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Our inhomogeneous and unique outer planets

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Abstract

We present interior models of the outer planets in the solar system. We find that none of these planets can have a constant metallicity throughout the interior. For Uranus we find a significantly smaller outer envelope metallicity than for Neptune. The cooling time of Uranus can be brought into agreement with the age of the solar system if the deep interior is assumed to have a lower heat flux than along an adiabatic gradient. For Saturn, our models predict an atmospheric He/H mass fraction of ~ 0.1, i.e. smaller than Jupiter's.

1. Introduction

Several criteria have been suggested to distinguish giant planets (GPs) from brown dwarfs (BDs), such as the deuterium burning mass limit (~ 13 $\mathrm{M_J}$), the BD desert (~ 35 $\mathrm{M_J}$), heavy element enrichment, and the formation mechanism. We show that the outer planets in the solar system share the property of an inhomogeneous interior in contrast to a fully convective and homogeneous interior as often proposed for BDs. Exoplanets are often compared to our outer planets. Here we consider a possible unique nature of the 'ice giants' Uranus and Neptune.

2. Methods

We derive the core mass and envelope metallicities by numerically solving the standard stellar structure equations of mass conservation and hydrostatic equilibrium for a rotating oblate planet. The core mass is found by the requirement to meet the observed equatorial radius for given total mass, and the metallicities Z_1 and Z_2 in the two envelopes are adjusted to reproduce the observed gravitational moments J_2 and J_4. All models have an average He abundance $Y = M_{\mathrm{He}}/(M_{\mathrm{He}} + M_{\mathrm{H}})$ of 27.5%. The He abundance in the atmosphere of Jupiter is the *Galileo*-probe value $Y_1 = 0.238$, for Uranus and Neptune we take $Y_1 = 0.275$, and for Saturn we choose a value of 10%, which is between the original *Voyager* data value (1-11%) and the re-analyzed value (18-25%, [3]). For H, He, and water (representing metals in the envelope) we apply LM-REOS [7]. The transition pressure P_{1-2} between the envelopes is considered a free parameter.

3. Results

3.1. Jupiter and Saturn

Using the three-layer assumption as introduced in [5], we find Jupiter models that satisfy the observational constraints, if we allow for an inhomogeneous heavy element distribution, with $Z_1 \sim 2\times$solar and $Z_2 \sim 8\times$ solar. For transition pressures below 4 Mbar, Z_1 would drop below $2\times$ solar, whereas *Galileo*-probe measurements indicate an enrichment factor of $2-4$. For Saturn, we find lower transition pressures of at most 4 Mbar, where this limit is set by a zero-mass core. A non-hydrogen mass fraction below 20% is necessary to meet the J_4 value of -0.000935 from the *Cassini* mission [1]. Future work will include the determination of an internal layer boundary by requiring consistency with H/He phase separation and He sedimentation. Because of higher internal temperatures in BDs, a layer boundary because of H/He phase separation is not expected to occur in BDs.

3.2. Uranus and Neptune

Until recently, Uranus and Neptune were considered similar (*ice giants*) when models of the interior, the magnetic field, or the thermal evolution were calculated. The work in [4] showed that Jupiter-like models with a quasi-adiabatic interior can explain the intrinsic luminosity of Neptune, but not that of Uranus. Here we use such a quasi-adiabatic interior model for Uranus (Fig. 1), and calculate a cooling time of 9.1 Gyr. The steep rise in metallicity from 10 to 90% at 0.8 M_{U} (typical Neptune model: from 40 to 80%) suggests an inhibition of convective energy transport across the layer boundary. In real Uranus, this may not be as sharp as idealized here but form a bound-

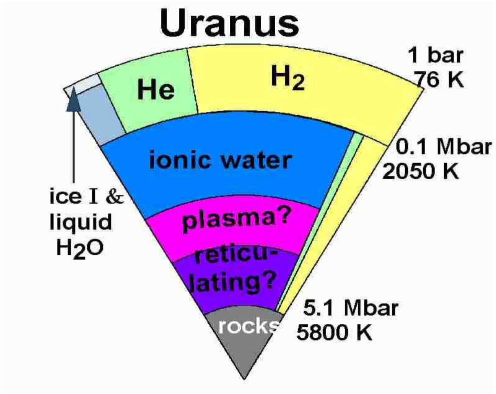

Figure 1: Three layer Uranus interior model calculated with 10% water, representative for ices, in the outer envelope and 88% water in the inner envelope, and a rock core. The mass fraction of hydrogen (yellow) and helium (green) are shown, wheras the water mass fraction is coded by color according to the preferred thermodynamic phase: ice I and liquid (light grey), supercritical molecular water (grey-blue), ionic (blue), plasma (magenta), reticulating (indigo).

ary layer with double-diffusive convective cells and an conductive energy flux $F_{\rm c}$. For $F_{\rm c}$ about 40% of the maximum energy flux $F_{\rm ad}$ along an adiabatic gradient, the correct cooling time is achieved (Fig. 2). However, magnetic field models [9] give better agreement with the observed field if only the inner 0.4 $M_{\rm U}$ are stable against convection. Such a boundary might be related to the formation and sedimentation of C-N chains in the reticulating phase of a mixture of various ices [2] and occur in both Uranus and Neptune. Importantly, the cooling time calculations are subject to the significant uncertainty in Uranus' intrinsic luminosity.

4. Conclusions and Outlook

Our three-layer models predict a low ($\sim\ 10\%$ by mass) helium abundance in Saturn's atmosphere, and a $2\times$ solar heavy element enrichment in Jupiter's atmosphere. Uranus might differ from Neptune by having a more pronounced heavy element discontinuity. We encourage to measure Saturn's atmospheric helium abundance, Jupiter's atmospheric oxygen abundance, and Uranus' intrinsic luminosity.

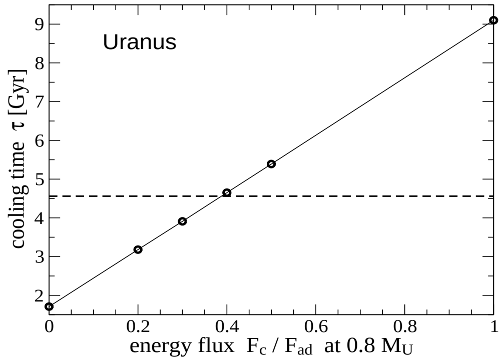

Figure 2: Cooling time of Uranus in dependence on the energy flux that is allowed to pass from the inner layer into to outer layer mimicking the effect of a stable interior with limited energy transport across. The correct cooling time is obtained for $F_{\rm c}/F_{\rm ad}\sim 0.4$.

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