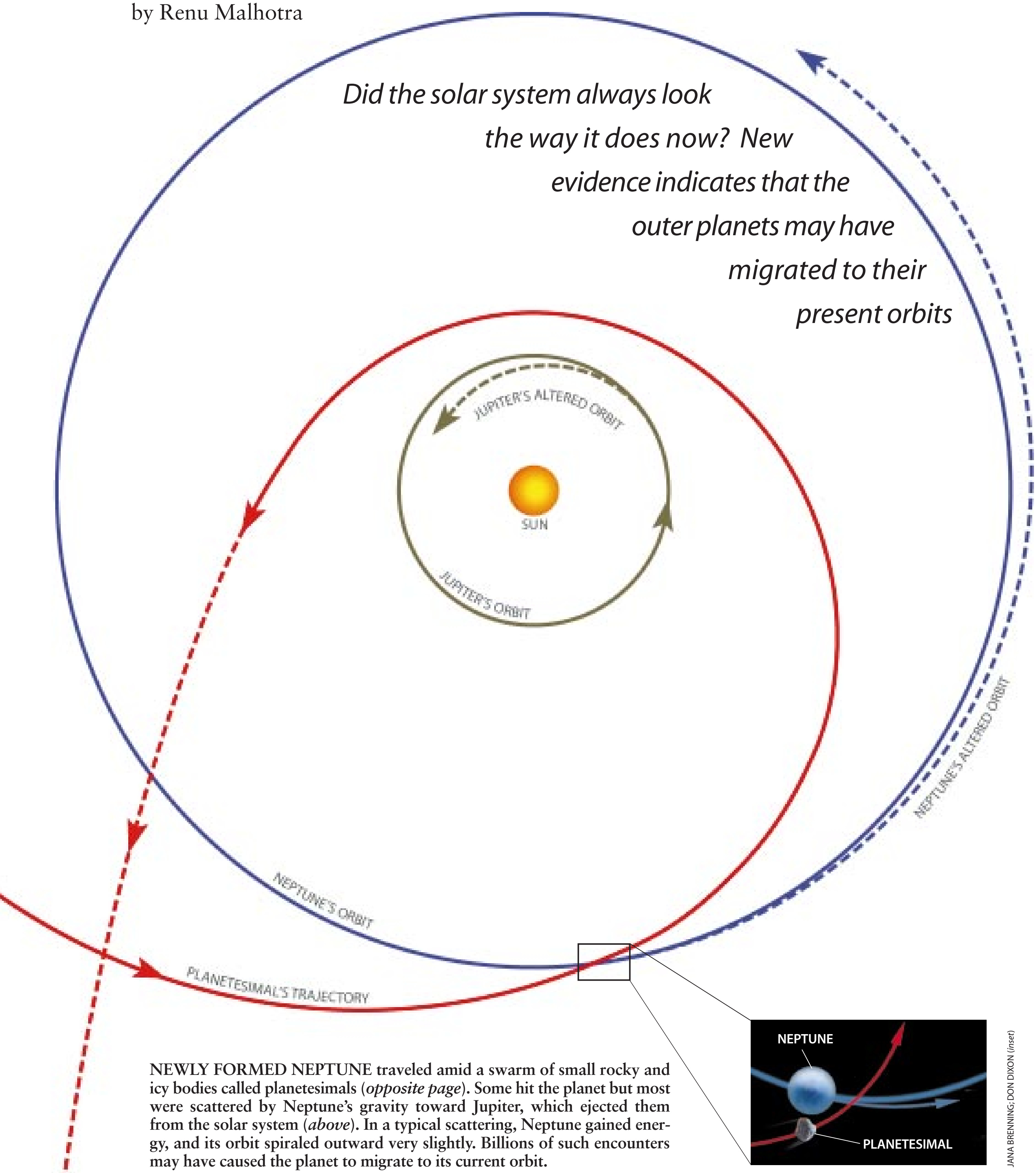
Migrating Planets

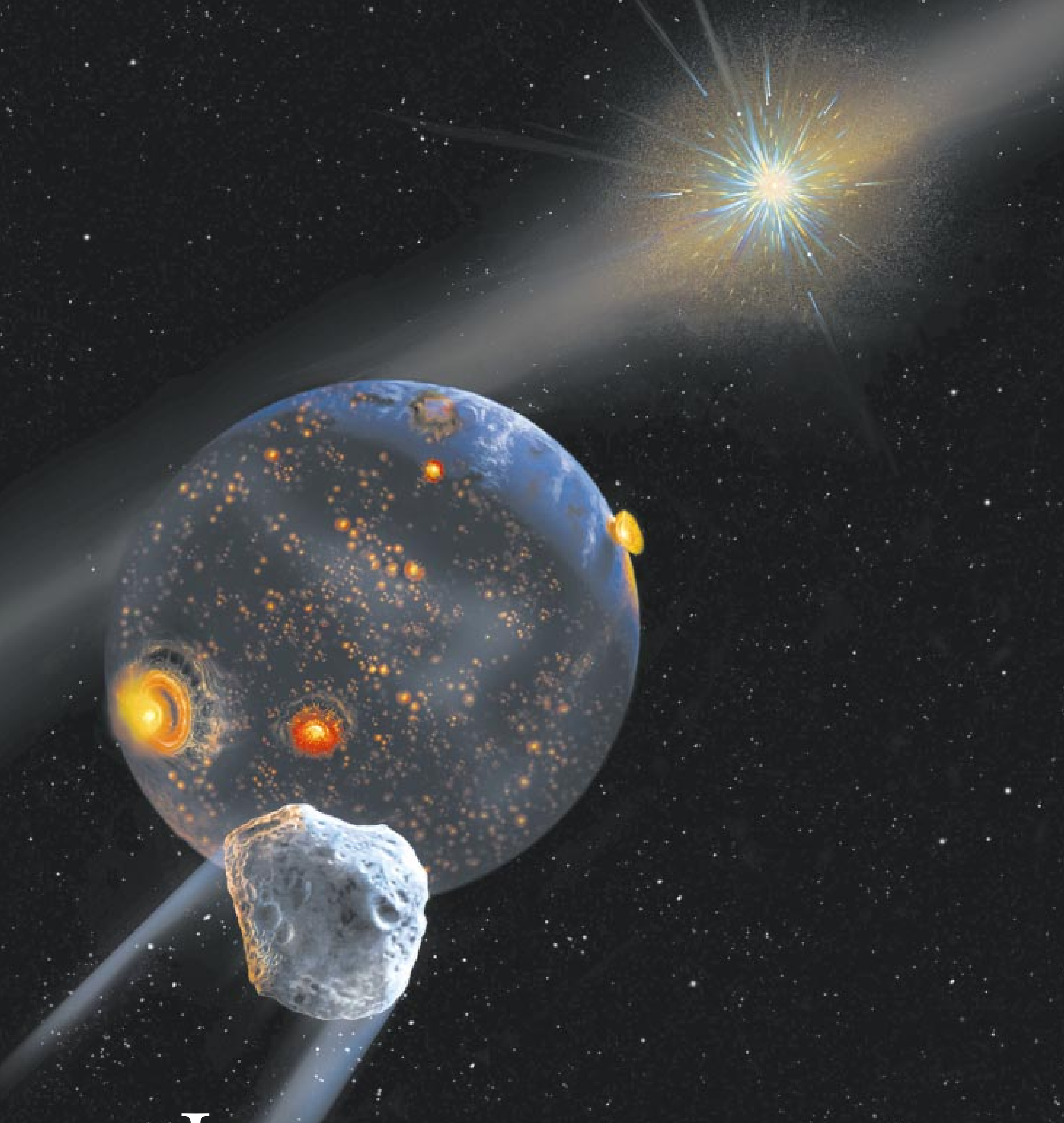
by Renu Malhotra

Did the solar system always look the way it does now? New evidence indicates that the outer planets may have migrated to their present orbits



NEWLY FORMED NEPTUNE traveled amid a swarm of small rocky and icy bodies called planetesimals (*opposite page*). Some hit