# The Shared Evolutionary History of Uranus and Neptune

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Astronomers have long struggled to explain the formation of Uranus and Neptune. The ice giants have comparable chemical compositions, deuterium-hydrogen ratios, masses, and radii (NASA Science Editorial Team, 2022; Feuchtgruber et al., 2013, 1), indicating a similar evolutionary path (Harvard CFA, n.d.a; Otegi et al., 2022, 9). They differ, however, in their average density, heat flux, rotation direction, and axial tilt (Williams, 2024a; Williams, 2024b; Zlimen et al., 2024, 2; Meeus, 1997, 332; *Neptune: Facts*, 2024). According to the Nice model, these planets may have formed closer to the sun and collided with planetesimals during their migration outward (Zlimen et al., 2024, 1). Uranus and Neptune's commonalities suggest a shared evolutionary history, and a Nice model in which Uranus formed exterior to Neptune accounts for their differences.

Uranus and Neptune have similar elemental compositions. They have comparable proportions of hydrogen, helium, and methane—82.5% and 80%, 15.2% and 19%, and 2.3% and 1.5%, respectively (Williams, 2024a; Williams, 2024b)—and are classified as "ice giants" for the significant amounts of water, ammonia, and methane ices in their atmospheres (Astronomy Staff, 2019; *Neptune: Facts*, 2024; *Uranus: Facts*, 2024). These substances only condense beyond the frost line—the region between the orbits of Mars and Jupiter where it is cold enough for volatile condensation  (NASA & Goddard Space Flight Center, n.d.; Laboratory for Atmospheric and Space Physics, 2007a). Moreover, Uranus and Neptune have a nearly identical deuterium-to-hydrogen ratio (D/H), $4.4 \times 10^{-5}$ and $4.1 \times 10^{-5}$, respectively (Feuchtgruber et al., 2013, 1), indicating the ice in their atmospheres originated from the same region (Ali-Dib et al., 2014, 1).  Thus, the ice giants' composition indicates they formed in close proximity beyond the frost line.

Uranus's mass and radius are akin to Neptune's. Uranus, the fourth most massive planet in the solar system (Stimac, 2023), has a mass of 8.681 x $10^{25}$ kg (Williams, 2024a), while Neptune, the third most massive, (Stimac, 2023) has a mass of 1.024 x $10^{26}$ kg (Williams, 2024b). Neptune, however, has a slightly shorter radius of 24,764 km (Williams, 2024b), than Uranus's 25,559 km radius (Williams, 2024a). The abundance of hydrogen and helium in the ice giants' atmospheres permit their high masses (Ryden & Peterson, 2020, 205). These volatile elements envelop their interiors (Seager, 2008, 43-44), augmenting the planets' already large volume because of their high masses (Harvard CFA, n.d.b, Figure 1).

Uranus's larger radius is a result of its lower average density. Uranus has an average density $\rho$ of 1270 kg $m^{-3}$ (Williams, 2024a), while Neptune's is 1638 kg $m^{-3}$ (Williams, 2024b). A planet's density is directly influenced by its composition (Lunar and Planetary Institute, n.d.), where the density of the gas is proportional to the molar mass of its components. Hydrogen, which exists in a greater proportion in Uranus than Neptune, has a molar mass of 1.008 g $mol^{-1}$, whereas helium, which exists in a greater proportion of Neptune than in Uranus, has a molar mass of 4.0 g $mol^{-1}$ (KnowledgeDoor, n.d.). The larger hydrogen concentration in Uranus explains its lower density, whereas the higher helium concentration, a heavier element, in Neptune explains its higher density. A planet with radius *R* is inversely proportional to density based on the relation $\rho = \frac{3M}{4\pi R^3}$. This relationship explains Uranus is wider than Neptune because the former's average density is lower. Since mass is also proportional to average density, a planet with a higher mass will have a larger average density, thus further explaining why Neptune is more dense. Therefore, it is unlikely formation location is the source of the discrepancy.

