Comet Populations and Cometary Dynamics

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CHAPTER 31

The Solar System formed from a collapsing cloud of dust and gas. Most of this material fell into the Sun. However, since the primordial cloud had a little bit of angular momentum or spin, a flattened disk also formed around the Sun. This disk contained a small amount of mass, as compared to the Sun, but most of the cloud's original angular momentum. This disk, known as the **protoplanetary nebula**, contained the material from which the planets, satellites, asteroids, and comets formed.

The first step in the planet formation process was that the dust, which contained ice in the cooler, distant regions of the nebula, settled into a thin central layer within the nebula. Although the next step has not been fully explained (*see* The Origin of the Solar System), as the dust packed itself into an ever-decreasing volume of space, larger bodies started to form. First came the objects called **planetesimals** (meaning small planets), which probably ranged in size from roughly a kilometer across to tens of kilometers across. As these objects orbited the Sun, they would occasionally collide with one another and stick together. Thus, larger objects would slowly grow. This process continued until the planets or the cores of the gas giant planets formed. (*See* Interiors of the Giant Planets.)

Fortunately for us, planet formation was a messy process and was not 100% efficient. There are a large number of remnants floating around the Solar System. Today we call these small bodies comets and asteroids. These pieces of refuse of planet formation are interesting because they can tell us a lot about how the planets formed. For example, because comets and asteroids are the least chemically processed objects in the Solar System (there is a lot of chemistry that happens on planets), studying their composition tells us about the composition of the protoplanetary nebula.

From our perspective, however, comets and asteroids are most interesting because their orbits can tell us the story of how the planets came together. Just as blood spatters on the wall of a murder scene can tell as much, or more, about the event than the body itself, the orbits of asteroids and comets play a pivotal role in unraveling the planetary system's sordid past.

In this chapter we present the story of where comets originated, where they have spent most of their lives, and how they occasionally evolve through the planetary system and move close enough to the Sun to become the spectacular objects we sometimes see in the night sky.

However, to tell this story, we must work backwards because the majority of observational information we have about these objects comes from the short phase when they are close to the Sun. The rest of the story is gleaned by combining this information with computer-generated dynamical models of the Solar System. Thus, in Section 1 we start with a discussion of the behavior of the orbits of comets. In Section 2 we present a classification scheme for comets.

This step is necessary because, as we will show, there are really two stories here. Comets can follow either one of them, but we must discuss each of them separately. In Section 3, we describe the cometary reservoirs that are believed to exist in the Solar System today. In addition, we discuss our current understanding of how these reservoirs came to be. We conclude in Section 4.

1. Basic Orbital Dynamics of Comets

For the most part, comets follow the basic laws of orbital mechanics first set down by Johannes Kepler and Isaac Newton. These are the same laws that govern the orbits of the planets. In this section, we present a brief overview of the orbits of small bodies in the Solar System. (For a more detailed discussion, *see* SOLAR SYSTEM DYNAMICS: REGULAR AND CHAOTIC MOTION.)

In the Solar System there are eight major planets, many smaller dwarf planets, and vast numbers of smaller bodies, each acting to perturb gravitationally the orbits of the others. The major planets in the Solar System follow nearly circular orbits. They also all lie in nearly the same plane, and so it has been long assumed that the planets formed in a disk. The planets never get close to each other. So, the first-order gravitational effect of the planets on one another is that each applies a torque on the other's orbit, as if the planets were replaced by rings of material smoothly distributed along their orbits. These torques cause both the longitude of perihelion, $\bar{\omega}$, and longitude of the ascending node, Ω, to precess. In particular, $\dot{\bar{\omega}} > 0$ and $\dot{\Omega} < 0$. The periods associated with these frequencies range from 47,000 to 2,000,000 years in the outer planetary system. Because the masses of the planets are much smaller than the Sun's mass, this is much longer than the orbital periods of the major planets, which are all less than 170 years.

There are four main differences between the orbits of the comets that we see and those of the planets. First, unlike planets, visible comets usually are on eccentric orbits, and so they tend to cross the orbits of the planets. So, they can suffer close encounters with the planets. While these encounters sometimes lead to direct collisions, like the impact of the comet D/Shoemaker-Levy 9 on Jupiter in 1994, more frequently the planet acts as a gravitational slingshot, scattering the comet from one orbit to another. The solid curve in Figure 1 shows the temporal evolution of comet 95P/Chiron's semimajor axis according to a numerical integration of the comet's orbit (black curve). This comet currently has $a = 14$ AU, which means it is between Saturn and Uranus, $e = 0.4$, and $i = 7°$. All the changes seen in the figure are due to gravitational encounters with the giant planets. Individual distant encounters lead to small changes, while close encounters lead to large changes. According to this integration, the comet will be ejected from the Solar System by a close encounter with Jupiter in 675,000 years.