the planet but most were scattered by Neptune's gravity toward Jupiter, which ejected them from the solar system (*above*). In a typical scattering, Neptune gained energy, and its orbit spiraled outward very slightly. Billions of such encounters may have caused the planet to migrate to its current orbit.

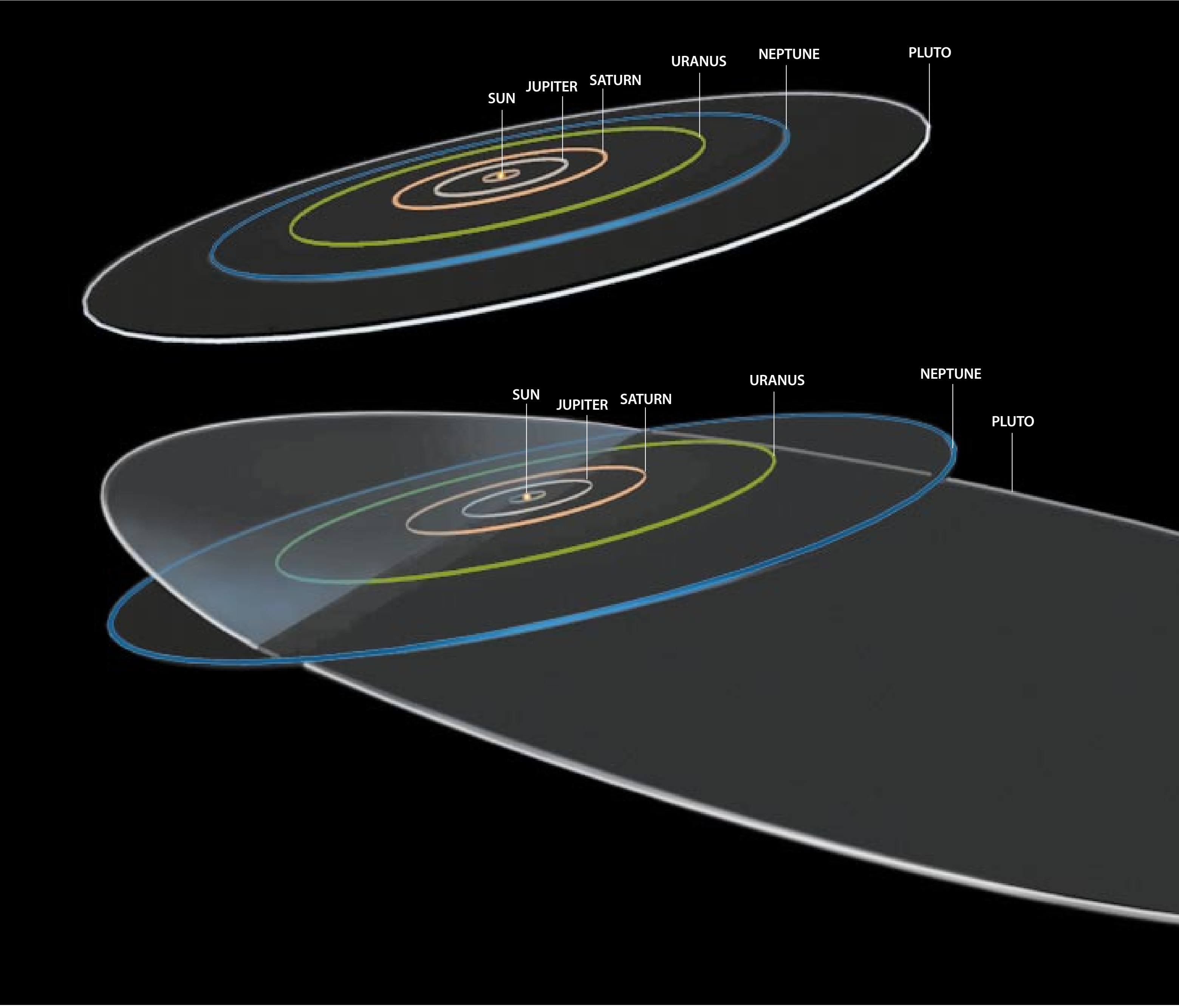
JANA BRENNING; DON DIXON (*inset*)



