvin, g and ρ are in cgs units, and γ is the adiabatic exponent or Grüneisen parameter. Using (8) and neglecting the term in dg/dt, we obtain

$$dt = -\alpha T_e^{-3.757} dT_e \tag{9}$$

where

$$\alpha = (4\pi R^2\sigma)^{-1} \int dm\, C_v(22.4\rho^{\gamma}) \tag{10}$$

is the cooling constant for an adiabatic planet. This relation is valid for planets without significant phase discontinuities which might contribute to the energy balance. It also assumes that the planetary density distribution is not a function of time and thus is only applicable to the late evolution of Jupiter.

Numerical integration of (10) for a Jupiter model gives $\alpha = 2.79 \times 10^{23}$ cgs units, and if we assume $T_e(t = 0) \gg 130°$K, the initial state contributes negligibly to the total time scale. Integration of (9) gives a cooling time of 4.4×10^9 years to reach $T_e = 134°$K and 5.1×10^9 years to reach $T_e = 127°$K. Thus a simple adiabatic cooling model appears to be adequate for Jupiter. Note that although there was an epoch when Jupiter had an effective temperature of 300°K, this occurred at an age of $\sim 0.5 \times 10^9$ years. The model thus confirms Jeffrey's estimate for the cooling time of such a model; however, Jupiter actually has a much lower effective temperature than his assumed value.

Convective cooling models for Jupiter thus imply a relatively high-luminosity origin for the planet. The first quantitative investigation of this problem was carried out by *Graboske et al.* [1975]. Subsequent independent investigations by *Hubbard* [1977] (described above) and by *Pollack et al.* [1977] indicate that the stored heat alone from the initial high-luminosity phase will yield a model consistent with the current heat flow parameters for Jupiter.

Gravitational Unmixing Models

In a sense, we may say that a cooling model involves release of gravitational binding energy, since cooling is accompanied by a slight contraction. However, this contribution to the luminosity is included in the bookkeeping of (5) and (6). In general, one would not expect the evolution of a planet to be so simple as to involve only continuous thermodynamic transformations in a single phase [*Smoluchowski,* 1967; *Salpeter,* 1973; *Stevenson and Salpeter,* 1977]. Thus one should consider the possibility that in the course of its evolution, a Jovian planet may develop denser phases which can separate from a less-dense component and sink toward the center, releasing additional energy. This problem has been considered in some detail by *Flasar* [1973]; a crude estimate of the adequacy of an unmixing mechanism is obtained as follows. Consider a uniform density planet composed of two incompressible and immiscible fluids. We allow the denser fluid to separate and sink to the center. The energy per gram which is released is given by

$$\Delta E = -\Omega_0 F \tag{11}$$

where Ω_0 is the gravitational binding energy per gram of the initially homogeneous sphere, and F is a dimensionless number less than unity, which depends on the density contrast of

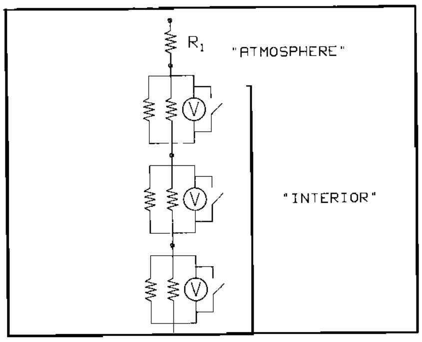

Fig. 6. An analogous 'circuit diagram' illustrating the role of the atmosphere in regulating the flow of heat from a liquid, convective planet.

the two fluids and the relative amounts of each. Approximating Jupiter as a homogeneous sphere, we have $\Omega_0 \sim -1.1 \times 10^{13}$ erg/g. In order for F to be reasonably large, the separating fluids must both be abundant in the planet, and so one considers hydrogen and helium for Jupiter and Saturn. According to *Stevenson* [1975], dense liquid hydrogen and helium should phase separate at temperatures of $\sim 10^4$ °K and lower, depending upon the pressure and the composition of the mixture (Figure 7). Although both hydrogen and helium are rather compressible at $P \sim$ 1-10 Mbar, our simple model will suffice to demonstrate the energetics of a hydrogen-helium phase separation luminosity source. Assume that the core density is twice the envelope density and that the core mass is 10% of the envelope mass. Then the radius of the core is approximately 0.375 of the radius of the planet, and we find $F \simeq 0.03$, yielding $\Delta E \simeq 3 \times 10^{11}$ erg/g. As was discussed above (see Table 1), this is essentially equal to the energy required to sustain the Jovian or Saturnian power source over the age of the solar system.

