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H/He demixing and the cooling behavior of Saturn

Robert Püstow [a,*], Nadine Nettelmann [a,b], Winfried Lorenzen [a], Ronald Redmer [a]

[a] Institute of Physics, University of Rostock, D-18051 Rostock, Germany
[b] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA

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ABSTRACT

The description of the interior structure and evolution of the Solar System giant planets continues to be a serious challenge. The most prominent example is Saturn for which simple homogeneous evolution models yield ages between 2 and 3 billion years (Gyr), i.e. much shorter than the age of the Solar System of $\tau_\odot = 4.56$ Gyr. It has long been suggested that H/He demixing might occur in the interior of Saturn after the planet has cooled off sufficiently. This incident would mark the begin of an inhomogeneous evolution period in which He droplets sink down and accumulate above the planetary core. The corresponding release of gravitational energy contributes to the intrinsic luminosity of the planet, thereby prolonging its cooling time, perhaps towards the correct value. Such scenarios have been studied in the past on the basis of rather approximate assumptions for the H–He phase diagram. Recently, various *ab initio* simulations have revealed details of the H–He phase diagram but also of remaining uncertainties (Morales, M.A. et al. [2009]. Proc. Nat. Acad. Sci. USA 106, 1324; Morales, M.A. et al. [2013a]. Phys. Rev. B 87, 174105; Lorenzen, W. et al. [2011]. Phys. Rev. B 84, 235109). In this paper we use the new predictions by Lorenzen et al. and modifications thereof to study the inhomogeneous evolution period of Saturn, with resulting values for the onset of H/He phase separation t_s, the cooling time τ, and the atmospheric helium abundance y_1. For the planetary interior during the inhomogeneous evolution we assume adiabatic, convective envelopes. We find $t_s = 1$ Gyr, $\tau = 5.8$ Gyr, and $y_1 = 0.18$, while $t_s \gtrsim 2$ Gyr for the Morales et al. data, for which we also estimate $\tau \approx 5.1$ Gyr. On the other hand, reasonable cooling times $\tau \approx \tau_\odot$ are obtained for shifts of the Lorenzen et al. phase diagram by respectively −1300 K and +500 K, yielding $y_1 = 0.22$ and $y_1 = 0.06$. More accurate knowledge of H–He phase diagram is necessary to understand cool gas giant planets. Our results indicate the H–He phase boundaries to occur at slightly higher pressures of $\Delta p \lesssim 1$ Mbar and higher temperatures compared to the predictions by Lorenzen et al., to be tested by future laboratory experiments, for instance by using LH-DACs. However, in addition to the uncertainty of the H–He phase diagram, further effects such as core erosion and non-convective heat transport might strongly influence the planetary structure and evolution. These features may lead to a revision of our assumption of adiabatic envelopes and have to be addressed in future work.

1. Introduction

The planets in the Solar System have formed out of the protosolar disk within a few million years about $\tau_\odot = 4.56$ Gyr ago (Pollack et al., 1996; Alibert et al., 2005; Helled and Schubert, 2008). This corresponds to the age of the Solar System and of the Sun. However, homogeneous evolution models for Saturn, a gas giant mostly composed of hydrogen and helium, lead to an age of only 2–3 Gyr, i.e. considerably less than the age of the Solar System. This well-known result is nearly independent on various uncertainties such as the possibility of a radiative subsurface window (Guillot et al., 1995), the model for the atmosphere (Fortney et al., 2011), or the equations of state (EOS) applied for the constituents hydrogen, helium, and heavy elements (Nettelmann et al., 2013). Thus, Saturn is said to exhibit a strong excess luminosity (Stevenson and Salpeter, 1977). This problem hints to major knowledge gaps in our understanding of the formation, evolution, and current structure of evolved jovian planets.

Saturn's excess luminosity has been recognized and addressed in numerous publications (e.g., Stevenson and Salpeter, 1977; Stevenson, 1982; Fortney and Hubbard, 2003; Leconte and Chabrier, 2013). For instance, Leconte and Chabrier (2013) showed that Saturn's excess luminosity could be explained by the assumption of an extended, semi-convective and thus superadiabatic zone deep inside the planet, which would delay the heat loss and thus

* Corresponding author.
E-mail address: robert.puestow@uni-rostock.de (R. Püstow).

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affect the luminosity as a function of time. Moreover, under the extreme conditions deep inside Saturn, demixing of helium from hydrogen has long been proposed to occur (Stevenson and Salpeter, 1977; Hubbard et al., 1999; Fortney and Hubbard, 2003; Lorenzen et al., 2009; Morales et al., 2008, 2009, 2010). In that case, helium-rich droplets would form and sink towards the planetary core, thereby releasing gravitational energy that, once transported to the surface, would naturally appear as an excess luminosity.

However, earlier thermal evolution studies made use of rather approximate H–He phase diagrams (Hubbard et al., 1999; Fortney and Hubbard, 2003). For instance, the Hubbard–DeWitt (HDW) phase diagram (Hubbard and DeWitt, 1985) predicts that the demixing temperature $T_{\mathrm{dmx}}(p;y)$ *decreases* with pressure p for given helium abundance y. Only by forcing the slope $T_{\mathrm{dmx}}(y)$ to adopt a probably unphysical behavior could $\tau \approxeq \tau_{\odot}$ be obtained, as shown in the extensive study by (Fortney and Hubbard, 2003). On the other hand, Pfaffenzeller et al. (1995) predict $T_{dmx}(p)$ to *increase* with pressure. Albeit promising, no demixing would occur at the high temperatures along the Saturn adiabat. Moderate modifications, however, would already allow for $\tau \approxeq \tau_{\odot}$, providing a valuable indication for the shape of the real H–He phase diagram (Fortney and Hubbard, 2003). It should intersect the Saturn adiabat at a few Mbar and then run nearly parallel to it down to the planet's core, furthermore should T_{dmx} rise with p, and also with y unless $y \approxeq 1$.