There are non-negligible differences between Uranus and Neptune that must be considered when investigating their formation. One such difference is that Uranus's heat flux is significantly lower than Neptune's. This is likely attributed to the lack of convection in Uranus's inner layers (Zlimen et al., 2024, 2) because stable compositional stratification, which occurs when the density of material in the outer core is less than that of the inner core (Labrosse, 2014, 119), is more prominent in Uranus (Hubbard et al., 1995, 119), trapping any heat gained during accretion deep inside (Podolak et al., 1991, 57). Moreover, Uranus rotates retrograde with an obliquity of 98º (Meeus, 1997, 332). This starkly contrasts with Neptune's prograde rotation at an obliquity of 28.32º (*Neptune: Facts*, 2024). Any model of the ice giants' proposing a similar evolution must explain these differences.

A scenario in which Uranus formed further away from the sun than Neptune explains their compositions, D/H ratios, and masses. Because volatiles are more prominent at greater distances from the sun (Zhang, 2015, 8), Uranus's higher volatile concentration insinuates it formed in an outer region of the protoplanetary disk (Williams, 2024a). Moreover, Neptune's D/H ratio, $4.1 \times 10^{-5}$ (Feuchtgruber et al., 2013, 1), is closer to that of Jupiter's $2.6 \times 10^{-5}$ (Pierel et al., 2017, 1), suggesting it formed closer to the gas giant than Uranus. The higher density of the protoplanetary disk at smaller radii from the sun explains Neptune's greater mass compared to Uranus, as density is proportional to mass (Andrews, 2021, 38; Zlimen et al.,2024, 1).

It is plausible Uranus and Neptune migrated to their present orbits after forming in a region closer to the sun as described by the Nice model. Developed as an attempt to explain Late Heavy Bombardment (*Nice Model*, 2013), a period towards the end of the solar system's formation during which the residual material in the protoplanetary disk impacted the planets

(Tillman, 2017), the Nice model proposes the Jovian planets initially orbited the sun at distances ranging from 5.5 to 17 AU, while a dense, rocky, icy disk of planetesimals existed between 17 and 35 AU (*Nice Model*, 2013). This model suggests that when Saturn achieved a 2:1 orbital resonance with Jupiter (NASA, 2018), the gravitational force between them intensified, destabilizing the solar system (Lee, 2021). These disturbances prompted Uranus and Neptune to have chaotic orbits (Malhorta, 1998, 41), ones which are unpredictable and respond significantly to minute fluctuations (Fiveable, n.d.), expelling Uranus and Neptune to the outermost regions of the solar system (*Nice Model,* 2013; Zlimet et al., 2024, 1).

The Nice model resolves the differences between Uranus and Neptune. If Uranus formed exterior to Neptune, models predict it would have accreted planetesimals originating between 20 and 24 AU from the sun, clearing Neptune's migration path. In turn, Neptune accreted the majority of its planetesimals from a region 25-29 AU or 36-40 AU from the sun (Zlimen et al. 2024, 8). The nature of the final impact explains their flux, tilt, and rotation. A final head-on collision of a planetesimal with Neptune would have mixed its gaseous layers (Hubbard et al., 1995, 119) and prompted convection, discouraging stratification (Hubbard et al., 1995, 119) and encouraging a greater heat flux (Zlimen et al. 2024, 2). The mixing within Neptune carries its methane to higher altitude, where it is blown into space by its strong winds (Moses et al., 2020, 9), thus providing another explanation as to why it contains less methane than Uranus. If Uranus's last major impact with a planetesimal occurred at an angle, it would have inhibited convection, produced its large axial tilt, and induced retrograde rotation by transferring angular momentum and altering its rotational direction (Hubbard et al., 1995, 119; Ryden & Peterson, 2020, 292; Fiveable, 2024)

While knowledge about the ice giants' evolutionary track will remain incomplete for years to come, a Nice model in which Uranus formed exterior to Neptune offers a promising avenue for future research. The ice giants' shared compositions signify a similar formation region, their D/H ratios and masses support Neptune's interior formation, and the Nice model resolves their flux, tilt, and rotation discrepancies. Understanding Uranus and Neptune's formation unveils the lingering mysteries surrounding the solar system's formation.

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