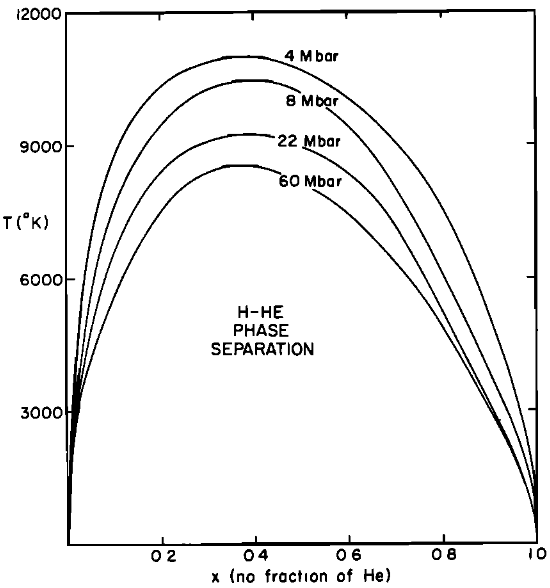

Fig. 7. Phase separation curves in temperature-helium abundance space for a mixture of liquid, pressure-ionized hydrogen and helium, at a variety of pressures [from *Stevenson and Salpeter,* 1976]. The mixture is homogeneous above the curve, and separates into helium-rich and helium-poor phases below the curve. (By permission from *Jupiter,* T. Gehrels, Editor, University of Arizona Press, Tucson, copyright 1976.)

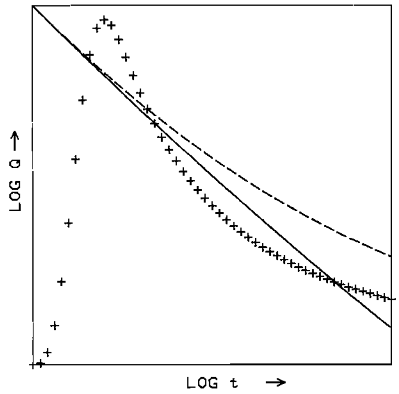

Fig. 8. A qualitative representation of the internal power as a function of time for three types of Jovian planet models: simple adiabatic cooling with homogeneous composition (solid curve), adiabatic or semi-adiabatic cooling with phase separation at later stage (dashed curve), and phase separation regulated by diffusion of helium with respect to hydrogen (crosses).

Having noted that gravitational unmixing is in principle an adequate energy source, one must next consider the processes which would regulate the emission of heat from the surface of the planet. It is also necessary to determine what fraction of the energy which is released actually becomes available for radiation into space.

Smoluchowski [1967] assumed that formation of a helium-rich core in Jupiter would be basically regulated by the rate of diffusion of helium with respect to hydrogen. The estimate for ΔE given above corresponds to a core growth rate of ~5 mm/year averaged over the age of the solar system, and this figure essentially agrees with Smoluchowski's figure of ~0.03–0.3 cm/year. In Smoluchowski's model, this rate could occur in hydrogen-helium under conditions with $P \sim 2$ Mbar, $T \sim 3500°$K. Most of the energy liberated would be available for radiation from the surface. It is important to note that the time evolution of such an energy source would differ radically from the time evolution of the adiabatic-convection model. The latter cools at a constantly decelerating rate from initially high temperatures, so that the initial state has little effect on the later evolution. In Smoluchowski's immiscible-diffusing model, one would expect the opposite behavior. The model is initially cold but would heat up as energy is released by core formation. Any increase in the interior temperature would have a major effect on the diffusion rate, which essentially has an exponential dependence on inverse temperature. Thus the luminosity would tend to have an unstable time dependence, peaking rapidly as the core is formed and thereafter tending to resemble the cooling model.

