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QnAs with Renu Malhotra

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Renu Malhotra has spent decades studying the orbital dynamics of the Solar System. Her pioneering work has illuminated the large-scale orbital migration of the giant planets and the formation and dynamics of the Kuiper Belt and asteroid belt. Malhotra's research has also uncovered the dynamic mechanisms underlying Pluto's unusual orbital characteristics, and she describes some of her latest findings on this topic in her Inaugural Article (1). Now a Regents Professor of Planetary Sciences at the University of Arizona, Malhotra was elected to the National Academy of Sciences in 2015.

Renu Malhotra. Image credit: Renu Malhotra.

PNAS: How did you become interested in Pluto?

Malhotra: I became interested in Pluto back when I was a graduate student and got into planetary dynamics. I went to graduate school to study physics, and I thought I would study either theoretical astrophysics or high-energy physics or black holes. But then, in graduate school I discovered nonlinear dynamics, which is at the cutting edge of new developments in classical mechanics. More or less around that time, I discovered that the preeminent nonlinear dynamical system to study is the Solar System and its orbital mechanics. So, I did my PhD research on orbital mechanics and, as I slowly became more familiar with the phenomenology in the Solar System, it became evident that one of the biggest puzzles in Solar System dynamics was the ninth planet, Pluto, which was still considered a planet at the time. It didn't fit in with the rest of the Solar System, so that's when I started thinking about Pluto.

PNAS: How did this Inaugural Article (1) come about?

Malhotra: Back in 1993, I wrote a paper in which I hypothesized that we could understand Pluto's orbit if we allowed that the giant planets had migrated (2). So, Neptune had not formed in the orbit that it is in currently, but it had formed closer to the sun and migrated outward, whereas Jupiter had migrated inward. As it migrated out, Neptune swept Pluto into its orbital resonance and changed its orbit from nearly circular and coplanar to very eccentric and tilted. I set about analyzing the consequences of the migration of the giant planets on the rest of the Solar System, and I made two major connections.

One was that as Jupiter migrated inward, it left an imprint on the asteroid belt, which is still visible today. The other major connection I made was the migration's effect on the impact crater record on the moon, Mars, Mercury, Venus, and, to a lesser extent, Earth. This migration of the giant planets explained quite satisfactorily two major peculiarities of Pluto's orbit: that it is in this orbital resonance with Neptune and that it is very elliptical.

However, it only partially explained Pluto being noncoplanar with the planets. Also, as people did more accurate computer simulations of the orbits of the planets over the age of the Solar System, they learned that Pluto's orbit is chaotic on the long time scale. Interestingly, it's chaotic in a mathematical sense only; it doesn't actually translate into any dramatic consequences for Pluto's orbit. Pluto still remains more or less very close to its current orbit, the resonance with Neptune is preserved, and nothing terrible happens to Pluto over billions of years. So, there was this understanding that Pluto's orbit is chaotic, but only weakly so. And then there was also this gap in understanding how Pluto's orbital tilt came about. In the back of my mind, I always remembered that we still had only a partial theory for understanding Pluto. I started working on this problem again about 3 years ago.

PNAS: How did you approach the problem?

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Malhotra: I began a collaboration with Takashi Ito, my coauthor on the Inaugural Article (1), who has knowledge about Pluto and about numerical simulations, and has a huge amount of computing power at his disposal at the National Astronomical Observatory of Japan. I suggested that we should go back to this problem and figure out what additional things are needed to understand Pluto's orbital tilt. We started doing some numerical experiments and just exploring the parameter space around Pluto's orbit. We knew that Pluto's orbit is shepherded by Neptune, but we wondered about the role of the other giant planets, Jupiter, Saturn, and Uranus. We did a systematic exploration of the influence of each of the other giant planets on Pluto's orbit.

PNAS: What did you find?

Malhotra: We discovered that these planets have a very strong influence. Basically, with the combination of their masses and orbits, Jupiter, Saturn, and Uranus produce, roughly speaking, an extra quadrupole moment in the Solar System, and it turns out that it is of just the right amount to make an extra orientation constraint on Pluto's orbital tilt. So, the new thing about this paper is that we understand better than we did before the very critical influence of Jupiter, Saturn, and Uranus to Pluto's orbital dynamics in the third dimension. We now understand that with the orbital arrangement of Jupiter, Saturn, and Uranus, there's only a small range of their effective quadrupole moment over which Pluto-like orbits are stable for billions of years. If that quadrupole moment were not in that narrow range, then Pluto would be very strongly chaotic. So, Pluto is much closer to strong chaos than had been previously understood.

PNAS: What are the broad implications of these findings?

Malhotra: The findings are important not only for Pluto but for thousands of other Kuiper Belt objects. Also, understanding the evolution of the orbital arrangement and the mass distribution of planets is an overarching question for all planetary systems. Gaining deeper knowledge of the history of the orbital arrangement in the Solar System shapes our understanding of our home planet and of the architectures of other planetary systems. It is deeply satisfying to come up with new knowledge about the Solar System, with potential connections to other planetary systems in other parts of the universe.

1. R. Malhotra, T. Ito, Pluto near the edge of chaos. *Proc. Natl. Acad. Sci. U.S.A.* **119**, 10.1073/pnas.2118692119 (2022).
2. R. Malhotra, The origin of Pluto's peculiar orbit. *Nature* **365**, 819–821 (1993).