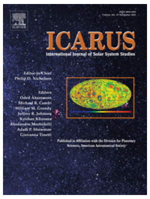
Icarus 297 (2017) 160–178

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Inhibition of ordinary and diffusive convection in the water condensation zone of the ice giants and implications for their thermal evolution

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ARTICLE INFO

Article history:
Received 26 July 2016
Revised 22 June 2017
Accepted 26 June 2017
Available online 30 June 2017

ABSTRACT

We explore the conditions under which ordinary and double-diffusive thermal convection may be inhibited by water condensation in the hydrogen atmospheres of the ice giants and examine the consequences. The saturation of vapor in the condensation layer induces a vertical gradient in the mean molecular weight that stabilizes the layer against convective instability when the abundance of vapor exceeds a critical value. In this instance, the layer temperature gradient can become superadiabatic and heat must be transported vertically by another mechanism. On Uranus and Neptune, water is inferred to be sufficiently abundant for inhibition of ordinary convection to take place in their respective condensation zones. We find that suppression of double-diffusive convection is sensitive to the ratio of the sedimentation time scale of the condensates to the buoyancy period in the condensation layer. In the limit of rapid sedimentation, the layer is found to be stable to diffusive convection. In the opposite limit, diffusive convection can occur. However, if the fluid remains saturated, then layered convection is generally suppressed and the motion is restricted in form to weak, homogeneous, oscillatory turbulence. This form of diffusive convection is a relatively inefficient mechanism for transporting heat, characterized by low Nusselt numbers. When both ordinary and layered convection are suppressed, the condensation zone acts effectively as a thermal insulator, with the heat flux transported across it only slightly greater than the small value that can be supported by radiative diffusion. This may allow a large superadiabatic temperature gradient to develop in the layer over time. Once the layer has formed, however, it is vulnerable to persistent erosion by entrainment of fluid into the overlying convective envelope of the cooling planet, potentially leading to its collapse. We discuss the implications of our results for thermal evolution models of the ice giants, for understanding Uranus' anomalously low intrinsic luminosity, and for inducing episodes of intense convection in the atmospheres of Saturn, Uranus, and Neptune.

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1. Introduction

The accretion of the outer planets is generally believed to have formed them with high initial temperatures and they have been slowly releasing the primordial heat of their formation over the age of the solar system. Historically, thermal evolution models of Uranus and Neptune have encountered difficulty in reproducing their present effective temperatures. Their current (4.6 Gy) effective temperatures could be explained only if they started with relatively low internal entropies, suggesting a "cold accretion" scenario for their formation, or if stable compositional stratification in their interiors suppressed convective cooling during some portion of their evolution (Hubbard and McFarlane 1980; Podolak et al., 1991; Hubbard et al., 1995). More recently, taking advantage of new data for the equation of state of water, Fortney et al. (2011) found that they could match the observations of Neptune's effective temperature with a model that included a fully convective interior. However, their model Uranus still cooled too slowly. As others had done previously, they surmised that a strong barrier to convective cooling of the interior has existed on Uranus but not on Neptune.

In these cooling calculations, it has been assumed that the thermal structure inside the planet can be adequately represented by a single adiabat running from the core to just below the visible atmosphere. Although water is predicted to be abundant in the envelopes of the ice giants, the effects of water condensation have not been included in the models.

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http://dx.doi.org/10.1016/j.icarus.2017.06.029
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Table 1
Critical Abundance for Inhibition of Convection. The abundance is given in terms of the factor of enrichment over the solar value that is required. Adapted from Guillot (1995), with solar abundances from Asplund et al. (2009).

Species	Jupiter	Saturn	Uranus	Neptune
CH_4*	–	–	20.9	22.1
NH_3	52.8	54.3	86.8	92.5
H_2O	8.0	8.5	11.0	11.7

* Methane does not condense in Jupiter and Saturn

The purpose of this paper is to examine how water condensation in the deep atmospheres of the ice giants may have affected the cooling of their interiors over the course of their thermal evolution. As will be explained below, the formation of a saturated water layer has the potential to suppress both ordinary and double-diffusive convection within the layer, providing a barrier to convective cooling of the interior. As a result, the layer acts effectively as an imperfect insulator separating the water-rich deep atmosphere below from a relatively cold, dry atmosphere above. The insulating effect of this gradient zone allows the atmosphere above and below to lie on potentially very different adiabats connected by a superadiabatic temperature gradient. In this way, incorporation of the effect of water condensation in ice giant cooling models may fundamentally alter calculated cooling trajectories by altering the relationship existing between the effective temperature of the planet at any given time and the entropy stored in its deep atmosphere and interior.