In the familiar visual renditions of the solar system, each planet moves around the sun in its own well-defined orbit, maintaining a respectful distance from its neighbors. The planets have maintained this celestial merry-go-round since astronomers began recording their motions, and mathematical models show that this very stable orbital configuration has existed for almost the entire 4.5-billion-year history of the solar system. It is tempting, then, to assume that the planets were "born" in the orbits that we now observe.

Certainly it is the simplest hypothesis. Modern-day astronomers have generally presumed that the observed distances of the planets from the sun indicate their birthplaces in the solar nebula, the primordial disk of dust and gas that gave rise to the solar system. The orbital radii of the planets have been used to infer the mass distribution within the solar nebula. With this

DON DIXON

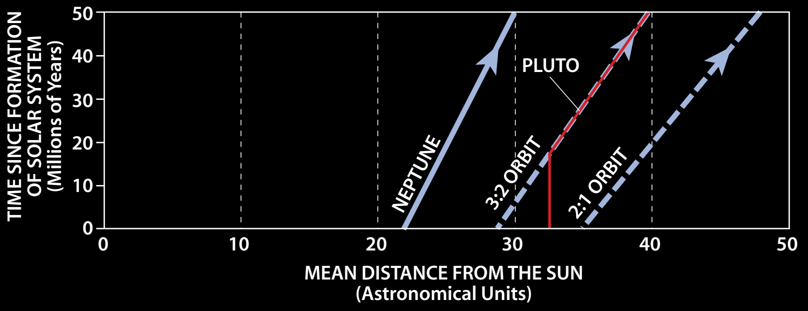


basic information, theorists have derived constraints on the nature and timescales of planetary formation. Consequently, much of our understanding of the early history of the solar system is based on the assumption that the planets formed in their current orbits.

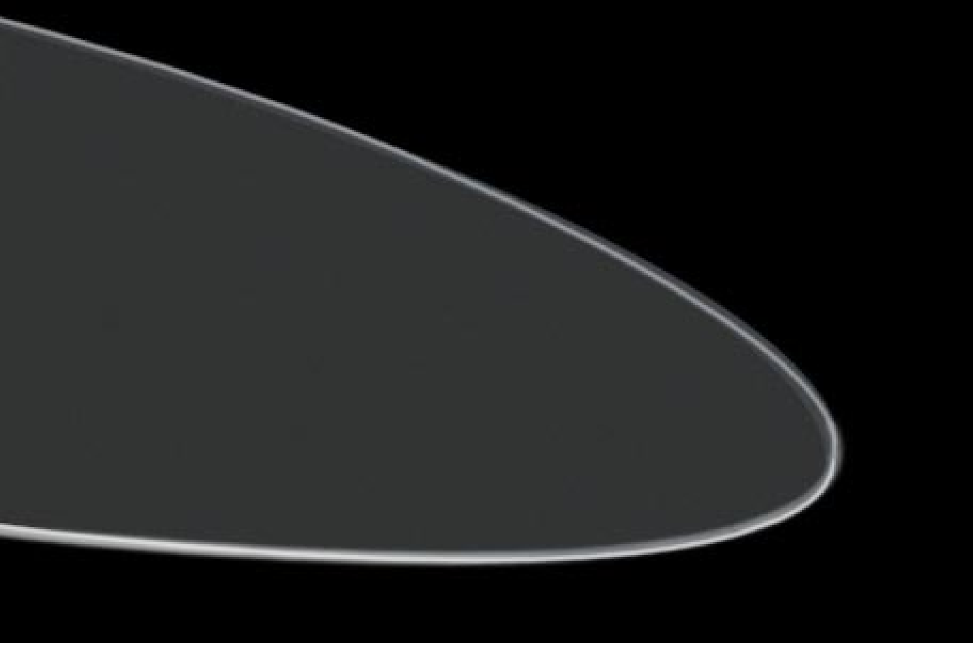
It is widely accepted, however, that many of the smaller bodies in the solar system—asteroids, comets and the planets' moons—have altered their orbits over the past 4.5 billion years, some more dramatically than others. The demise of Comet Shoemaker-Levy 9 when it collided with Jupiter in 1994 was striking evidence of the dynamic nature of some objects in the solar system. Still smaller objects—micron- and millimeter-size interplanetary particles shaken loose from comets and asteroids—undergo a more gradual orbital evolution, gently spiraling in toward the sun and raining down on the planets in their path.