This calculation illustrates that the orbits of objects on planet-crossing orbits, and thus the comets that we see, are generally unstable. This means that, on timescales very short compared to the age of the Solar System, most of these objects will be ejected from the Solar System by a gravitational encounter with a planet, or hit the Sun or a planet. (Some comets appear to disintegrate spontaneously, for reasons that are not well understood.) So, the comets that we see could not have formed on the orbits that we see them on, because if they had, they would no longer be there. They must have formed, or at least been stored, for long periods of time in a reservoir or reservoirs where their orbits are long-lived and they remain cold enough so that their volatiles are, for the most part, preserved. These reservoirs are mainly hidden from us because they are far from the Sun. We discuss cometary reservoirs in more detail in Section 3.

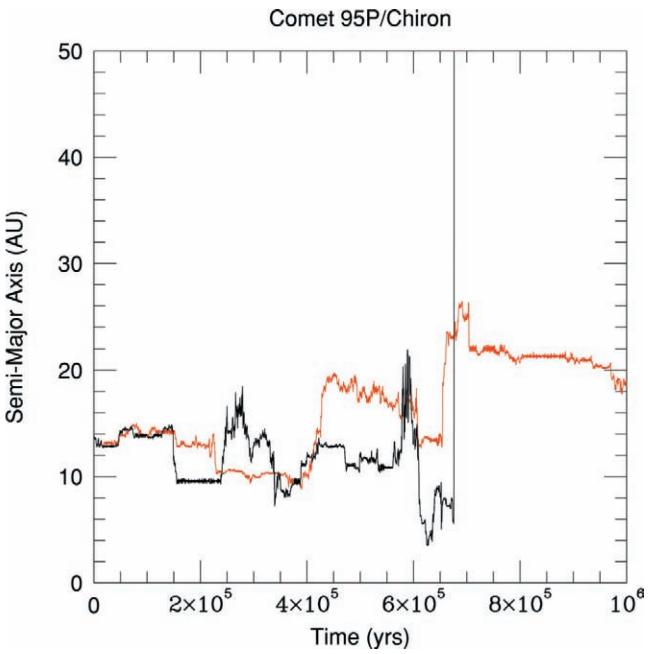

FIGURE 1 The long-term evolution of the semimajor axis of comet 95P/Chiron (black curve) and a *clone* of this comet (red curve). These trajectories were determined by numerically integrating the equations of motion of these comets, the Sun, and the four giant planets. The clone was an object with almost the exact same initial conditions as 95P/Chiron, but the position was offset by 1 cm. The fact that the two trajectories diverge shows that the orbit is chaotic.

Figure 1 also shows that cometary orbits are formally **chaotic**. If the Solar System consisted of only the Sun and one planet, interacting through Newton's law of gravity, the planet's orbit would remain a Keplerian ellipse for all time. The distance between the planet and the Sun would vary periodically, akin to a pendulum. This is an example of **regular** motion. For regular motion, if there were two planetary systems that were exactly the same, except that the position of the planet was slightly offset in one versus the other, this offset would increase linearly with time. However, if three or more bodies are present in the system, **chaos** is possible, meaning that any offset between two nearly identical systems would increase exponentially. In certain cases, such as if the orbit of a comet or asteroid crosses that of a planet, chaos leads to gross unpredictability. That is, in these cases it is impossible to foretell, even qualitatively, the orbit of a comet or asteroid very far into their future or past.

For example, in Figure 1, the black curve shows the predicted evolution of 95P/Chiron's semimajor axis, using its nominal orbit. The red curve shows the evolution of an object ("the clone") that initially had exactly the same velocity as 95P/Chiron, and an initial position that differed by 1 cm! In less than a million years, a tiny fraction of the age of the Solar System, the orbits are totally different. One clone has been ejected from the Solar System, while the other continues to orbit within the planetary region. This **sensitivity to initial conditions** means that we can never predict where any object in the Solar System will be over long periods of time. By "long periods" we mean at most tens of millions of years for the planets, but for many comets less than a few hundred years. On timescales longer than this, we can only make statistical statements about the ultimate fate of small bodies on chaotic orbits.

