Planets Marshal the Cometary Parade

How comets march into the inner solar system

By RON COWEN

A place for everything and everything in its place. That old proverb takes on new meaning when it comes to the inner workings of the solar system. A new study reveals that the locations of the four large, outer planets play a crucial role in shepherding comets into the inner solar system from a lair beyond the orbit of Pluto.

From Neptune to Uranus to Saturn to Jupiter, "comets are being handed off from planet to planet," says Harold F. Levison of the Boulder, Colo., office of the Southwest Research Institute. It's this celestial bucket brigade, he notes, that allows a select group of comets to grace the skies above Earth, flaunting their dusty tails as they deliver key organic compounds into our atmosphere.

If this gang of four were spread farther apart, comets that rank as frequent fliers to the inner solar system, visiting at least once every 60 years, could never make the journey. If the outer planets were bunched closer together, the orbits of these comets would look radically different.

This speculation, which may provide clues to the early lives of planets, stems from a computer model developed by Levison and Martin J. Duncan of Queen's University in Kingston, Ontario. They reported their findings in June at a comet workshop at the University of Toronto's Canadian Institute for Theoretical Astrophysics (CITA).

Some 4.5 billion years ago, the disk of gas and dust that surrounded the infant sun underwent a tumultuous transformation. Bits of material collided and stuck together, gathering into boulder-sized bodies. More collisions ensued, and the bodies grew bigger and more massive, developing into planets.

Not all of the material participated in this rough-and-tumble world. Some material in the outer, chillier part of the disk stayed out of the fray, remaining as small, frozen amalgams of ice and dust. Today, we know these icy relics as comets.

As fragile as snowballs, comets appear to be easily destroyed in the inner solar system—fragmenting, vaporizing, or suffering fatal collisions. Nonetheless, a steady stream of these icy bodies whizzes past Mercury, Venus, Earth, and Mars. Partly to account for the variety in the seemingly endless parade, astronomers nearly 50 years ago proposed that the solar system harbors two distinct reservoirs of comets.

The larger of these two storehouses, proposed by Dutch astronomer Jan Oort, takes the form of a huge spherical cloud residing on the far fringes of the solar system. The Oort cloud ranks as the source of comets that have highly elongated orbits and long periods. These comets travel at large as well as small angles to the plane in which most planets orbit the sun. Current theory holds that the Oort cloud originated in the region between Uranus and Neptune but now resides much farther out—about 20,000 times the distance from Earth to the sun.

The other, much closer and much smaller proposed storehouse consists of a flattened disk that has scarcely budged since it formed. Named the Kuiper belt for Dutch astronomer Gerard P. Kuiper, one of two reseachers who independently postulated its existence in the late 1940s and early 1950s, its inner edge lies just beyond the orbits of Pluto and Neptune.

In 1988, three Canadian astrophysicists—Duncan, Scott Tremaine, now at CITA, and Thomas Quinn, now at the University of Oxford in England—used a mathematical model to show that the Kuiper belt could be the source of comets that visit the inner solar system at least once every 200 years and travel at small angles to the plane in which the planets move (SN: 5/21/90, p. 248).

Refining their calculations, the researchers subsequently concluded that comets from the Kuiper belt have even shorter periods, completing an orbit around the sun at least once every 60 years.

Unlike the Oort cloud, the Kuiper belt lies close enough to Earth for large telescopes to have successfully surveyed small patches of it. Ground-based instruments have spied at least 36 objects, each about 10 times the size of the typical comet, in the inner part of the belt. The Hubble Space Telescope may have detected another 30 or so smaller, comet-sized objects, although the evidence so far is not decisive (SN: 6/22/96, p. 395).

With the existence of the Kuiper belt no longer in doubt, researchers have turned to another question: How do short-period comets leave this storehouse and how do they venture into the inner solar system? A year ago, researchers provided the definitive answer to the first part of this riddle.

In simplest terms, comets leave the belt because it has a slow leak. In 1995, Duncan and Stuart M. Budd of Queen's University, along with Levison, reported the results of the most extensive computer simulation ever done of the Kuiper belt. The simulations tracked the evolution of the belt for 4 billion years—nearly its entire existence.