Furthermore, the orbits of many planetary satellites have changed significantly since their formation. For example, Earth's moon is believed to have formed within 30,000 kilometers (18,600 miles) of Earth—but it now orbits at a distance of 384,000 kilometers. The moon has receded by nearly 100,000 kilometers in just the past billion years because of tidal forces (small gravitational torques) exerted by our planet. Also, many satellites of the outer planets orbit in lockstep with one another: for instance, the orbital period of Ganymede, Jupiter's largest moon, is twice that of Europa, which in turn has a period twice that of Io. This precise synchronization is believed to be the result of a gradual evolution of the satellites' orbits by means of tidal forces exerted by the planet they are circling.

Until recently, little provoked the idea that the orbital configuration of the planets has altered significantly since their formation. But some remarkable developments during the past five years indicate that the planets may indeed have migrated from their original orbits. The discovery of the Kuiper belt has shown that our solar system does not end at Pluto. Approximately 100,000 icy "minor planets" (ranging between 100 and 1,000 kilometers in diameter) and an even greater number of smaller



PLANETARY MIGRATION is shown in illustrations of the solar system at the time when the planets formed (*top left*) and in the present (*bottom left*). The orbit of Jupiter is believed to have shrunk slightly, while the orbits of Saturn, Uranus and Neptune expanded. (The inner planetary region was not significantly affected by this process.) According to this theory, Pluto was originally in a circular orbit. As Neptune migrated outward, it swept Pluto into a 3:2 resonant orbit, which has a period proportional to Neptune's (*above*). Neptune's gravity forced Pluto's orbit to become more eccentric and inclined to the plane of the other planets' orbits.



DON DIXON; LAURIE GRACE (*graph*)

bodies occupy a region extending from Neptune's orbit—about 4.5 billion kilometers from the sun—to at least twice that distance. The distribution of these objects exhibits prominent nonrandom features that cannot be readily explained by the current model of the solar system. Theoretical models for the origin of these peculiarities suggest the intriguing possibility that the Kuiper belt bears traces of the orbital history of the gas-giant planets—specifically, evidence of a slow spreading of these planets' orbits subsequent to their formation.

What is more, the recent discovery of several Jupiter-size companions orbiting nearby sunlike stars in peculiarly small orbits has also focused attention on planetary migration. It is difficult to understand the formation of these putative planets at such small distances from their parent stars. Hypotheses for their origin have proposed that they accreted at more comfortable distances from their parent stars—similar to the distance between Jupiter and the sun—and then migrated to their present positions.

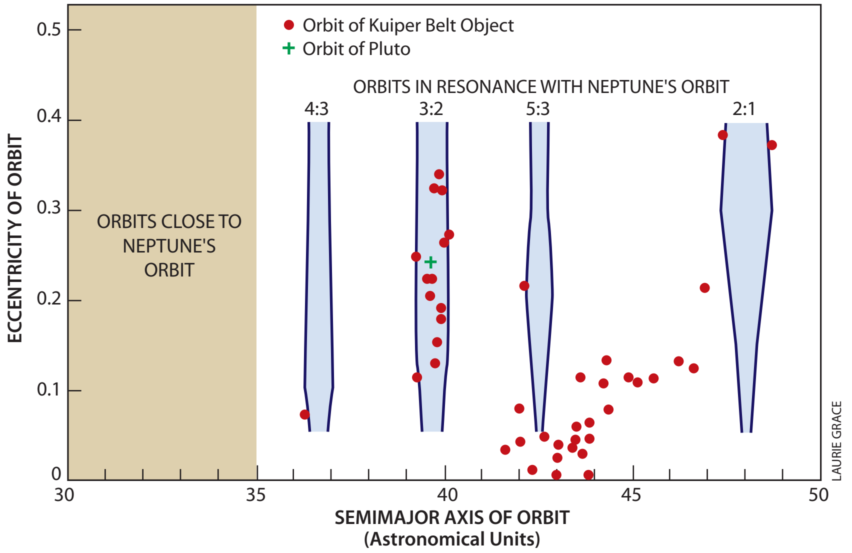
Pluto: Outcast or Smoking Gun?

Until just a few years ago, the only planetary objects known beyond Neptune were Pluto and its satellite, Charon. Pluto has long been a misfit in the prevailing theories of the solar system's origin: it is thousands of times less massive than the four gas-giant outer planets, and its orbit is very different from the well-separated, nearly circular and co-planar orbits of the eight other major planets. Pluto's is eccentric: during one complete revolution, the planet's distance from the sun varies from 29.7 to 49.5 astronomical units (one astronomical unit, or AU, is the distance between Earth and the sun, about 150 million kilometers). Pluto also travels 8 AU above and 13 AU below the mean plane of the other planets' orbits [*see illustration at left*]. For approximately two decades in its orbital period of 248 years, Pluto is closer to the sun than Neptune is.

In the decades since Pluto's discovery in 1930, the planet's enigma has deepened. Astronomers have found that most Neptune-crossing orbits are unstable—a body in such an orbit will either collide with Neptune or be ejected from the outer solar system in a relatively short time, typically less than 1 percent of the age of the solar system. But the particular Neptune-crossing orbit in which Pluto travels is protected from close approaches to the gas giant by a phenomenon called resonance libration. Pluto makes two revolutions around the sun during the time that Neptune makes three; Pluto's orbit is therefore said to be in 3:2 resonance with Neptune's. The relative motions of the two planets ensure that when Pluto crosses Neptune's orbit, it is far away from the larger planet. In fact, the distance between Pluto and Neptune never drops below 17 AU.