The chaotic nature of cometary orbits has important implications for our study of cometary reservoirs. Once we determine the current orbit of a comet, it would be ideal if we could calculate how the orbit has changed with time and trace it backward to its source region. Thus, by studying the physical characteristics of these comets, we could determine what the cometary reservoirs are like. Unfortunately, the unpredictability of chaotic orbits affects orbital integrations that go backward in time as well as those that go forward in time. Thus, it is impossible to follow a particular comet backward to its source region. To illustrate this point, consider the analogy of an initially evacuated room with rough walls and a large open window into which molecules are injected through a narrow hose. Once the system has reached a steady state (i.e., the number of molecules entering through the hose is equal to the number leaving through the window), suppose that the position and velocity of all the particles in the room were recorded, but with less than perfect accuracy. If an attempt were made to integrate the system backwards, the small errors in our initial positions and velocities would be amplified every time a molecule bounced off a wall. Eventually, the particles would have "forgotten" their initial state, and thus, in our backwards simulation of the gas, more particles would leave through the window than through the hose, simply because the window is bigger. In our case, injection through the hose corresponds to a comet's leaving its reservoir, and leaving through the window corresponds to the many more avenues of escape available to a comet.

So, it is not possible to directly determine which comet comes from which reservoir. Therefore, the only way to use visible comets to study reservoirs is to dynamically model the behavior of comets after they leave the reservoir, and follow these hypothetical comets through the Solar System, keeping track of where they go and what kind of comets they become. By comparing the resulting orbital element distribution of the hypothetical comets to real comet types, we can determine, at least statistically, which type of comets come from which reservoir.

A second major difference between cometary and planetary orbits is that many comets are active. That is, since they are mainly made of dust (or rock) and water ice, and water ice only sublimates within ~4 AU of the Sun, comets that get close to the Sun spew out large amounts of gas and dust. This activity is what makes comets so noticeable and beautiful in the night sky. However, outgassing also acts like a rocket engine that can push the comet around and change its orbit. The most obvious effect of these so-called **nongravitational forces** is to change the orbital period of the comet. For example, nongravitational forces increase the orbital period (ΔP) of comet 1P/Halley by roughly 4 days every orbit.

The magnitude, direction, and variation with time of nongravitational forces are functions of the details of an individual comet's activity. Most of the outflow is in the sunward direction; however, the thermal inertia of the spinning nucleus delays the maximum outgassing toward the afternoon hemisphere. Thus, there is a nonradial component of the force. This delay is a function of the angle between the equator of the cometary nucleus and its orbital plane and will vary with time due to seasonal effects. Also, localized jetting can also produce a nonradial force on the comet and will also change the spin state and orientation of the nucleus.

As a result, there is a huge variation of nongravitational forces from comet to comet. For example, for many comets there is no measurable nongravitational force because they are large and/or relatively inactive. Some active comets, like Halley, have nongravitational forces that behave similarly from orbit to orbit. For yet other comets, the magnitude of these forces has been observed to change over long periods of time. A good example of this type of behavior is comet 2P/Encke, which had $\Delta P = -0.13$ days in the early nineteenth century, but now has ΔP of –0.008 days.

In general it is possible to describe the nongravitational accelerations $\vec{a}_{ng}$ that a comet experiences by:

$$\vec{a}_{ng} = g(r)\ \left[A_1\hat{r} + A_2\hat{t} + A_3\hat{n}\right],$$

where the A's are constants fit to each comet's behavior, r is the instantaneous helocentric distance, and $\hat{r}$, $\hat{n}$, and $\hat{t}$ are unit vectors in the radial direction, the direction normal to the orbit of the comet, and the transverse direction, respectively. The value $g(r)$ is related to the gas production rate as a function of helocentric distance and is usually given as:

$$g(r) = 0.111262\left(\frac{r}{r_0}\right)^{-2.15}\left[1 + \left(\frac{r}{r_0}\right)^{5.093}\right]^{-4.6142},$$

where the parameter $r_0 = 2.808$ AU is the heliocentric distance at which most of the solar radiation goes into sublimating water ice.

A third difference between a planetary orbit and a cometary orbit arises because visible comets tend to be on eccentric (sometimes very eccentric) orbits and on orbits that are inclined with respect to the ecliptic (sometimes even **retrograde** orbits with inclinations greater than 90°). The rates at which the **apse** and **node** of a comet ($\bar{\omega}$ and Ω) precess depend upon the comet's eccentricity and inclination. Thus, although cometary orbits precess, like the orbits of the planets, their behavior can be very different from the subtle behavior of the planets. Of particular interest, if the inclination of a comet is large, it can find itself in a situation in which, on average, $\dot{\bar{\omega}} = \dot{\Omega}$, i.e., $\bar{\omega}$ and Ω are said to be in resonance with one another. Since these two frequencies are linked to changes in eccentricity and inclination, this resonance allows eccentricity and inclination to become coupled, and allows each to undergo huge changes at the expense of the other. And, since a comet's semimajor axes is preserved in this resonance, changes in inclination also lead to changes in perihelion distance.