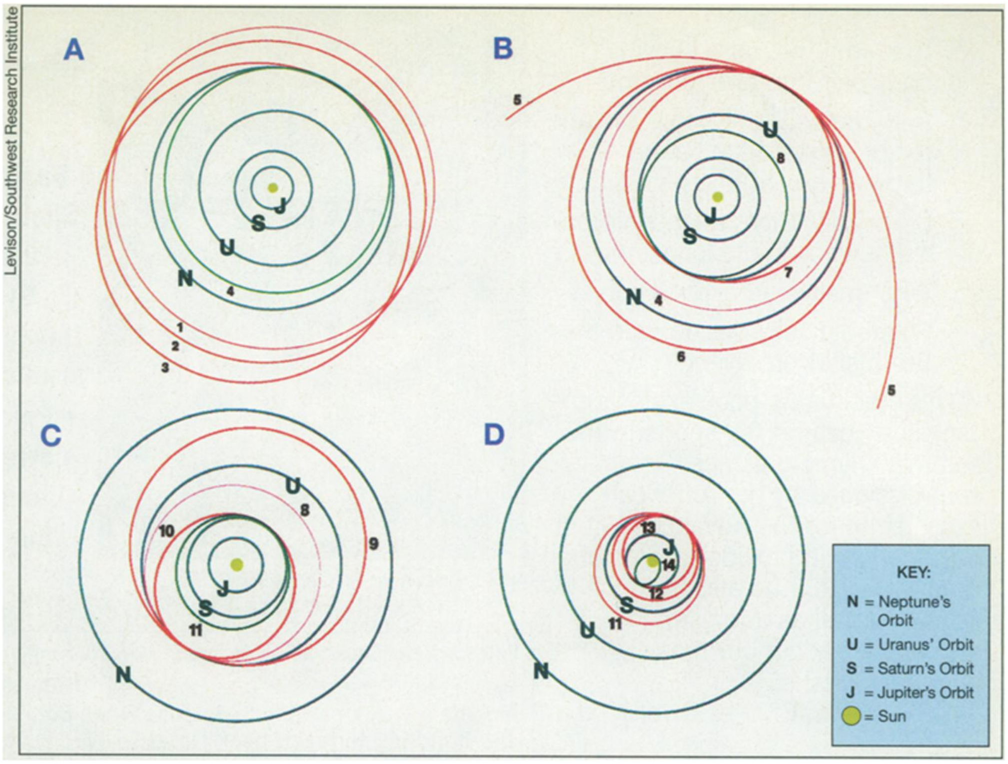
Two kinds of orbits, characterized by their relationships to the orbit of Neptune, place members of the inner part of the belt in a precarious position. Vulnerable to sudden, chaotic changes in their motion, Kuiper belt denizens in these orbits stand a reasonable chance, over a 10-million-year interval, of leaving the reservoir they call home.

Some of the Kuiper belt escapees move away from the solar system; others get flung inward, toward Neptune. Once a comet falls into Neptune's gravitational clutches, the other large, outer planets start to exert their own gravitational influence. In this way, some comets from the Kuiper belt make their way toward the inner solar system, where they come alive in the sun's warmth, gracing the skies of the inner planets with their tails and shrouds of highly reflective dust. The late U.S. astronomer Edgar Everhart proposed such a scenario in 1977.

Yet the new calculations by Levison and Duncan show that one shouldn't take such a model for granted. It's only because Neptune, Uranus, Saturn, and Jupiter are spaced exactly far enough apart that each has a chance of handing off a comet to the next. The gravitational tug of tiny Pluto is too small to play a role.

In mathematical terms, notes Levison, the cometary parade proceeds because of the special balance of a quantity that approximates the total energy of a comet and the planet nearest it. Known as the Tisserand parameter, that quantity depends on three orbital elements: the inclination of a comet's orbit to the plane of the solar system, the shape of its orbit, and the planet's average distance from the sun. Levison and Duncan find that although the Tisserand parameter varies as a comet moves from one planet to the next, the comet has roughly the same numerical value just before and after it encounters a planet.