An enormous progress on the H–He phase diagram has been made recently by using *ab initio* simulation techniques. Especially, molecular dynamics simulations for the ions coupled with accurate electronic structure calculations based on density functional theory (DFT-MD) have led to revised predictions for the lightest and most abundant elements hydrogen and helium high-pressure EOS (Vorberger et al., 2011; Militzer, 2013; Militzer and Hubbard, 2013), the high-pressure phase diagram (Lorenzen et al., 2009, 2011; Morales et al., 2009, 2013a), and the nonmetal-to-metal transition in hydrogen (Lorenzen et al., 2010; Morales et al., 2013b). For a recent review, see McMahon et al. (2012). This *ab initio* data are better suited for the treatment of matter under extreme conditions in the interior of giant planets than chemical model EOS. Some of the advantages of the DFT-MD method are that no pair potentials are used, short- and long-lived correlations are treated on the same footing, and that quantum effects are incorporated in a well-defined manner (i.e. within the Kohn–Sham theory). However, DFT-MD simulations are usually time-consuming and require a considerable computer capacity.

In this paper we study the evolution of Saturn using first-principles based data for the EOS of planetary materials H, He, and water, (see Nettelmann et al., 2012 for details) as well as for the H–He phase diagram (Lorenzen et al., 2009, 2011). The focus of this paper lies in the study of the impact of H/He demixing and its related excess luminosity on the cooling behavior of Saturn. For this purpose we apply standard two- and three-layer planetary models. In particular, we perform the first calculation of the cooling behavior of Saturn using *ab initio* EOS data and corresponding H/He demixing data. We determine the age of Saturn when H/He demixing sets in. An epoch with constant composition distribution over time (homogeneous evolution) is replaced by an era with vertical mass transport which leads to a changing composition throughout the planet (inhomogeneous evolution). While helium droplets descent towards the core, hydrogen is lifted upwards due to buoyancy. The related excess luminosity can retard the cooling process substantially.

Of course, the calculated cooling time of Saturn depends strongly on the H–He phase diagram, which is not entirely understood yet. Further improvements in the determination of the H–He phase diagram, for instance with respect to the exchange–correlation functional used in the DFT part of the *ab initio* simulations, and of the non-ideal entropy of mixing, may shift the predicted demixing region considerably. Therefore, we have also studied the influence of shifted demixing regions compared to the data of Lorenzen et al. (2009, 2011), hereafter LHR0911.

In Section 2 we describe our method of planetary structure and homogeneous evolution modeling. In Section 3 we describe the LHR0911 H–He phase diagram, and in Section 4 how we apply it to Saturn's inhomogeneous evolution. Results for Saturn's cooling time with He sedimentation based on the original LHR0911 data and modifications are presented in Section 5. In Section 6 we summarize this paper, discuss possible directions for improvement, and give our conclusions.

2. Methods I: Standard modeling

2.1. Layered planetary structure

We follow the conventional approach and assume a layered structure for Saturn (Saumon and Guillot, 2004; Helled and Guillot, 2013). The location of the layer boundaries and the composition in the layers are adjusted to match observational constraints. In this work we apply a three-layer planetary model in order to obtain profiles of Saturn which meet the todays constraints and observables, while a two-layer model to describe evolutionary profiles for a homogeneously evolving planet.

The *two-layer model* assumes a spherical shape of the planet which is composed of an isothermal core of heavy elements (metals) and a homogeneous, adiabatic envelope of hydrogen, helium and metals. Note that all species heavier than helium are summarized as metals. We represent metals, both in the core and in the envelope by the water EOS H2O-REOS.1, which includes the water *ab initio* EOS data of French et al. (2009). For hydrogen we use H-REOS.2 and for He we use He-REOS.1 (see Nettelmann et al., 2012), both of which contain *ab initio* EOS data at pressure higher than about 1 kbar. These EOSs are then linearly mixed (LM-REOS). Of course, the development of the EOSs of hydrogen and helium for application to giant planets is an ongoing story—as is that of the H–He phase diagram. We point out that more recent versions, H-REOS.3 and He-REOS.3 (Becker et al., 2014) than applied in this work exist. However, H-REOS.3 has been improved over H-REOS.2 at temperatures and densities far off the present Saturn adiabat, and for the young and warm Saturn we expect the effect of the more recent EOS data on the computed adiabats to be still small. On the other hand, at low densities and low temperatures along the Saturn adiabat He-REOS.3 constitutes a significant step forward, primarily through the use of an accurate Virial EOS that smoothly connects to the *ab initio* EOS data, leading to higher P/ρ ratios. As a result of the thus improved He-EOS Becker et al. (2014) find the computed metallicity in Jupiter's outer envelope to increase by $\Delta z \approx 0.5$. Slightly higher metallicities for Saturn may slightly affect the temperature profile along the adiabat, which may result in slightly different amounts of helium that remain soluble in Saturn's outer envelope and do not sink down, see Sections 3 and 4.1. On the other hand, whether the metallicty acts to enhance or lower the temperature depends on the EOS and composition of the heavy elements in Saturn, which is not known. Therefore, we consider the effect of the application of just slightly different H–He EOS of minor impact on our results compared to other inherent uncertainties, such as, most of all, from the H–He phase diagram itself (Sections 3 and 5.3).

The mass of the core and the metallicity of the envelope z_{env} are provided by a planetary model according to Saturn's present-day observational parameters, which is a three-layer model as described below. The abundances of helium and metals in the envelope are $y = y_{solar} = 0.27$ and $z_{env} = 0.06$, respectively. The