An example of this so-called **Kozai resonance** can be seen in the behavior of comet 96P/Machholz 1 (Fig. 2). 96P/Machholz 1 currently has an eccentricity of 0.96 and an inclination of 60°. Its perihelion distance, q, is currently 0.12 AU, well within the orbit of the planet Mercury. Figure 2 shows the evolution of the orbit of 96P/Machholz 1 over the next few thousand years. The Kozai resonance is responsible for the slow, systematic oscillations in both inclination and eccentricity (or q, which equals $a \times (1 - e)$). These oscillations are quite large; the inclination varies between roughly 10° and 80°, while the perihelion distance gets as large as 1 AU. According to these calculations, the Kozai resonance will drive this comet into the Sun ($e = 1$) in less than 12,000 years! Similarly, the Kozai resonance was important in driving comet D/Shoemaker-Levy 9 to collide with Jupiter. However, in that case, the comet had been captured into orbit around Jupiter, and the oscillations in i and e were with respect to the planet, not the Sun.

The final gravitational effect that we want to discuss in this section is the effect that the galactic environment has on cometary orbits. Up to this point, our discussion has assumed that the Solar System was isolated from the rest of the Universe. This, of course, is not the case. The Sun, along with its planets, asteroids, and comets, is in orbit within the Milky Way Galaxy, which contains hundreds of billions of stars. Each of these stars is gravitationally interacting with the members of the Solar System. Luckily for the planets, the strength of the Galactic perturbations varies as a^2, so the effects of the Galaxy are not very important for objects that orbit close to the Sun. However, if a comet has a semimajor axis larger than a few thousand AU, as some do (see Section 2), the Galactic perturbations can have a major effect on its orbit.

For example, Figure 3 shows a computer simulation of the evolution through time of the orbit of a hypothetical comet with an initial semimajor axis of 20,000 AU, roughly 10% of the distance to the nearest star. (For scale remember that Neptune is at 30 AU.) For the sake of discussion, it is useful to divide the evolution into two superimposed parts: (1) a slow secular change in perihelion distance (i.e., eccentricity) and inclination, and (2) a large number of small, but distinct jumps leading to a **random walk** in the orbit.

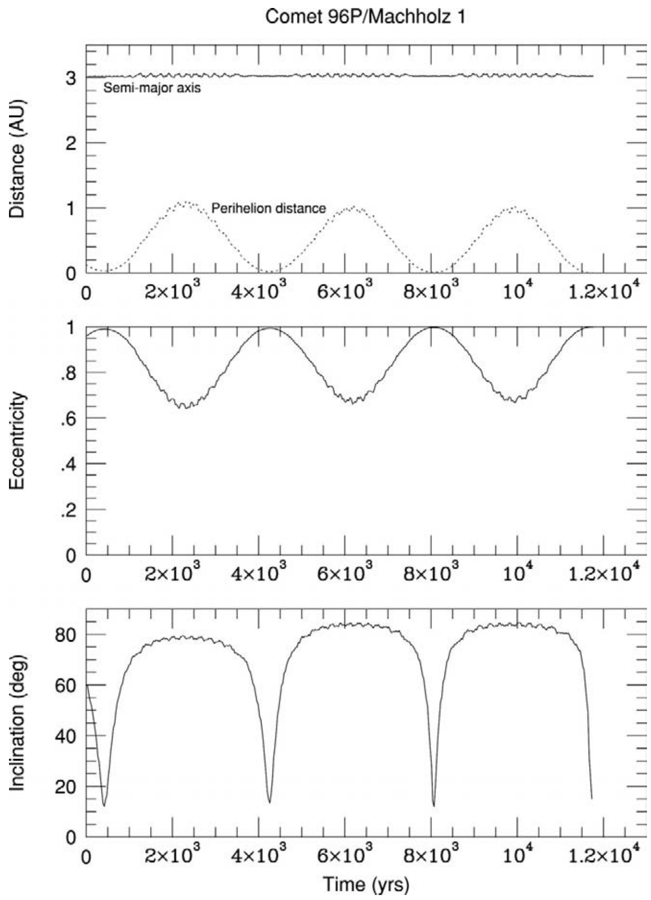

FIGURE 2 The long-term dynamical evolution of comet 96P/Machholz 1, which is currently in a Kozai resonance. Three panels are shown. The top presents the evolution of the comet's semimajor axis (solid curve) and perihelion distance (dotted curve). The middle and bottom panels show the eccentricity and inclination, respectively. Because of the Kozai resonance, the eccentricity and inclination oscillate with the same frequency, but are out of phase (i.e., eccentricity is large when inclination is small and vice versa). According to this calculation, this comet will hit the Sun in less than 12,000 years.

