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An outer planet beyond Pluto and the origin of Kuiper belt architecture

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Trans-Neptunian objects (TNOs) carry precious information about the origin and evolution of the Solar System. In contrast to results predicted using accretion theory, TNOs exhibit surprisingly large eccentricities, e, and inclinations, i, which can be grouped into distinct dynamical classes: resonant, scattered, detached, and classical TNOs. Here we propose that the orbital history of an outer planet with tenths of the Earth's mass ($M_{\oplus}$) can explain the Kuiper belt orbital structure. In order to satisfy several observational constraints, extensive simulations allowed us to build a model for the origin and evolution of the trans-Neptunian region (at semimajor axes $a >$30AU). The model is divided into three main stages: *I. Pre-migration excitation of the planetesimal disk*. Near the end of planet formation, a massive body (the outer planet) was likely scattered by one of the giant planets, then it stirred the primordial planetesimal disk over tens of Myr to the levels observed at 40–50AU and truncated it at ∼48AU before planet migration. *II. Planet migration*. Later, in addition to the giant planets, the outer planet was probably captured by a strong sweeping resonance with Neptune of the type r:1 or r:2 (e.g., 6:1, 7:1, ... or 13:2, 15:2, ...), which then transported the planet to large distances. Because Kozai resonance is quite common inside these resonances, the outer planet likely exhibited decreased eccentricity, e_P,(increased perihelion, q_P) at the expense of increased inclination, i_P. At the end, the outer planet acquired an inclined stable orbit (≥100 AU; 30–50˚), guaranteeing the stability of the Kuiper belt. Timescales of this stage should be on the order of ∼100-200Myr. *III. Long-term sculpting by the planets (∼4Gyr)*. The outer planet model naturally explains the following: 1) Depletion of the inner Kuiper belt; 2) The entire currently known resonant structure in the Kuiper belt, including Neptune Trojans and resonant

TNOs in distant resonances (>50AU); 3) Formation of scattered and detached TNOs, including analogs of (136199) Eris, 2004 XR_{190}, (148209) 2000 CR_{105}, and (90377) Sedna; 4) Classical TNOs and their dual nature of physically distinct cold and hot populations; 5) Orbital excitation of classical TNOs; 6) The Kuiper belt outer edge at ~48AU; 7) Loss of ~99% of the initial total mass of the Kuiper belt through dynamical depletion and enhanced collisional grinding; 8) Neptune's current orbit at 30.1 AU. In summary, our scenario consistently reproduces all main aspects of Kuiper belt architecture with unprecedented detail. It also offers insightful observationally testable predictions, especially the existence of a massive distant outer planet within the Solar System. We conclude that the orbital excitation at 40–50AU and the truncation near 48AU probably represent fossilized signatures of the outer planet, while the detached population, and perhaps TNOs with i >40˚, resulted from the planetoid's perturbation over billions of years. The best constraints obtained from the model for the outer planet are: a_P=100-160AU (currently near or inside a distant r:1 or r:2 resonance), q_P >80AU, i_P=30-50˚, and apparent magnitude m_P ~15-17 mag at perihelion (assuming an albedo of 0.1-0.3 and q_P=80-90AU).