Uranus and Neptune: Interior, Shape, and Rotation

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The internal structures and compositions of Uranus and Neptune are not well constrained. We suggest that the relatively large error bars on the gravitational coefficients as well as the uncertainty in rotation period and flattening result in a fairly large range of possible solutions.
While Uranus and Neptune are similar in mass (~ 14.5 and 17.1 $M_\oplus$, respectively) they differ in other physical properties such as thermal emission, obliquity, and atmospheric enrichment. We present new interior models of Uranus and Neptune ; using the *Voyager 2* rotation periods it is found that the major difference between Uranus and Neptune in terms of internal structure is that Neptune requires a non-solar envelope, while Uranus is best matched with an envelope of solar composition. We also find that is possible to fit the gravitational moments of the planets without sharp compositional transitions (i.e. density discontinuities). However, when the uncertainty in rotation period and flattening of the planets is included, the derived internal structures of Uranus and Neptune can differ substantially. We suggest that Uranus and Neptune may not be "twin planets", and that it is possible that each planet represents a different "class" of planets in this mass range in terms of composition, internal structure, and possibly, formation mechanism.

Empirical Interior Models (Helled et al., 2011):

We present 'empirical' models (pressure vs. density) of Uranus and Neptune interiors constrained by the gravitational coefficients J_2, J_4, and the planetary radii and masses, using Voyager's solid-body rotation periods (table 1). Figure 1 shows the p-ρ derived from the model. We show that Uranus and Neptune could have interiors with no density discontinuities.

Parameter	Uranus	Neptune
Rotation period (h)	17.24	16.11
GM (km^3 s^{-2})	5,793,964 ± 6	6,835,100±10
R_{ref} (km)	26,200	25,225
J_2 (×10^6)	3341.29 ± 0.72	3408.43 ± 4.5
J_4 (×10^6)	-30.44 ± 1.02	24,764 ± 15
a (km)	25,559 ± 4	24,764 ± 15

Table 1: Physical data, taken from JPL database: http://ssd.jpl.nasa.gov. R_{ref} is the reference equatorial radius in respect to the measured gravitational harmonics J_2 and J_4, and a is the equatorial radius.

We next use physical equations of state (EOSs) of hydrogen, helium, ice (H_2O), and rock (SiO_2) to test the physical plausibility of the derived pressure-density profiles. By assuming adiabatic structures we can find the compositions that fit the density-pressure relation of the empirical model at both the surfaces and centers of the planets. We consider two models: A model with a linear increase of the high-Z material with depth (Case I) and a three-layer model, where the outermost layer has Z constant and equals to its value at the surface, the innermost layer has Z constant and equals to its value at the center; and a middle transition layer with Z increasing linearly with depth (Case II).
The models' results are presented in figure 2.

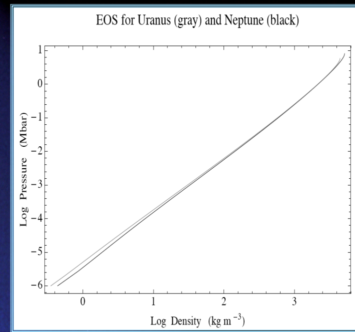


Fig 1: Uranus and Neptune pressure-density relations

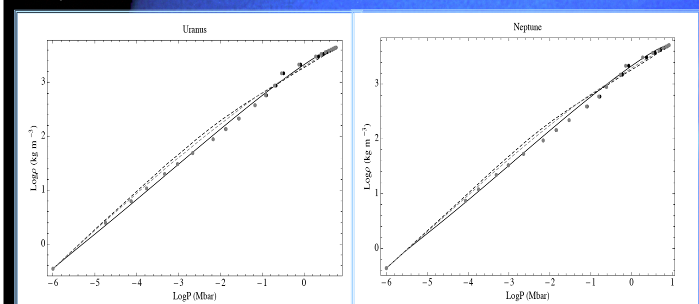


Fig 2: Pressure-density relation for Uranus (left) and Neptune (right) models. The black solid curve is the polynomial that fits the gravitational data. The black and gray dashed curves are the compositional models described in the text taking the high-Z material to be SiO_2 and H_2O, respectively, for case I. The black and gray points are for Case II and correspond to rock and ice, respectively.

	SiO_2	H_2O
Case I: Uranus	X=0.181; Y=0.0616; Z=0.757	X=0.0848; Y=0.0288; Z=0.886
Case I: Neptune	X=0.181; Y=0.0615; Z=0.758	X=0.0795; Y=0.0270; Z=0.893
Case II: Uranus	X=0.164; Y=0.0556; Z=0.781	X=0.0641; Y=0.0218; Z=0.914
Case II: Neptune	X=0.175; Y=0.0694; Z=0.766	X=0.0719; Y=0.0244; Z=0.904

Table 2: Derived planetary compositions (in mass fractions) for Uranus and Neptune. The two different columns correspond to different materials representing the heavy elements (SiO_2 and H_2O). The hydrogen to helium ratio (X/Y) is set to the protosolar value. The sum of the mass fractions does not exactly total one because of numerical roundoff.