"The Tisserand parameter constrains what orbital elements the comet can have after the interactions," says Levison. "What we find numerically is that the evolution of a comet is determined mainly by the close encounters with the [outer] planets."



A comet's progress: In panel A, a comet moving in a circular orbit (1) in the Kuiper belt changes its path (2) until it finally crosses the orbit of Neptune (3) and comes under the gravitational influence of the planet (4). In panel B, Neptune's gravity initially kicks the comet outward (5 and 6) but ultimately pulls it inward—just enough for the comet to cross the path of Uranus (7) and succumb to that planet's gravitational tug (8). In panel C, Uranus initially enlarges the comet's orbit (9) but ultimately pulls it inward so that the comet's path crosses the orbit of Saturn (10). Saturn then removes the comet from Uranus' influence (11). In panel D, the comet, now under Saturn's control (12), moves inward, intersecting the orbit of Jupiter (13). Massive Jupiter takes control of the comet, carrying it all the way to the inner solar system (14).

When a comet leaves the Kuiper belt and encounters Neptune, it begins a critical interaction with this planetary partner. Neptune may fling the comet out of the solar system or hurl it inward. But because the comet's Tisserand parameter relative to Neptune depends on the planet's distance from the sun, Neptune can only send the comet a certain distance inward—just far enough, as it happens, to cross the orbit of Uranus.

The Tisserand parameter—now calculated from the comet's path relative to Uranus—is once again conserved. Uranus can either send the comet back to Neptune or deliver it deeper into the solar system—but only as far as Saturn, according to the model developed by Levison and Duncan.

From Saturn, the comet can move inward only as far as Jupiter. If Jupiter weren't there, skywatchers on Earth would see far fewer comets, notes Levison. Once under the control of this massive planet, the comet gets either kicked out of the solar system for good or nudged into the inner solar system.

Surprisingly, these encounters serve as an efficient delivery system. A comet from the Kuiper belt that encounters Neptune has a 30 percent chance of making it all the way to the inner solar system, Levison and Duncan reported last month at the CITA workshop.

They calculate that the whole process takes about 20 million years. By counting the number of short-period comets now visible in the sky and running their computer simulation backward in time, the researchers reason that the inner part of the Kuiper belt must contain about a billion comets, a number that roughly matches estimates derived from observations with Hubble and other telescopes. Levison and Duncan also calculate that a Kuiper belt comet strikes Jupiter about once every 400 years and Earth every 13 million years or so.

The study, says Levison, yields much more than a bunch of numbers. It raises a key question, he notes: "Why do the planets in the solar system happen to be spaced just far enough apart so that this [cometary march] works?"

The question is particularly intriguing, he adds, because several studies suggest that in the distant past the outer planets didn't reside exactly where they are now. Wing-Huen Ip of the Max Planck Institute for Aeronomy in Katlenburg-Lindau, Germany, and Julio A. Fernández of the University of the Republic in Montevideo, Uruguay, suggested this possibility in the early 1980s.

Newer work by Renu Malhotra of the Lunar and Planetary Institute in Houston indicates that the fledgling outer planets had important gravitational interactions with a population of comets that originally inhabited the region between the orbits of Neptune and Uranus. Those interactions shifted the planets and also ejected the comets far beyond the solar system to become the distant Oort cloud.

Malhotra's study shows that in response to the gravitational skirmish between the comets and the planets, Neptune, Uranus, and perhaps Saturn moved away from the sun, while Jupiter moved slightly inward. Malhotra reported her work in a series of papers, including one in the July 1995 ASTRONOMICAL JOURNAL.

Neptune's migration probably amounted to about 750 million kilometers, roughly five times Earth's distance from the sun. Jupiter moved inward about 30 million km, Malhotra calculates. These orbital changes may have sufficed to fine-tune the position of the outer planets, allowing them to draw in comets from the Kuiper belt, Levison speculates.

Levison isn't sure exactly what these myriad encounters between comets and planets say about the formation and architecture of the solar system. But he adds: "If this configuration is not the result of something to do with the way the planets formed, if it's just a coincidence, then it's an *amazing* coincidence. The distribution of comets would look very, very different in a solar system that wasn't set up like ours." □