The secular changes are due to the smooth background gravitational potential of the Galaxy as a whole. If we define a rectangular coordinate system ($\tilde{x}$, $\tilde{y}$, $\tilde{z}$), centered on the Sun, such that $\tilde{x}$ points away from the galactic center, $\tilde{y}$ points in the direction of the galactic rotation, and $\tilde{z}$ points toward the south, it can be shown that the acceleration of a comet with respect to the Sun is

$$\mathrm{a_{gal}} = \Omega_0^2\left[(1-2\delta)\tilde{x}\hat{\tilde{x}} - \tilde{y}\hat{\tilde{y}} - \left(\frac{4\pi G_{\rho 0}}{\Omega_0^2} - 2\delta\right)\tilde{z}\hat{\tilde{z}}\right],$$

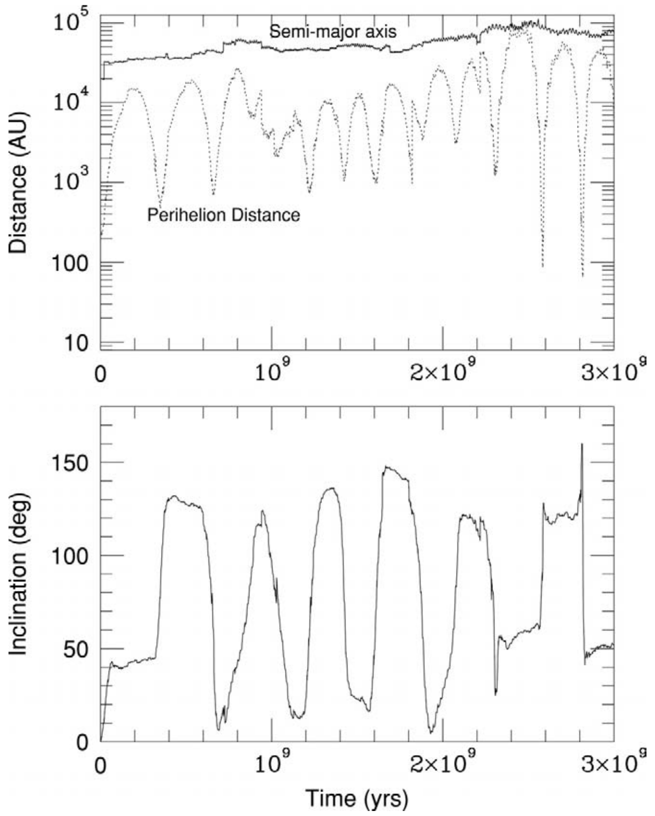

FIGURE 3 The long-term dynamical evolution of a fictitious object initially at 20,000 AU from the Sun under the gravitational perturbations of the Galaxy. Two panels are shown. The top presents the evolution of the comet's semimajor axis (solid curve) and perihelion distance (dotted curve; recall that $e = 1 - q/a$). The bottom panel shows the inclination.

where $\Omega_0 = 27.2 \pm 0.9$ km/s/kpc is the Sun's angular speed about the Galactic center, $\delta \equiv -\frac{A+B}{A-B}$ and $A = 14.5 \pm 1.5$ km/s/kpc and $B = -12 \pm 3$ km/s/kpc are Oort's constants of Galactic rotation, $\rho_0 = 0.1 M_\odot$ pc^{-3} is the density of the galactic disk in the solar neighborhood, and G is the gravitational constant. The value of δ is usually assumed to be zero.

Due to the nature of the above acceleration, it acts as a torque on the comet. As a result, the smooth part of the Galactic perturbations can change a comet's eccentricity and inclination, but not its semimajor axis. In addition, the eccentricity and inclination oscillate in a predictable way. In this example, in Figure 3 the oscillation period is approximately 300 million years. However, this period scales as $a^{-3/2}$, and thus the oscillations are faster for large semimajor axes. The small jumps are due to the effects of individual stars passing close to the Sun. Since these stars can come in from any direction, the kick that the comet feels can affect all the orbital elements, including the semimajor axis. The apparent random walk of the comet's semimajor axis seen in the figure is due to this effect.