In addition, Pluto's perihelion—its closest approach to the sun—always occurs high above the plane of Neptune's orbit, thus maintaining Pluto's long-term orbital stability. Computer simulations of the orbital motions of the outer planets, including the effects of their mutual perturbations, indicate that the relationship between the orbits of Pluto and Neptune is billions of years old and will persist for billions of years into the future. Pluto is engaged in an elegant cosmic dance with Neptune, dodging collisions with the gas giant over the entire age of the solar system.

How did Pluto come to have such a peculiar orbit? In the past, this question has stimulated several speculative and ad hoc explanations, typically involving planetary encounters. Recently, however, significant advances have been made in understanding the complex dynamics of orbital resonances and in identifying their Jekyll-and-Hyde role in producing both chaos and exceptional stability in the solar system. Drawing on this body



LAURIE GRACE

DON DIXON

KUIPER BELT OBJECTS occupy a torus-shape region beyond Neptune's orbit (*right*). The theory of planetary migration predicts that concentrations of these objects would be found in orbits in resonance with Neptune's (*inside blue brackets in illustration above*). Recent observations indicate that about one third of the Kuiper belt objects for which orbits are known (*red dots*) are in 3:2 resonant orbits similar to Pluto's (*green cross*). Few objects are expected to be found in orbits that are very close to Neptune's (*shaded area*).

of knowledge, I proposed in 1993 that Pluto was born somewhat beyond Neptune and initially traveled in a nearly circular, low-inclination orbit similar to those of the other planets but that it was transported to its current orbit by resonant gravitational interactions with Neptune. A key feature of this theory is that it abandons the assumption that the gas-giant planets formed at their present distances from the sun. Instead it proposes an epoch of planetary orbital migration early in the history of the solar system, with Pluto's unusual orbit as evidence of that migration.

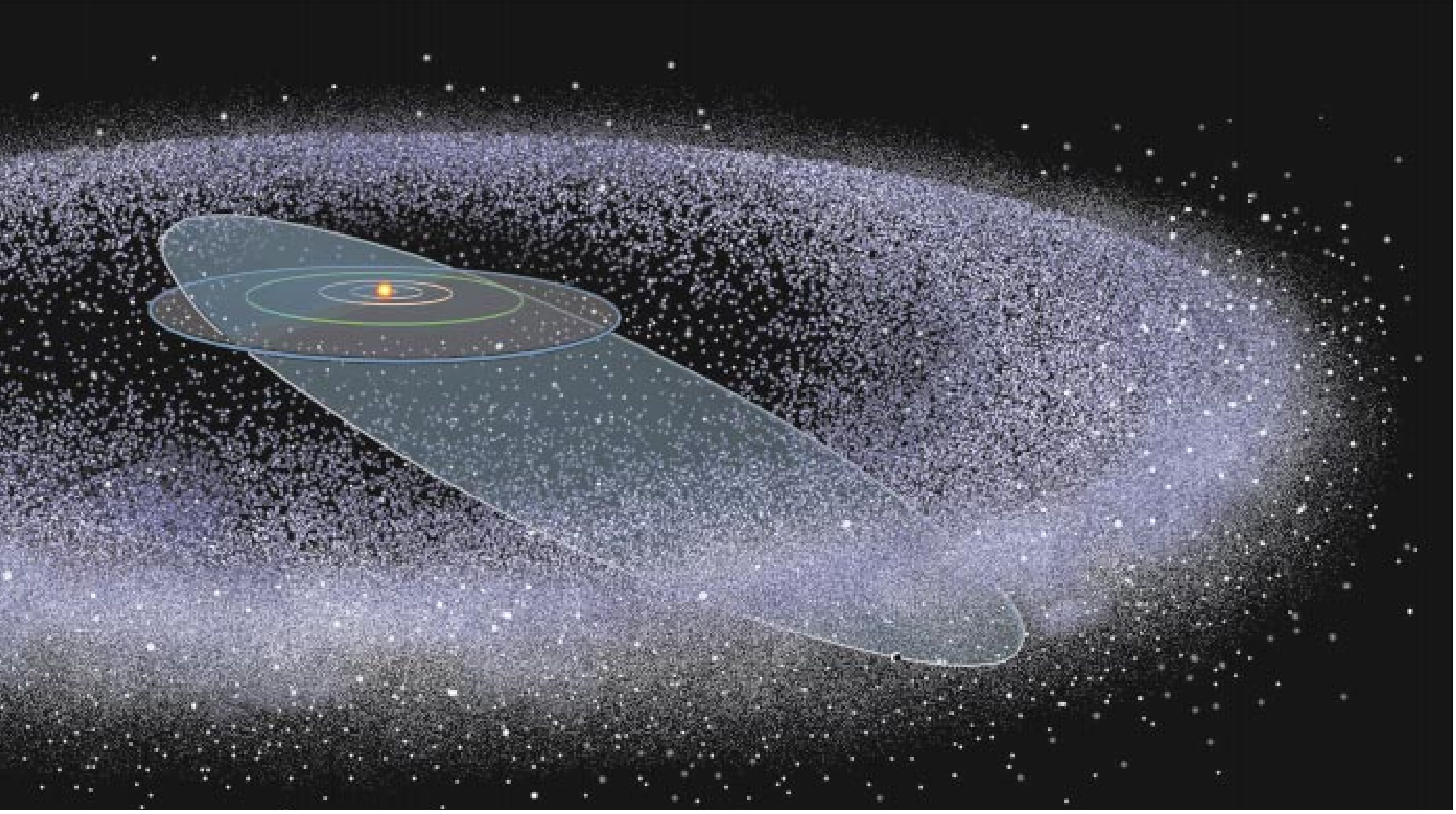
The story begins at a stage when the process of planetary formation was almost but not quite complete. The gas giants—Jupiter, Saturn, Uranus and Neptune—had nearly finished coalescing from the solar nebula, but a residual population of small planetesimals—rocky and icy bodies, most no larger than a few tens of kilometers in diameter—remained in their midst. The relatively slower subsequent evolution of the solar system consisted of the scattering or accretion of the planetesimals by the major planets [*see illustration on page 56*]. Because the planetary scattering ejected most of the planetesimal debris to distant or unbound orbits—essentially throwing the bodies out of the solar system—there was a net loss of orbital energy and angular momentum from the giant planets' orbits. But because of their different masses and distances from the sun, this loss was not evenly shared by the four giant planets.