The model of *Stevenson and Salpeter* [1977] is in some degree a synthesis of the models of *Hubbard* [1968] and *Smoluchowski* [1967]. It assumes that the planet is initially hot and essentially homogeneous, with no major chemical discontinuities (other than a possible discontinuity at the molecular hydrogen–metallic hydrogen phase transition). Thus the initial evolution of the planet resembles the evolution of the adiabatic model. The planet is almost fully convective, although the molecular-metallic hydrogen phase transition, if it is first order, may produce a very thin conductive region and a jump in specific entropy. Such an entropy discontinuity could in principle cause the metallic core to be at temperatures which differ by up to a factor of 2 from the core temperatures of an adiabatic homogeneous planet, although Stevenson and Salpeter consider temperature differences of ~10%–20% to be more likely. As the planet cools at a rate regulated by the atmosphere, the critical temperature for phase separation in a hydrogen-helium fluid mixture will be reached. There is no question that this will eventually occur; the only question is whether Jupiter or Saturn has evolved to sufficiently low temperatures for phase separation to have begun at present. As is indicated in Figure 7, phase separation should commence in the outer layers of Jupiter, with the formation of two fluid phases, one rich in helium compared with solar composition and the other poorer. In order for the helium-rich fluid to overcome the effects of turbulent flows (~10 cm/s velocity) and efficiently sink toward the center, liberating gravitational energy, helium-rich droplets of dimensions ~1 cm must be formed. According to *Stevenson and Salpeter* [1977], droplets of such size can form within ~10^3 s, whereas a typical large-scale convective time scale is ~10^8 s. Most of the energy released by the helium 'rain' becomes available for radiation from the surface.

As the helium droplets sink, they eventually encounter a region where a single liquid phase is once again stable, and the droplets dissolve [*Salpeter,* 1973]. This process leads to a gradual helium enrichment of the core at the expense of the envelope, and eventually a predominantly helium core is formed. Note, however, that unlike Smoluchowski's model, the thermal evolution of the Stevenson-Salpeter model is essentially regulated by the atmosphere. The rate of cooling of the planet depends essentially on the atmospheric bottleneck, as in the Hubbard model. The planet must cool off in order to produce more immiscible helium-rich droplets to liberate energy; if the temperature is raised, the helium goes back into solution. Thus the evolution of the planet is stable. After the initial homogeneous convective-adiabatic stage of evolution, a Jovian planet enters the gravitational unmixing stage, with phase separation acting as a kind of thermostat, greatly slowing further cooling.

Figure 8 qualitatively summarizes the different luminosity history for the three Jovian planet models discussed above. Our state of knowledge about the hydrogen-helium phase diagram is such that it is not currently possible to plot these curves quantitatively and thus distinguish between models. However, in the following section we will discuss observational evidence which seems to indicate that the radiative properties of the atmosphere do govern the escape of internal heat from the Jovian planets.

4. ROLE OF THE ATMOSPHERE

Uniformity of the Effective Temperature

Although most of the surface flux from Jupiter, Saturn, and Neptune is derived from interior processes, the flux due to thermalization of sunlight is not negligible. The ratio of converted solar flux to total (converted solar plus interior) flux is clearly just $(T_S/T_e)^4$; see Table 1. The effect of sunlight on the thermal evolution of the planet may depend critically on the region in the atmosphere where the conversion of sunlight to thermal flux takes place. Figures 9*a* and 9*b* show two extreme possibilities. In case (*a*), sunlight is thermalized well above the photosphere and therefore contributes little to the energy flow in the deep interior. Using the analogy of Figure 6, it is as if current flow involving solar input were on a completely separate circuit from the rest of the planet.