2. Taxonomy of Cometary Orbits

The first step toward understanding a population is to construct a classification scheme that allows one to place like objects with like objects. This helps us begin to construct order from the chaos. However, before we talk about comet classification, we need to make the distinction between what we see and what is really out there. As we describe in much more detail below, most of the comets that we see are on orbits that cross the orbits of the planets. For example, the most famous comet, 1P/Halley (the "1P" stands for the first known *periodic* comet, see below), has $q = 0.6\,AU$ and an **aphelion distance** (farthest distance from the Sun) of 35 AU. Thus, it crosses the orbits of all the planets except Mercury. But planet-crossing comets represent only a very small fraction of the comets in the Solar System, because we can only easily see those comets that get close to the Sun.

Comets are very small compared to the planets. As a result, we cannot see comets very far away. For example, 1P/Halley, a relatively large comet, is a roughly (American) football-shaped object roughly 16 km long and 8 km wide. The farther away an object is, the fainter it is. The brightness (b) of a light-bulb decreases as the square of the distance d from the observer ($b \propto 1/d^2$). However, this is not true for objects in the Solar System that shine by reflected sunlight. To first approximation, the brightness of a solid sphere seen from the Earth is proportional to $1/(d_\odot^2\, d_\oplus^2)$, where $d_\odot$ and $d_\oplus$ are the distance between the object and the Sun and Earth, respectively. As objects get farther from the Sun, they get less light from the Sun and so reflect less (that is the $1/d_\odot^2$ term). Also, the further they get from us, the fainter they appear (that is the $1/d_\oplus^2$ term). In the outer Solar System, $d_\oplus$ and $d_\odot$ are nearly equal and thus $b \sim 1/d^4$.

It is even worse for a comet since it is not simply a solid sphere. As described above, as a comet approaches the Sun, its ice begins to sublimate. The resulting gas entrains dust from the comet's surface, forming a halo known as the **coma**. Because the dust is made of small objects with a lot of surface area, it can reflect a lot of sunlight. So, this cometary activity makes the comet much brighter. Observational studies show that as a comet approaches the Sun, its brightness typically increases as $1/(d_\odot^4\, d_\oplus^2)$! The result of all this activity is that it can make an object that would normally be very difficult to see, even through a telescope, into a body visible with the naked eye. Thus, we know of only a very small fraction of comets in the Solar System and this sample is **biased** because it represents only those objects that get close to the Sun. However, before we can try to understand the population as a whole, we need to first try to understand the part that we see.

The practice of developing a classification scheme or taxonomy is widespread in astronomy, where it has been applied to everything from Solar System dust particles to clusters of galaxies. Classification schemes allow us to put the objects of study into a structure in which we can look for correlations between various physical parameters and begin to develop evolutionary models. In this way, classification schemes have played a crucial role in advancing our understanding of the universe. However, we must be careful not to confuse these schemes with reality. In many cases, we are forcing a classification scheme on a continuum of objects. Then we argue over where to draw the boundaries. The fact that we astronomers find cubbyholing objects convenient does not imply that the universe will necessarily cooperate. With this caveat in mind, in the remainder of this section we present a scheme for the classification of cometary orbits.

Historically, comets have been divided into two groups: long-period comets (with periods greater than 200 years) and short-period comets (with $P < 200$ years). This division was developed to help observers determine whether a newly discovered comet had been seen before. Since orbit determinations have been reliable for only about 200 years, it may be possible to link any comet with a period less than this length of time with previous apparitions. Conversely, it is very unlikely to be possible to do so for a comet with a period greater than 200 years, because even if it had been seen before, its orbit determination would not have been accurate enough to prove the linkage. Thus this division has no physical justification and is now of historical interest only. Unfortunately, there does not yet exist a physically meaningful classification scheme for comets that is universally accepted. Nonetheless, such schemes exist. Here we present a scheme developed by one of the authors roughly 10 years ago. A flowchart of this scheme is shown in Figure 4.