In particular, consider the orbital evolution of the outermost giant planet, Neptune, as it scattered the swarm of planetesimals in its vicinity. At first, the mean specific orbital energy of the planetesimals (the orbital energy per unit of mass) was equal to that of Neptune itself, so Neptune did not gain or lose energy from its gravitational interactions with the bodies. At later times, however, the planetesimal swarm near Neptune was depleted of the lower-energy objects, which had moved into the gravitational reach of the other giant planets. Most of these planetesimals were eventually ejected from the solar system by Jupiter, the heavyweight of the planets.

Thus, as time went on, the specific orbital energy of the planetesimals that Neptune encountered grew larger than that of Neptune itself. During subsequent scatterings, Neptune gained orbital energy and migrated outward. Saturn and Uranus also gained orbital energy and spiraled outward. In contrast, Jupiter lost orbital energy; its loss balanced the gains of the other planets and planetesimals, hence conserving the total energy of the system. But because Jupiter is so massive and had so much orbital energy and angular momentum to begin with, its orbit decayed only slightly.

The possibility of such subtle adjustments of the giant planets' orbits was first described in a little-noticed paper published in 1984 by Julio A. Fernandez and Wing-Huen Ip, a Uruguayan and Taiwanese astronomer duo working at the Max Planck Institute in Germany. Their work remained a curiosity and escaped any comment among planet formation theorists, possibly because no supporting observations or theoretical consequences had been identified.

In 1993 I theorized that as Neptune's orbit slowly expanded, the orbits that would be resonant with Neptune's also expanded. In fact, these resonant orbits would have swept by Pluto, assuming that the planet was originally in a nearly circular, low-inclination orbit beyond Neptune. I calculated that any such objects would have had a high probability of being "captured" and pushed outward along the resonant orbits as Neptune migrated. As these bodies moved outward, their orbital eccentricities and inclinations would have been driven to larger values by the resonant gravitational torque from Neptune. (This effect is analogous to the pumping-up of the amplitude of a playground swing by means of small periodic pushes at the swing's natural frequency.) The final



maximum eccentricity would therefore provide a direct measure of the magnitude of Neptune's migration. According to this theory, Pluto's orbital eccentricity of 0.25 suggests that Neptune has migrated outward by at least 5 AU. Later, with the help of computer simulations, I revised this to 8 AU and also estimated that the timescale of migration had to be a few tens of millions of years to account for the inclination of Pluto's orbit.

Of course, if Pluto were the only object beyond Neptune, this explanation of its orbit, though compelling in many of its details, would have remained unverifiable. The theory makes specific predictions, however, about the orbital distribution of bodies in the Kuiper belt, which is the remnant of the primordial disk of planetesimals beyond Neptune [see "The Kuiper Belt," by Jane X. Luu and David C. Jewitt; Scientific American, May 1996]. Provided that the largest bodies in the primordial Kuiper belt were sufficiently small that their perturbations on the other objects in the belt would be negligible, the dynamical mechanism of resonance sweeping would work not only on Pluto but on all the trans-Neptunian objects, perturbing them from their original orbits. As a result, prominent concentrations of objects in eccentric orbits would be found at Neptune's two strongest resonances, the 3:2 and the 2:1. Such orbits are ellipses with semimajor axes of 39.5 AU and 47.8 AU, respectively. (The length of the semimajor axis is equal to the object's average distance from the sun.)

More modest concentrations of trans-Neptunian bodies would be found at other resonances, such as the 5:3. The population of objects closer to Neptune than the 3:2 resonant orbit would be severely depleted because of the thorough resonance sweeping of that region and because perturbations caused by Neptune would destabilize the orbits of any bodies that remained. On the other hand, planetesimals that accreted beyond 50 AU from the sun would be expected to be largely unperturbed and still orbiting in their primordial distribution.

Fortunately, recent observations of Kuiper belt objects, or KBOs, have provided a means of testing this theory. More than 174 KBOs have been discovered as of mid-1999. Most have orbital periods in excess of 250 years and thus have been tracked for less than 1 percent of their orbits. Nevertheless, reasonably reliable orbital parameters have been determined for about 45 of the known KBOs [*see illustration on opposite page*]. Their orbital distribution is not a pattern of uniform, nearly circular, low-inclination orbits, as would be expected for a pristine, unperturbed planetesimal population. Instead one finds strong evidence of gaps and concentrations in the distribution. A large fraction of these KBOs travel in eccentric 3:2 resonant orbits similar to Pluto's, and KBOs in orbits interior to the 3:2 orbit are nearly absent—which is consistent with the predictions of the resonance sweeping theory.