Conclusions: of high-Z material. The big difference between the two planets is that Neptune requires a non-solar composition envelope whereas Uranus is best matched with a solar composition envelope. Our analysis suggests that the concentration of heavy elements inside both Uranus and Neptune interiors could increase gradually towards the planetary centers without having sharp compositional transitions as typically assumed. We find that the compositions of Uranus and Neptune are similar with somewhat different distributions

Shape and Rotation (Helled et al., 2010):

Uranus and Neptune (solid-body) rotation periods, 17.24h and 16.11h, respectively, are based on *Voyager 2* measurements of variations in the planets' radio signals and on fits to the planets' magnetic fields. The realization that Saturn's radio period may not represent the planet's deep interior rotation and the complexity of the magnetic fields of Uranus and Neptune raise the possibility that the *Voyager 2* radio and magnetic periods might not represent the deep interior rotation periods of the planets. We use wind and shape data to investigate the rotation of Uranus and Neptune. Minimization of wind velocities or dynamic heights of the 1 bar isosurfaces, constrained by the single occultation radii and gravitational coefficients of the planets, leads to solid-body rotation periods of ~16.58h for Uranus and ~17.46h for Neptune. We derive shapes for the planets based on these rotation rates (see table 3).

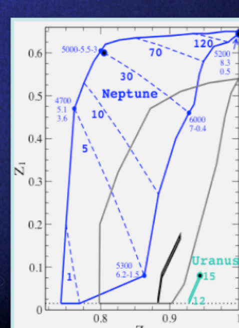
Parameter	U data 1	U data 2	N data 1	N data 2
M_p ($M_\oplus$)	14.536	14.536	17.148	17.148
$\omega/2\pi$	17h 14m 40s^a	16h 34m 24s^c	16h 6m 40s^a	17h 27m 29s^c
T_1 (K)	76(2)^b	76(2)	72(2)^a	72(2)
R'_{eq}	26,200^{d,e}	26,200^{d,e}	25,225^{d,f}	25,225^{d,f}
$J'_2/10^{-2}$	0.334129(72)^{d,e}	0.334129(72)^{d,e}	0.340843(450)^{d,f}	0.340843(450)^{d,f}
$J'_4/10^{-4}$	-0.3044(102)^d	-0.3044(102)	-0.334(29)^{d,f}	-0.334(29)^{d,f}
R_{eq} (km)	25,559(4)^a	25,559(4)^c	24,766(15)^a	24,787(4)^c
$J_2/10^{-2}$	0.351099(72)^c	0.351099(72)^c	0.35294(45)^c	0.35294(45)^c
$J_4/10^{-4}$	-0.3361(100)^c	-0.3361(100)^c	-0.358(29)^c	-0.358(29)^c

Table 3: Numbers in parenthesis are the observational error bars in the last digits. The gravitational moments J_{2n}' are the measured ones, and refer to a reference equatorial radius R_{eq}'. The gravitational moments J_{2n} refer to the equatorial radius at the 1-bar pressure level, R_{eq}.

Interior Models with Modified Shapes and Rotation Periods (Nettelmann et al., 2013):

We next model the interior structures of the planets using physical EOSs, assuming 3-layers structure with the modified rotation periods and shapes. We find that Uranus and Neptune could be quite different: Uranus would have an outer envelope with a few times the solar metallicity which transitions to a heavily enriched (~ 90% by mass heavy elements) inner envelope at 0.9 M_{Uranus}, giving a rather low moment of inertia of 0.22. In Neptune, this transition can occur deeper inside at 0.6 $M_{Neptune}$ and be accompanied by a more moderate increase in metallicity, leading to a less centrally condensed planet.

Fig 3. Heavy element mass fraction in the outer envelope (Z_1) and inner envelope (Z_2) using the modified shape and rotation data for Uranus (cyan) and Neptune (blue). The solid lines frame the full set of solutions for each planet. Dashed lines within the box of Neptune models indicate solutions of same transition pressure in [GPa] as labeled. Numbers at selected models (filled circles) give Tc [K], Pc [Mbar], and Mc [M$_\oplus$]. The dotted line is a guide to the eye for the solar metallicity $Z_\odot$ = 0.015. Also shown are the boxes for the interior models using *Voyager 2* rotation periods (black and gray). More details can be found in Nettelmann et al. (2013).



Conclusions:
Uranus and Neptune may differ to an observationally significant level in their atmospheric heavy element mass fraction Z_1 and nondimensional moment of inertia.
Each planet might represent a different "class" of planets in this mass range in terms of composition, internal structure, and possibly, formation mechanism.

References:

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