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Molecular Opacities: Application to the Giant Planets

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Abstract

Present available interior models of giant planets assume that the internal transport of energy is entirely convective and, accordingly, rule out any possibility of radiative transport. New opacity calculations at temperatures and densities occurring within the giant planets, taking into account H_2-H_2 and H_2-He collision-induced absorption as well as infrared and visible absorption due to hydrogen, water, methane and ammonia are presented. These opacities are not high enough to exclude the presence of a radiative zone in the molecular H_2 envelope of Jupiter, Saturn and Uranus.

Abstract

Les modèles de structure interne des planètes géantes développés actuellement supposent que le transport de l'énergie s'effectue entièrement par convection, ce qui élimine toute possibilité de transport radiatif. Des nouveaux calculs d'opacité aux températures et densités caractéristiques des planètes étudiées, tenant compte de l'absorption induite par collisions H_2-H_2 et H_2-He ainsi que de l'absorption dans l'infrarouge et dans le visible de l'hydrogène, l'eau, le méthane et l'ammoniaque, sont présentées. Ces opacités ne sont pas suffisamment élevées pour exclure la présence d'une zone radiative dans l'enveloppe d'hydrogène moléculaire de Jupiter, Saturne et Uranus.

35.1 Introduction

Since the estimations of the conductive and radiative opacities in Jupiter by Hubbard (1968) and Stevenson (1976) all the interior models of the four giant planets have been calculated under the assumption that the energy is transferred by convection through the entire hydrogen-helium envelope. Consequently, the thermal profile is assumed to be adiabatic at all depths. This hypothesis is based on the fact that these conductive and radiative opacities are high and that at least Jupiter, Saturn and Neptune have a substantial intrinsic luminosity.

New facts prompt us to reexamine the question. Firstly, new calculations have permitted to improve substantially the hydrogen-helium opacity. Secondly, progress in molecular spectroscopy allows one to take into account the opacity due to the most abundant minor atmospheric components. Thirdly, *Voyager* measurements have provided a new upper limit of the intrinsic luminosity of Uranus which is significantly weaker than that previously thought.

In the next Section, we present the method used to determine the presence of a radiative zone. Then we calculate radiative opacities. In the last section we comment our results.

35.2 Method

Neglecting rotation and compositional gradients, we use the Schwarzschild criterion: the medium is convective when $\nabla_{\mathrm{ad}} < \nabla_{\mathrm{rad}}$, and radiative otherwise. $\nabla_{\mathrm{ad}} \equiv (\partial \ln T/\partial \ln P)_S$ is the adiabatic gradient and ∇_{rad} the radiative gradient. This latter is proportional to the intrinsic luminosity of the planet (taken from Pearl and Conrath, 1991) and to the Rosseland mean opacity:

$$\kappa_R = \left[\int_0^\infty \frac{1}{\kappa_\nu}\frac{\mathrm{d}B_\nu}{\mathrm{d}T}\mathrm{d}\nu\right]^{-1}\left[\int_0^\infty \frac{\mathrm{d}B_\nu}{\mathrm{d}T}\mathrm{d}\nu\right],$$

where κ_ν is the monochromatic absorption and B_ν is the Planck function.

Therefore, we have to calculate Rosseland opacity tables for each planet with chemical abundances compatible with the infrared observations of their atmospheres (Gautier & Owen, 1989). In particular, the abundances of the CNO compounds and heavier elements are set to 2, 4 and 50 times the solar value for Jupiter, Saturn and Uranus, respectively.

We use for this comparison the interior models of Chabrier *et al.* (1992) for Jupiter and Saturn, and those of Hubbard & Marley (1989) for Uranus.

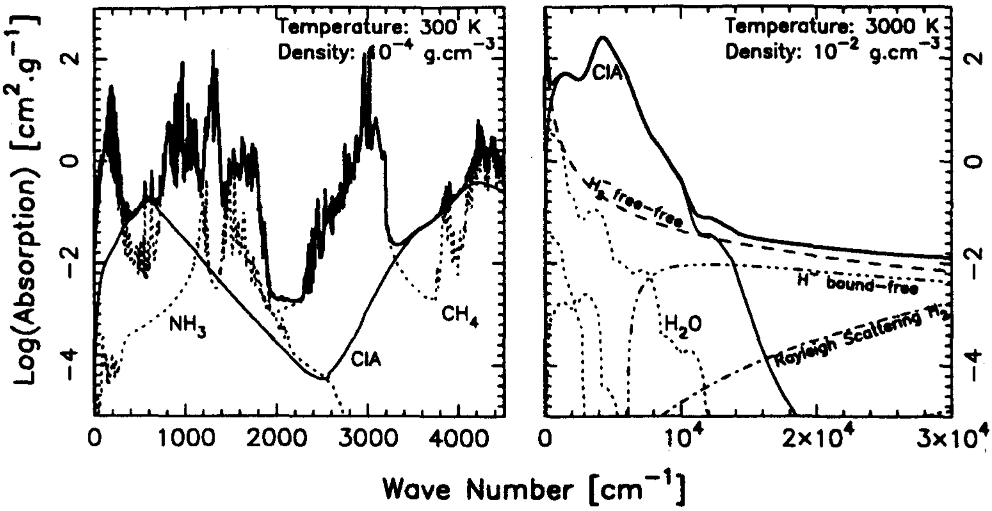

Fig. 35.1 Synthetic absorption spectra for Jupiter, at T=300 K (left) and T=3000 K (right). The cut-off is equal to 1000 cm^{-1}. The heavy line represents the total absorption while the other lines show different contributions.