Still, one outstanding question remains: Are there KBOs in the 2:1 resonance comparable in number to those found in the 3:2, as the planet migration theory would suggest? And what is the orbital distribution at even greater distances from the sun? At present, the census of the Kuiper belt is too incomplete to answer this question fully. But on Christmas Eve 1998 the Minor Planet Center in Cambridge, Mass., announced the identification of the first KBO orbiting in 2:1 resonance with Neptune. Two days later the center revealed that another KBO was traveling in a 2:1 resonant orbit. Both these objects have large orbital eccentricities, and they may turn out to be members of a substantial population of KBOs in similar orbits. They had previously been identified as orbiting in the 3:2 and 5:3 resonances, respectively, but new observations made last year strongly indicated that the original identifications were incorrect. This episode underscored the need for continued tracking of known KBOs in order to map their orbital distribution correctly. We must also acknowledge the dangers of overinterpreting a still small data set of KBO orbits.

In short, although other explanations cannot be ruled out yet, the orbital distribution of KBOs provides increasingly strong evidence for planetary migration. The data suggest that Neptune was born about 3.3 billion kilometers from the sun and then moved about 1.2 billion kilometers outward—a journey of almost 30 percent of its present orbital radius. For Uranus, Saturn and Jupiter, the magnitude of migration was smaller, perhaps 15, 10 and 2 percent, respectively; the estimates are less certain for these planets because, unlike Neptune, they could not leave a direct imprint on the Kuiper belt population.

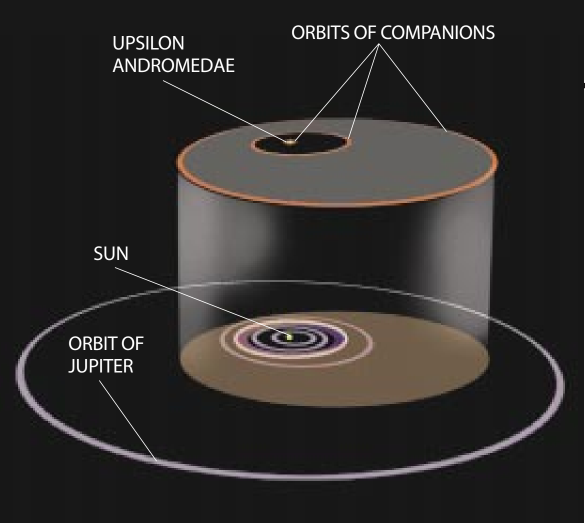
Most of this migration took place over a period shorter than 100 million years. That is long compared with the timescale for the formation of the planets—which most likely took less than 10 million years—but short compared with the 4.5-billion-year age of the solar system. In other words, the planetary migration occurred in the early history of the solar system but during the later stages of planet formation. The total mass of the scattered planetesimals was about three times Neptune's mass. The question arises whether even more drastic orbital changes might occur in planetary systems at earlier times, when the primordial disk of dust and gas contains more matter and perhaps many protoplanets in nearby orbits competing in the accretion process.

Other Planetary Systems?

In the early 1980s theoretical studies by Peter Goldreich and Scott Tremaine, both then at the California Institute of Technology, and others concluded that the gravitational forces between a protoplanet and the surrounding disk of gas, as well as the energy losses caused by viscous forces in a gaseous medium, could lead to very large exchanges of energy and angular momentum between the protoplanet and the disk. If the torques exerted on the protoplanet by the disk matter just inside the planet's orbit and by the matter just beyond it were slightly unbalanced, rapid and drastic changes in the planet's orbit could happen. But again, this theoretical possibility received little attention from other astronomers at the time. Having only our solar system as an example, planet formation theorists continued to assume that the planets were born in their currently observed orbits.

In the past five years, however, the search for extrasolar planets has yielded possible signs of planetary migration. By measuring the telltale wobbles of nearby stars—within 50 light-years of our solar system—astronomers have found evidence of more than a dozen Jupiter-mass companions in surprisingly small orbits around main-sequence stars. The first putative planet was detected orbiting the star 51 Pegasi in 1995 by two Swiss astronomers, Michel Mayor and Didier Queloz of the Geneva Observatory, who were actually surveying for binary stars.

A Planetary System at Last?



UPSILON ANDROMEDAE SYSTEM is believed to include three Jupiter-mass companions orbiting the star (*top*). Their theorized orbits are much tighter than Jupiter's orbit in our solar system (*bottom*).

DON DIXON

In April 1999 astronomer R. Paul Butler of the Anglo-Australian Observatory and his colleagues announced the discovery of what is apparently the first known case of a planetary system with several Jupiter-mass objects orbiting a sunlike star. (Previously, only systems with one Jupiter-mass companion had been detected.) The star is Upsilon Andromedae; it is approximately 40 light-years from our solar system and is slightly more massive and about three times more luminous than our sun.

The astronomers say their analysis of the observations shows that Upsilon Andromedae harbors three companions. The innermost object is at least 70 percent as massive as Jupiter and is moving in a nearly circular orbit only 0.06 AU—or about nine million kilometers—from the star. The outermost companion object is at least four times as massive as Jupiter and travels in a very eccentric orbit with a mean radius of 2.5 AU—half the radius of Jupiter's orbit. The intermediate object is at least twice as massive as Jupiter and has a moderately eccentric orbit with a mean radius of 0.8 AU.

If confirmed, the architecture of this system would pose some interesting challenges and opportunities for theoretical models of the formation and evolution of planetary systems. A number of dynamicists (including myself) have already determined that the orbital configuration of this putative system is at best marginally stable. The system's dynamical stability would improve greatly if there were no middle companion. This is noteworthy, as the observational evidence for the middle companion is weaker than that for the other two.