In case (*b*), sunlight penetrates to well below the photosphere, where it is thermalized and then acts like an additional shell of energy sources in the planet. This case is analogous to an additional input of current somewhere in the 'interior' circuit of Figure 6. The flow of energy through the atmosphere is then a sum of flows from the interior plus thermalized sunlight. Provided that there is still enough outward flux everywhere in the planet to maintain convective equilibrium up to the photosphere, case (*b*) is the same as the simple cooling model except that the total flux through the atmosphere determines the cooling rate. It is assumed that the interior flux alone, below the conversion layer, is sufficient to maintain convection. When this is no longer true, then the conductive properties of the interior become important for planetary cooling, and the adiabatic model breaks down.

Model atmospheres for Jovian planets were originally calculated by *Trafton* [1967] and subsequently by *Graboske et al.* [1975]. The results indicate that although case (*b*) is nearer to the truth than case (*a*), the conversion layer may lie within a few scale heights of the photosphere. Possibly a complete resolution of the problem can only be accomplished by an atmospheric entry probe.

Assuming that the appropriate boundary condition is given by case (*b*), *Ingersoll and Porco* [1978] studied the effect of latitude-dependent conversion of solar flux on the interior temperature distribution of a rotating Jovian planet with zero obliquity. Their results are an extension of an earlier investigation by *Ingersoll* [1976], who considered the problem of the redistribution of converted solar energy in Jupiter. Ingersoll found that if internal convection is highly efficient, the input of solar energy at low latitudes tends to 'choke off' the flow of heat from the interior, redirecting it to the poles. The planet would then be expected to have an essentially uniform distribution of T_e with respect to latitude, and to within the accuracy of measurement of $\sim\pm3°K$ [*Ingersoll et al.,* 1976], such is observed. Ingersoll and Porco found that as long as $(T_e/T_S)^4 \gtrsim 1.25$, the internal heat source is powerful enough to reroute excess flux to the poles, and guarantees a constant T_e over the planet. Note that for case (*a*), one would expect a higher T_e at the equator than the poles.

An alternative method of visualizing this effect makes use of (8) [*Ingersoll et al.,* 1976, *Hubbard,* 1977]. If the temperature follows an adiabat everywhere in the planet, then T/ρ^γ must be independent of latitude. This implies that

$$T_e \propto g^{0.134} \tag{12}$$

so that T_e becomes a function of latitude. Equation (12) implies that the polar effective temperature of Jupiter should be higher than the equatorial effective temperature by about 2°K. This predicted effect has not yet been confirmed or disproved by observations.

For case (*b*) the equation of thermal evolution of the planet is

$$4\pi R^2\sigma(T_e^4 - T_S^4) = -\int dm\left(\frac{dE}{dt} - \frac{P}{\rho^2}\frac{d\rho}{dt}\right) \tag{13}$$

and the new version of (9) is then

$$dt = -\alpha T_e^{-3.757}\,[1-(T_S/T_e)^4]^{-1}dTe \tag{14}$$

i.e., the effect of the sunlight is to arrest the thermal evolution of a fully convective planet. Obviously, (14) must fail when $(T_S/T_e)^4$ becomes larger than some critical value, and the planet ceases to be fully convective. For Jupiter the effect of the term in T_S/T_e is a small one and acts to extend the cooling time by ~20–30%.