35.3 Opacities

Rosseland opacity tables, adapted from the work of Lenzuni *et al.* (1991) in order to account for heavier elements than hydrogen and helium, are calculated for $200 < T < 5000$ K, and $10^{-5} < \rho < 1$ g.cm^{-3}. The following absorption sources are taken into account:

- H_2-He and H_2-H_2 Collision–Induced Absorption (CIA) (Borysow & Frommhold, 1989, 1990)
- Rayleigh scattering by H_2 (Dalgarno & Williams, 1965)
- Rayleigh scattering by H and He (Kurucz, 1970)
- H_2^- free-free absorption (Bell, 1980)
- H^- bound-free absorption (John, 1988)
- Infrared and visible absorption of H_2O, CH_4, NH_3 (GEISA data bank - Husson *et al.*, 1991)

A chemical equilibrium is calculated, taking into account the following species: H, H^+, H^-, H_2, H_2^+, H_3^+, e^-, Na, Na^+, Mg, Mg^+, Al, Al^+, Si, Si^+, K, K^+, Ca, Ca^+, Fe, Fe^+, Cl, NaCl, KCl, CaCl. All the C,N,O atoms are assumed to form CH_4, NH_3 and H_2O, respectively, according to the results of Barshay & Lewis (1979).

The absorption of H_2O, CH_4, NH_3 is calculated assuming a Lorentz profile with a cut–off set to 100, 500, and 1000 cm^{-1}, respectively: at this distance from the line–center, the absorption is supposed to be exponentially decreasing (Birnbaum, 1979).

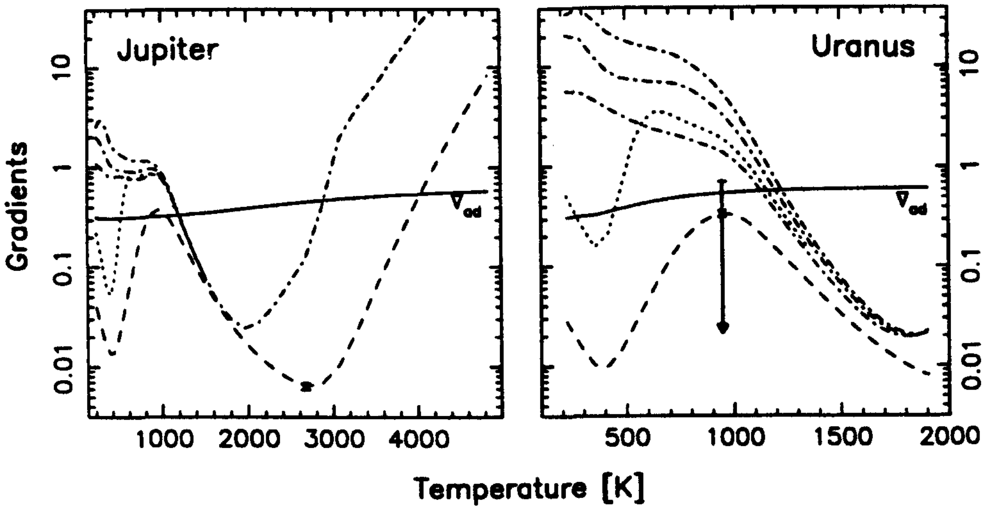

Fig. 35.2 Comparison of the radiative (dot-dashed lines) to the adiabatic gradients (plain lines) in the case of Jupiter (left) and Uranus (right). The medium is expected to be radiative when $\nabla_{ad} > \nabla_{rad}$. The dashed lines correspond to the radiative gradient calculated with the opacity of hydrogen and helium alone. The various dot-dashed lines correspond to values of the cut-off equal to 100, 500 and 1000 cm^{-1}. The vertical bars show the uncertainties on the measured intrinsic luminosities.

Non-ideal effects for the CIA of H_2-H_2 and H_2-He are taken into account, following the method described by Lenzuni & Saumon (1992).

Figure 35.1shows two synthetic spectra at T=300 K and T=3000 K. One can see that the contribution of H_2O, CH_4, NH_3 to the total opacity is significant at low temperatures, as these molecules are strong absorbers in the infrared, region which has then the most important weight in the Rosseland opacity. At higher temperatures and larger densities, the CIA, proportional to ρ^2, and H_2^- free-free and H^- bound-free absorptions dominate the spectrum.

35.4 Results

We compare in Fig 35.2 the radiative and adiabatic gradients for Jupiter and Uranus. Saturn and Jupiter have similar internal structures. Therefore all the results for Jupiter are also true for Saturn, at least qualitatively. The case of Neptune has not been treated here.

The dashed lines in Fig35.2 correspond to radiative gradients calculated with hydrogen and helium only. A comparison of these curves to the adiabatic gradients (plain lines) shows that hydrogen and helium cannot ensure convection in the entire molecular hydrogen-rich envelopes of Jupiter and

Uranus. In both planets, the presence of H_2O, CH_4 and NH_3 (dot-dashed lines) restore convection at temperatures below 1200 K (corresponding to pressures below 1 and 10 kbar for Jupiter and Uranus, respectively). According to our calculations, a deep radiative window is therefore present in Jupiter, Saturn and Uranus. In the case of Jupiter, convection appears again at temperatures above 2900 K for which the absorption of H^- and H_2^- becomes preponderant. At these levels the contribution of metals is significant. In the case of Uranus the comparison ends at 2000 K, as our calculations cannot apply to the "ices"+"rocks" core of this planet.

We emphasis that our opacity calculations are uncertain, due to the lack of knowledge on both the chemical composition and absorption of the medium considered. However the predicted radiative zones will vanish only if these opacities are underestimated by more than one order of magnitude. Moreover, the observations do not preclude a very low value for Uranus' intrinsic luminosity. This would lead to a still larger radiative zone in this planet.

Non-adiabatic models of the giant planets are needed for studying the consequences of the presence of a radiative zone on their internal structure. This is the subject of our next communication.

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