The Planet Nine hypothesis

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The putative planet accounts for similarities in the orbits of a collection of objects in the distant Kuiper belt.

In 1820 Alexis Bouvard, the director of the Paris Observatory, made what could have been a huge discovery. The planet Uranus, whose position he had tracked back 130 years in old star catalogs, didn't quite go around the Sun the way that he predicted it should. It traveled along its elliptical orbit as expected, but sometimes the old observations suggested it was a little ahead of its predicted position and sometimes a little behind. Bouvard might have realized that there was something beyond Uranus, but instead he was convinced the old star catalogs were simply wrong.

Twenty more years of careful observation showed that Uranus still deviated from its predicted orbit. By 1840 it became widely accepted that the likely reason for the discrepancy was that a more distant planet was perturbing Uranus's orbit—sometimes pulling it a little faster, sometimes holding it back. Within the next five years, French mathematician Urbain Leverrier used Bouvard's data to work out the orbital mechanics. In a single night of searching in 1846, astronomer Johann Galle discovered Neptune—within a single degree of its predicted position. (See the article by Deborah Kent, PHYSICS TODAY, December 2011, page 46.)

That story of prediction, discrepancy, new theory, and triumphant confirmation is classic, and Leverrier became famous for it; his statue still stares up the Avenue de l'Observatoire in Paris today. Almost immediately people tried predicting even more planets. In the past 173 years, dozens of scientists have used some sort of alleged orbital discrepancy to motivate the effort. Their predictions have invariably been wrong. The most famous of them came in the early years of the 20th century from businessman, mathematician, and astronomer Percival Lowell, who called the planet he thought was perturbing the orbits of Uranus and Neptune Planet X.

When Pluto was discovered at the Lowell Observatory in 1930, it was thought to be Planet X. Astronomers now know that Pluto is about 0.03% as massive as the predicted Planet X. After the *Voyager 2* flyby of Neptune in 1989, new calculations revealed that the giant planets were where they should be. There is no Planet X after all.

Just as that hypothetical planet was disappearing from the picture, though, astronomers started noticing that the outer solar system is far from empty. Thousands of tiny icy bodies orbit the Sun just beyond the known planets. Most of the objects in that region, now known as the Kuiper belt, have mildly eccentric orbits. They are constantly pushed and pulled by the planets' gravity, which produces intricate resonances, vast unstable regions, and violent gravitational scattering. A combination of analytic celestial mechanics and powerful computer simulations has traced the influences of planets throughout the Kuiper belt and placed the thousands of known objects in the context of the rest of the solar system. (See my article, PHYSICS TODAY, April 2004, page 49.)

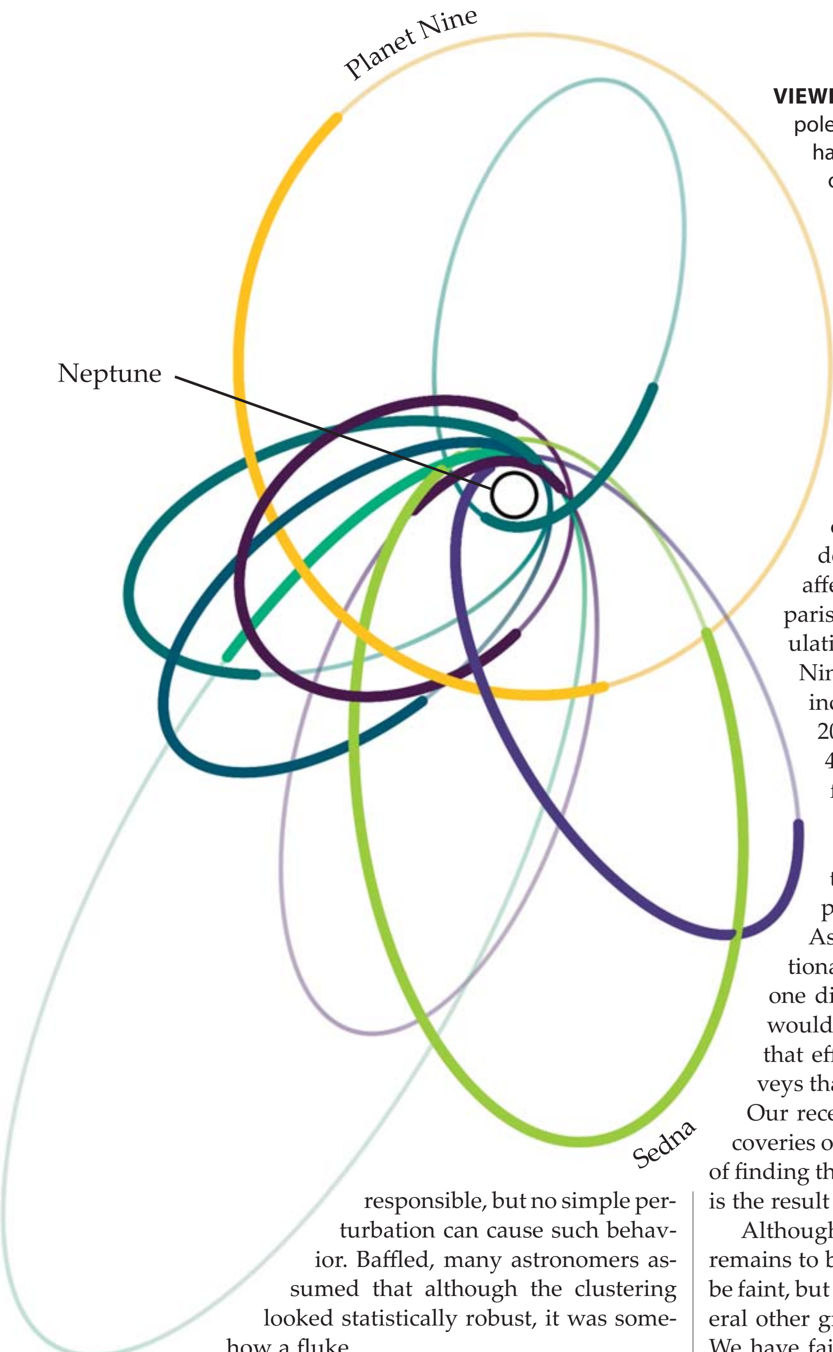
Everything is where it is supposed to be. Almost.