The most abundant species able to condense in the atmospheres of the outer planets all have molecular weights much larger than that of hydrogen and helium, the two principal components of the dry air. Guillot (1995) demonstrated that condensation of these species could inhibit moist convection within a saturated layer provided their abundance at the base of the layer exceeds a critical value. If it does, then a region near the base of the layer becomes stable to convection as a consequence of the density stratification imparted by the mean molecular weight gradient induced by the decreasing mixing ratio of the saturated species. Under such conditions, a layer possessing a superadiabatic temperature gradient becomes buoyantly stable. With ordinary convection inhibited, heat must be transported through the gradient zone by a less efficient mechanism, such as by double-diffusive convection or radiation.

Table 1 lists the critical abundances for CH_4, NH_3, and water in the atmospheres of the outer planets. The data are taken from Guillot (1995). The abundances are given in terms of the enrichment of the C, N, or O mole fraction relative to solar composition (Asplund et al., 2009). The modest enrichments of NH_3 observed in Jupiter and Saturn (Atreya et al., 2003; Briggs and Sackett 1989) are much lower than the critical values shown in the table. Therefore ammonia condensation should not be effective in inhibiting convection in these planets. In contrast, the best estimates for the methane abundances observed on Uranus and Neptune exceed ~35 times solar (Sromovsky et al., 2011; Baines et al., 1995), well above their critical values. Guillot (1995) concluded that moist convection is inhibited where the methane saturates. A similar conclusion can be drawn for the water condensation layer in these planets if their oxygen abundance is supercritical, and the degree that carbon is enriched over solar suggests that this may well be likely. Interior models of Uranus and Neptune, constrained by the gravity field measurements, generally favor solutions having water abundances in the molecular envelope that are several times the critical value (Fortney and Nettelmann 2010). This opens the possibility that condensation of water may have played an important role in inhibiting internal cooling in the ice giants during the course of their thermal evolution.

The abundances of water in the deep atmospheres of Jupiter and Saturn are unknown. If oxygen is at least as enriched over the solar value as carbon in these planets (i.e, between ~4 to 10 times solar), then it is possible that water condensation can potentially inhibit convection in these atmospheres as well. However, the criterion for convective inhibition is likely to be only marginally satisfied. As will be shown below, this implies that stable layers formed in this way would be relatively quite thin and therefore especially susceptible to erosion and catastrophic failure. Consequently, we do not expect formation of saturated water zones in Jupiter and Saturn substantially affected their cooling histories. Effects associated with the molecular weight of water may nevertheless have observable consequences for the dynamics of moist convection in Saturn (Li and Ingersoll 2015).

In Section 2, we discuss the inhibition of ordinary moist convection in the water condensation zone, introduce the dynamical equations we use to calculate motion associated with buoyancy in the layer, and explore the stability of the layer to infinitesimal upward and downward displacements in the absence of viscosity and thermal diffusion. In Section 3, we set up the linear perturbation equations that govern small-amplitude motions and investigate the conditions for which viscosity and thermal (radiative) diffusion lead to instability to double-diffusive convection. We find that diffusive convection in the condensation layer is suppressed in the limit where the condensate precipitates rapidly out of the system.

In a contemporaneous study, Leconte et al. (2017) also explore the inhibition of double-diffusive convection in the condensation layers of hydrogen-rich atmospheres. They find, as we do, that diffusive convection can be suppressed in the condensation zone if the condensable species is sufficiently abundant, provided the condensate is rapidly removed from buoyant fluid elements where condensation occurs.

Leconte et al. (2017) do not perform an analogous calculation examining the opposite extreme, where rainout of the condensate is assumed to proceed very slowly. We find that the layer can undergo diffusive convection when the motion of condensed droplets is tightly coupled to that of the gas (that is, in the limit of slow precipitation). In Section 4, we explore whether the ensuing diffusive instability takes the form of disorganized, homogeneous turbulence or organizes into layered convection. A discussion of the potential implications of our results for the cooling histories of Uranus and Neptune is offered in Section 5; in particular, we consider the ability of a stable layer, once formed, to resist persistent, erosive entrainment of its fluid into the overlying convective envelope as the outermost layers of the planet continue to cool. We summarize our conclusions in Section 6.

2. Inhibition of moist convection in the water condensation zone

In Earth's atmosphere, the vertical density stratification is dominated by the vertical temperature variation; variation in the water mixing ratio has only a weak effect. This is because the water mixing ratio is relatively low and because water is lighter than nitrogen. In the outer planets, saturation of vapor in a condensation zone sets up a vertical gradient in the mean molecular weight of the air (Guillot 1995). If the vapor is sufficiently abundant, the gradient can stabilize the layer against moist convection. This can be seen by considering the buoyancy force acting on a parcel of fluid displaced vertically in a saturated layer in which the temperature decreases with altitude faster than the moist pseudoadiabat. As the parcel rises, its temperature follows the pseudoadiabat, it becomes warmer than its surroundings, and if there were no molecular weight effect, it would become positively buoyant. However, by virtue of being warmer than its surroundings, it also

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