The Upsilon Andromedae system appears to contradict all the theorized mechanisms that would cause giant planets to migrate inward from distant birthplace orbits. If disk-protoplanet interactions caused the orbits to decay, the more massive planet would most likely be the earliest born and hence found at the shortest distance from the star—contrary to the pattern in the Upsilon Andromedae system. If only the innermost and outermost companions are real, the system could represent an example of the planet-planet scattering model in which two massive planets migrate to nearby orbits, then gravitationally scatter each other, eventually yielding one in a close, nearly circular orbit and the other in a distant, eccentric orbit. A difficulty with this scenario is that the more massive companion would be expected to evolve to the small orbit and the less massive one to the distant orbit—again, contrary to the characteristics of the Upsilon Andromedae system.

Could this system represent a hybrid case of these two scenarios—that is, orbital decay caused by disk-protoplanet interactions in the case of the innermost object and mutual gravitational scattering for the other two companions? Perhaps entirely different formation and evolution processes are also involved, such as the fragmentation of the protostellar gas cloud that is thought to produce multiple-star systems and brown dwarf companions.

If only the innermost and outermost companions are real, the system would be architecturally similar to classic triple-stellar systems consisting of a tight binary with a distant third star in an eccentric orbit. At present, we have only speculations for the Upsilon Andromedae system. More observations and further analysis should help firm up the evidence for the number of companions and for their masses and orbital parameters.

The discovery methods employed so far are unable to detect planetary systems like our own because the stellar wobble from Earth-size planets in close orbits—or from Jupiter-size planets in more distant orbits—is below the observable threshold. Therefore, it would be premature to leap to conclusions about the astronomical frequency of Earth-like planets. Our understanding of the origin of the recently identified companions to sunlike stars is sure to evolve and thereby expand our understanding of our own solar system. *—R.M.*

Their observations were quickly confirmed by Geoffrey W. Marcy and R. Paul Butler, two American astronomers working at Lick Observatory near San Jose, Calif. As of June 1999, 20 extrasolar planetary candidates have been identified, most by Marcy and Butler, in search programs that have surveyed almost 500 nearby sunlike stars over the past 10 years. The technique used in these searches—measuring the Doppler shifts in the stars' spectral lines to determine periodic variations in stellar velocities—yields only a lower limit on the masses of the stars' companions. Most of the candidate planets have minimum masses of about one Jupiter-mass and orbital radii shorter than 0.5 AU.

What is the relationship between these objects and the planets in our solar system? According to the prevailing model of planet formation, the giant planets in our solar system coalesced in a two-step process. In the first step, solid planetesimals clumped together to form a protoplanetary core. Then this core gravitationally attracted a massive gaseous envelope from the surrounding nebula. This process must have been completed within about 10 million years of the formation of the solar nebula itself, as inferred from astronomical observations of the lifetime of protoplanetary disks around young sunlike stars.

At distances of less than 0.5 AU from a star, there is insufficient mass in the primordial disk for solid protoplanetary cores to condense. Furthermore, it is questionable whether a protoplanet in a close orbit could attract enough ambient gas to provide the massive envelope of a Jupiter-like planet. One reason is simple geometry: an object in a tight orbit travels through a smaller volume of space than one in a large orbit does. Also, the gas disk is hotter close to the star and hence less likely to condense onto a protoplanetary core. These considerations have argued against the formation of giant planets in very short-period orbits.

Instead several theorists have suggested that the putative extrasolar giant planets may have formed at distances of several AU from the star and subsequently migrated inward. Three mechanisms for planetary orbital migration are under discussion. Two involve disk-protoplanet interactions that allow planets to move long distances from their birthplaces as long as a massive disk remains.

With the disk-protoplanet interactions theorized by Goldreich and Tremaine, the planet would be virtually locked to the inward flow of gas accreting onto the protostar and might either plunge into the star or decouple from the gas when it drew close to the star. The second mechanism is interaction with a planetesimal disk rather than a gas disk: a giant planet embedded in a very massive planetesimal disk would exchange energy and angular momentum with the disk through gravitational scattering and resonant interactions, and its orbit would shrink all the way to the disk's inner edge, just a few stellar radii from the star.

The third mechanism is the scattering of large planets that either formed in or moved into orbits too close to one another for long-term stability. In this process, the outcomes would be quite unpredictable but generally would yield very eccentric orbits for both planets. In some fortuitous cases, one of the scattered planets would move to an eccentric orbit that would come so near the star at its closest approach that tidal friction would eventually circularize its orbit; the other planet, meanwhile, would be scattered to a distant eccentric orbit. All the mechanisms accommodate a broad range of final orbital radii and orbital eccentricities for the surviving planets.

These ideas are more than a simple tweak of the standard model of planet formation. They challenge the widely held expectation that protoplanetary disks around sunlike stars commonly evolve into regular planetary systems like our own. It is possible that most planets are born in unstable configurations and that subsequent planet migration can lead to quite different results in each system, depending sensitively on initial disk properties. An elucidation of the relation between the newly discovered extrasolar companions and the planets in our solar system awaits further theoretical and observational developments. Nevertheless, one thing is certain: the idea that planets can change their orbits dramatically is here to stay.

The Author

RENU MALHOTRA did her undergraduate studies at the Indian Institute of Technology in Delhi and received a Ph.D. in physics from Cornell University in 1988. After completing postdoctoral research at the California Institute of Technology, she moved to her current position as a staff scientist at the Lunar and Planetary Institute in Houston. In her research, she has followed her passionate interest in the dynamics and evolution of the solar system and other planetary systems. She also immensely enjoys playing with her four-year-old daughter, Mira.

Further Reading

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