The first step is to divide the population of comets into two groups. Astronomers have found that the most physically reasonable way of doing this is to employ the so-called **Tisserand parameter**, which is defined as

$$T \equiv a_J/a + 2\sqrt{(1-e^2)a/a_J}\;\cos i,$$

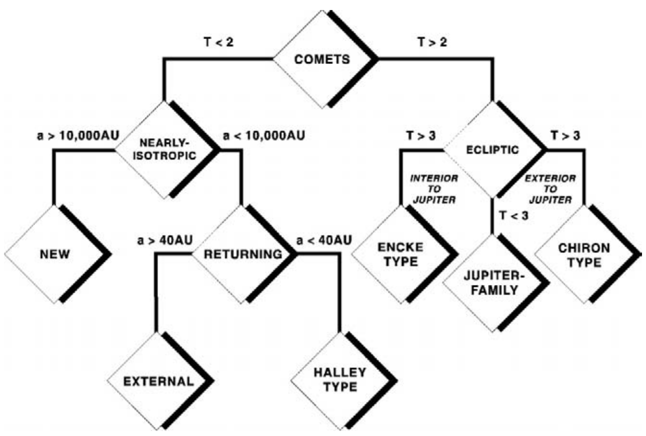

FIGURE 4 A flow chart showing the cometary classification scheme used in this chapter.

where a_J is Jupiter's semimajor axis. This parameter is an approximation to the **Jacobi constant**, which is an **integral of the motion** in the **circular restricted three-body problem**. The circular restricted three-body problem, in turn, is a well-understood dynamical problem consisting of two massive objects (mainly the Sun and Jupiter in this context) in circular orbits about one another, with a third, very small, body in orbit about the massive pair. If, to zeroth order, a comet's orbit is approximately a perturbed Kepler orbit about the Sun, then, to first order, it is better approximated as the small object in the circular restricted three-body problem with the Sun and Jupiter as the massive bodies. This means that as comets gravitationally scatter off Jupiter or evolve due to processes like the Kozai resonance, T is approximately conserved. The Tisserand parameter is also a measure of the relative velocity between a comet and Jupiter during close encounters, $v_{rel} \sim v_J\sqrt{3-T}$, where v_J is Jupiter's orbital speed around the Sun. Objects with $T > 3$ cannot cross Jupiter's orbit in the circular restricted case, being confined to orbits either totally interior or totally exterior to Jupiter's orbit.

Figure 5 shows a plot of inclination versus semimajor axis for known comets. Astronomers put the first division in our classification scheme at $T = 2$. Objects with $T > 2$ are shown as open circles in the figure, while those with $T < 2$ are the filled circles. The bodies with $T > 2$ are confined to low inclinations. Thus, we call these objects **ecliptic comets**. We call the $T < 2$ objects **nearly-isotropic**

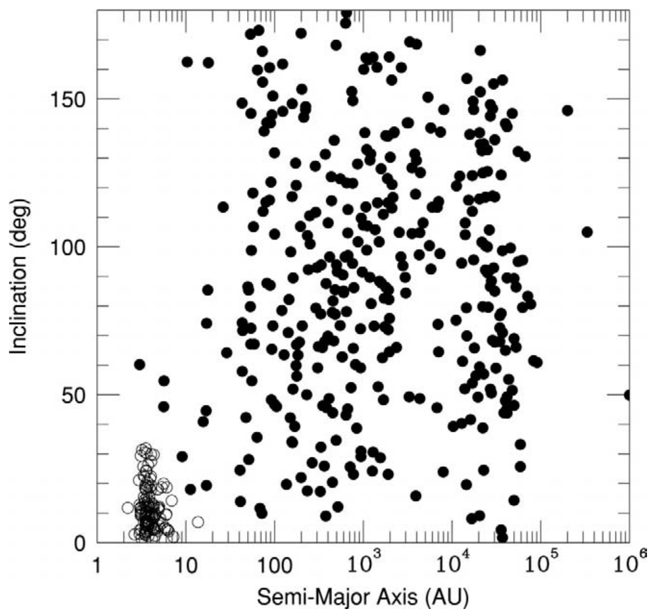

FIGURE 5 The inclination–semimajor axis distribution of all comets in the 2003 version of Marsden and Williams' *Catalogue of Cometary Orbits*. Comets with $T > 2$ are marked by the open circles, while comets with $T < 2$ are indicated by the filled circles.

comets to reflect their broad inclination distribution. We now discuss each of these in turn.

2.1 Nearly-Isotropic Comets

Nearly-isotropic comets (hereafter NICs) are divided into two groups: dynamically "new" comets and "returning" comets. This division is one that has its roots in the dynamics of these objects and is based on the distribution of their semimajor axes, a. Figure 6 shows a histogram of $1/a$, which is proportional to orbital binding energy $E = -\frac{GM_{\odot}}{2a}$. These values of semimajor axes were determined by numerically integrating the observed trajectory of each comet backwards in time to a point before it entered the planetary system. Taken at face value, a comet with $1/a < 0$ is unbound from the Sun, i.e., it follows a hyperbolic orbit. However, all of the negative values of $1/a$ are due to errors in orbit determination either due to poor astrometry or uncertainties in the estimates of the nongravitational forces. Thus, we have yet to discover a comet from interstellar space. The fraction of comets that suffer from this problem is small and we will ignore them for the remainder of this chapter.