The discovery of Sedna

In 2002 I led a survey that uncovered an object now known as Sedna (see PHYSICS TODAY, June 2004, page 23). It has a hugely elongated orbit that takes 10 000 Earth years to complete. The extreme eccentricity is unusual but not unprecedented. A modest number of Kuiper belt objects have strayed too close to Neptune and been flung deep into the outer solar system. If not ejected, they return and will probably have to deal with Neptune again in the future. The surprising aspect of Sedna's orbit, however, is that it never comes close to Neptune. At its closest approach to the Sun, Sedna is two and a half times as far away as Neptune ever is. Its strange orbit can't be the fault of Neptune; something else must be responsible.

At the time of Sedna's discovery, Chadwick Trujillo (then at the Gemini Observatory), David Rabinowitz (Yale University), and I suggested that Sedna's orbit was likely modified by a passing star early in the history of the solar system, when the Sun would still have been part of the cluster of stars in which it was born. The close proximity of potentially thousands of stars could have given Sedna enough of a nudge to move its orbit away from that of Neptune. When the cluster of stars dispersed, Sedna would have been left as a fossil record of the distant past. But in 2012 Brazilian astronomer Rodney Gomes pointed out that Sedna and others like it could instead be the natural consequence of a distant massive planet.

Another odd property of such distant objects was pointed out by Trujillo and Scott Sheppard (Carnegie Institution for Science) in 2015. They noted that when objects with extremely elongated orbits are at points closest to the Sun, they preferentially move from below the plane of the solar system to above it. They speculated that a distant planet may somehow be



VIEWED FROM THE DIRECTION of the solar system's north pole, almost all the stable objects in the outer solar system have orbits that cluster strongly in one direction. Those orbits are also tilted in the same direction, which is evident from the thickness of the lines; the thinner, fainter lines denote when the orbits are below the plane of the solar system. The yellow ellipse is our best estimate of the current orbit of Planet Nine. A massive body on an eccentric orbit will force a population of distant orbits to be mostly anti-aligned to its direction.

responsible, but no simple perturbation can cause such behavior. Baffled, many astronomers assumed that although the clustering looked statistically robust, it was somehow a fluke.

The pieces of that puzzle fell into place in 2016, when Konstantin Batygin and I realized that when viewed correctly, all of the most elongated objects point in the same direction and are tilted in the same direction. In terms of orbital elements, they are clustered in the longitude of perihelion and in pole position. Such a clustering shouldn't persist; with nothing holding the orbits in place, differential precession would randomize their longitudes and pole positions in a scant 100 million years.

Batygin and I further realized that a massive, distant, eccentric, and inclined planet would produce exactly that result. It also explains the confusing clustering. Finally, we had found an effect in the distant Kuiper belt that could be caused by perturbations from a distant, giant planet. The Planet Nine hypothesis was born. (See PHYSICS TODAY, April 2016, page 23.)

In the three years since the original publication of the hypothesis, we have come to a much more detailed understanding of how Planet Nine might affect the outer solar system. In a sophisticated comparison of solar-system observations to numerical simulations, we find a best match to be a putative Planet Nine that is approximately six times the mass of Earth, inclined with respect to the ecliptic by a little less than 20 degrees, and in a moderately eccentric orbit about 400 times as distant from the Sun as Earth. (See the figure.)

Shockingly, no alternative hypothesis has come forward to explain the observations of orbital clustering. If the observations are trustworthy, it appears that Planet Nine is probably real. But are they? Astronomers are always concerned with observational bias. For example, if an observer looked in only one direction in the sky, all distant objects found there would appear to be tilted in that direction. Correcting that effect has proven challenging for the scores of surveys that have been done. But we finally have the answer. Our recently published meta-analysis of all previous discoveries of Kuiper belt objects shows only a 0.2% probability of finding that the extreme clustering in the distant Kuiper belt is the result of bias and chance.

Although the statistical analysis is convincing, the planet remains to be found. At its extreme distance, Planet Nine will be faint, but not too faint for our largest telescopes. We and several other groups are using our predictions to track it down. We have failed to match the record of a one-night discovery of a planet by Leverrier and Galle, but we have confidence that within a few years an astronomer somewhere will find a faint, slow-moving point of light in the night sky and triumphantly announce the discovery of another new planet in our solar system.

Additional resources

▶ C. A. Trujillo, S. S. Sheppard, "A Sedna-like body with a perihelion of 80 astronomical units," *Nature* **507**, 471 (2014).
▶ K. Batygin, M. E. Brown, "Evidence for a distant giant planet in the solar system," *Astron. J.* **151**, 22 (2016).
▶ M. E. Brown, K. Batygin, "Orbital clustering in the distant solar system," *Astron. J.* **157**, 62 (2019). PT