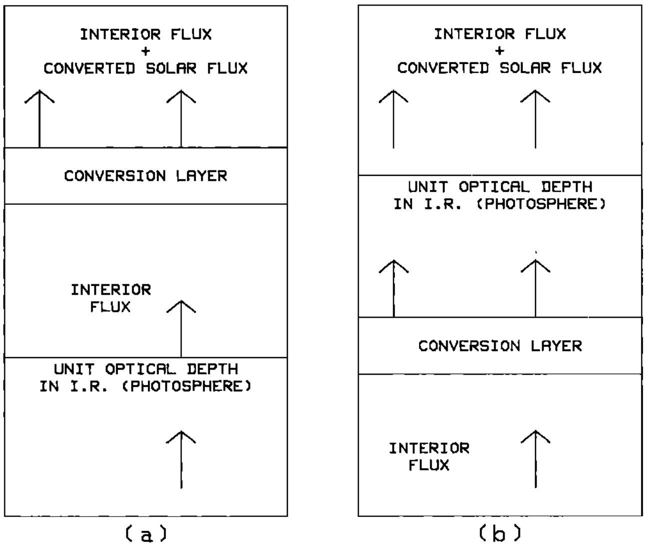

Fig. 9. Schematic representation of two extreme possibilities for the deposition of solar energy in a Jovian planet atmosphere. In case (*a*) the conversion of solar flux to infrared flux takes place well above the photosphere and does not affect thermal evolution. In case (*b*), conversion occurs well below the photosphere and the total flux through the photosphere governs thermal evolution.

Saturn

Estimates for the cooling time of Saturn have been made by *Pollack et al.* [1977] and by *Stevenson and Salpeter* [1977]. They find that a simple homogeneous, adiabatic cooling model gives a total age of $\sim 2 \times 10^9$ years, essentially using the theory of (14) and the data of Table 1. As in the case of Jupiter, the effect of T_S/T_e is a small one. It thus appears that Saturn may be overluminous for its age, necessitating additional energy sources, such as separation of helium from hydrogen as mentioned above [*Pollack et al.,* 1977]. Thus Saturn may have already entered the 'Stevenson-Salpeter' stage of its evolution, while the more massive Jupiter remains in the homogeneous stage. This conjecture must remain quite tentative until more accurate results are available for T_e and T_S.

Uranus and Neptune

The considerable discrepancy in the net heat flow values for these two bodies can be qualitatively explained by the effect of differing amounts of sunlight on the atmospheric boundary condition of a convective planet [*Hubbard,* 1978]. Since Uranus and Neptune have similar masses (14.6 and 17.3 earth masses, respectively) and mean radii (25,900 and 24,550 km, respectively), any difference in their thermal properties should be sought in terms of differing T_S, differing obliquity, or some other gross difference. A larger obliquity would change the amplitude with which solar input varies over the surface of the planet but would not change its average value. As long as the thermal time constant for the atmosphere is long in comparison with a Uranian or Neptunian year, the obliquity may not play a large role in the secular thermal evolution of a Jovian planet. *Fazio et al.* [1976] found that the atmospheric temperature changes very little over a Uranian year even neglecting advection between the day and the night hemisphere. Thus despite the difference in obliquity between Uranus (98°) and Neptune (29°), it seems doubtful at present that this could play a major role in the observed energy balance difference, although the problem has not yet been studied quantitatively.

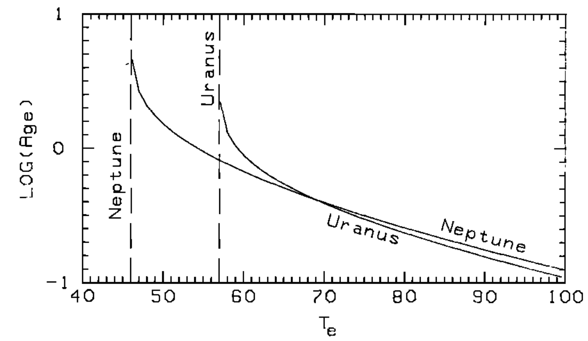

Fig. 10. Cooling curves for Uranus and Neptune, where the age is in units of 4.6 × 10^9 years. Dashed curves are vertical asymptotes at $T_e = T_S$.

Trafton [1974] proposed that a difference might arise due to deposition of energy in Neptune from the decay of the retrograde orbit of its massive satellite Triton, although this model requires a privileged position in time for current observers, since the required decay time is short in comparison with the age of the solar system.

Current interior models of Uranus and Neptune [*Hubbard and MacFarlane,* 1979] suggest that these planets are closely similar and that both differ fundamentally from Jupiter and Saturn in terms of chemical abundances. Whereas Jupiter and Saturn are primarily hydrogen and helium, these elements are only minor constituents of Uranus and Neptune, comprising the outer ~12% of Uranus' mass and the outer ~7% of Neptune's mass. Other major constituents are the 'ices' H_2O, CH_4, and NH_3 (~55% in Uranus and ~68% in Neptune) and dense cores composed of iron and silicates (~12% in Uranus, ~7% in Neptune). These models are based on recently measured equations of state of H_2O, CH_4, and NH_3 [*Mitchell and Nellis,* 1979, also personal communication, 1978] and on reasonable cosmogonical assumptions. *Zharkov and Trubitsyn* [1972] have pointed out that the relatively poor thermal conductivity of such materials and the large size of Uranus and Neptune should enable these planets to retain primordial heat and have adiabatic temperature distributions in their interiors. As a result, both planets should be essentially liquid. We will now assume that the adiabatic cooling model used for Jupiter and Saturn can be extended to Uranus and Neptune. That is, we assume that internal opacities are high, thermal conduction is poor, and efficient convection prevails as a heat transport mechanism in the interior. As a result, we assume that (14) or an analogous equation is applicable, where α is poorly known for Uranus and Neptune but should have a similar value for both. Inspecting (10), we expect that α for Neptune should be somewhat larger than for Uranus, since α scales approximately as (mass)/(radius)^2 for objects of similar chemical composition.

Figure 10 shows cooling curves calculated by *Hubbard* [1978] assuming the validity of (14) for the thermal evolution of Uranus and Neptune. In this calculation we have treated α as an unknown and therefore free parameter except that it should be approximately the same for Uranus and Neptune because of their similar structure. From scaling considerations we expect α for these planets to be of order 10^{22} cgs units, and Figure 10 shows results for Uranus where α is taken to be 1.59 × 10^{22}. The curve for Neptune uses a value of α which is larger by 18% to account for the larger mass. Attempts to calculate more accurate values of α for these planets are in progress, but it appears that the difference in luminosity between Uranus and Neptune can be satisfactorily explained by this model and is primarily caused by the difference in T_S.

5. CONCLUSIONS

The evidence and interpretations which we have presented in this discussion seem to indicate that (1) all four Jovian planets were once more luminous and are presently cooling to a state of equilibrium with sunlight; (2) the thermal evolution of the Jovian planets is predominantly controlled by their photospheres and does not depend upon interior conductivity. Additional support for conclusion (1) comes from the observed distribution of mean densities in the Galilean satellites [*Cameron and Pollack,* 1976], and similar effects may be discovered in the other satellite systems. Both conclusion (1) and conclusion (2) are consistent with either the simple adiabatic cooling model or with more complicated gravitational unmixing models of the type discussed by *Stevenson and Salpeter* [1977]. The latter will be primarily applicable to Jupiter and Saturn, where large abundances of hydrogen and helium in an initially mixed state are to be expected. There seems to be no process which could effectively separate these elements prior to the formation of a collapsed planet, and it is predicted that the unmixing phase will occur at a late phase in planetary cooling, possibly later than the present epoch.

For Uranus and Neptune, the situation is even less clear. Because of their low relative abundance, hydrogen and helium should have relatively little influence on internal energy stores, although the hydrogen-helium atmospheres do act as 'valves' for the escape of heat. The two major constituents seem to be the ices H_2O, CH_4, and NH_3 on the one hand, and iron-silicate on the other. One suspects that these constituents will either accrete inhomogeneously or else separate early, leaving an initially hot planet which then follows an evolutionary course similar to Jupiter's in the homogeneous cooling phase. We have assumed that the temperature distribution in the interior remains adiabatic owing to efficient convection. This convection may not succeed in homogenizing the interior, and indeed there may be conductive regions and specific entropy discontinuities across chemical boundaries. Ignoring all of these complications, the adiabatic cooling model seems to work at our present level of ignorance.

Future work should be directed toward improving the heat flow measurements for all four Jovian planets, particularly for Saturn. In situ measurement of hydrogen-helium abundances in the atmosphere of Jupiter and Saturn should be a helpful diagnostic. It is also evident that more quantitative thermal models for Uranus and Neptune are needed.

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