The most striking feature of this plot is the peak at about $1/a \sim 0.00005$ AU^{-1}, i.e., $a \sim 20{,}000$ AU. In 1950, this feature led Jan Oort to conclude that the Solar System is surrounded by a spherically symmetric cloud of comets, which we now call the Oort cloud. The peak in the $1/a$ distribution of NICs is fairly narrow. And yet, the typical kick that a comet receives when it passes through the planetary system is approximately ± 0.0005 AU^{-1}, i.e., a factor of 10 larger than the energy of a comet initially in the peak (Fig. 6). Thus it is unlikely that a comet that is in the peak when it first passes through the Solar System will remain there during successive passes. We conclude from this argument that comets in the peak are dynamically "new" in the sense that this is the first time that they have passed through the planetary system.

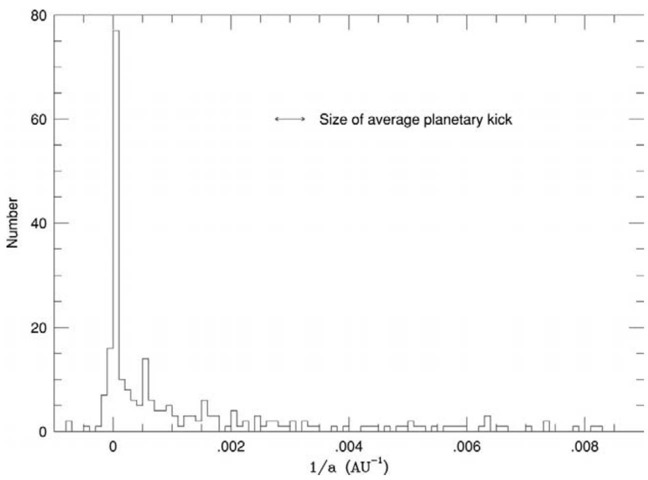

FIGURE 6 The distribution of inverse semimajor axis a, which measures the strength with which comets are gravitationally bound to the Solar System, for the known nearly-isotropic comets.

Comets not in the peak ($a \lesssim 10{,}000$ AU) are most likely objects that have been through the planetary system before. Comets with $a \ll 20{,}000$ AU that are penetrating the planetary system for the first time cannot make it into the inner Solar System where we see them as active comets without first encountering a planet (see Section 3.1 for a more complete discussion). Therefore, we should expect to see few comets directly from the Oort cloud with semimajor axes smaller than this value. We can conclude that a NIC not in the peak is a comet that was initially in it but has evolved to smaller a during previous passes through the planetary system. These comets are called "returning" comets. The boundary between new and returning comets is usually placed at $a = 10{,}000$ AU.

Returning comets are, in turn, divided into two groups based on their dynamics. Long-term numerical integrations of the orbits of returning comets show that a significant fraction of those with semimajor axes less than about 40 AU are temporarily trapped in what are called **mean motion resonances** with one of the giant planets during a significant fraction of the time they spend in this region of the Solar System. Such a resonance is said to occur if the ratio of the orbital period of the comet to that of the planet is near the ratio of two small integers. For example, on average Pluto orbits the Sun twice every time Neptune orbits three times. So, Pluto is said to be in the 2:3 mean motion resonance with Neptune. Comet 109P/Swift-Tuttle, with a semimajor axis of 26 AU, is currently trapped in a 1:11 mean motion resonance with Jupiter. Mean motion resonances can have a large effect on the orbital evolution of comets because they can change eccentricities and inclinations, as well as protecting the comet from close encounters with the planet it is resonating with. This is true even if the comet is only temporarily trapped. In our classification scheme, comets that have a small enough semimajor axis to be able to be trapped in a mean motion resonance with a giant planet are designated as **Halley-type** comets, named for its most famous member comet 1P/Halley. Returning comets that have semimajor axes larger than this are known as **external** comets. Although it is not really clear exactly where the boundary between these two type of comets should be, we place the boundary at $a = 40$ AU.

2.2 Ecliptic Comets

Recall that ecliptic comets are those comets with $T > 2$. These comets are further divided into three groups. Comets with $2 < T < 3$ are generally on Jupiter-crossing orbits and are dynamically dominated by that planet. Thus, we call these **Jupiter-family** comets. This class contains most of the known ecliptic comets. As described above, comets with

$T > 3$ cannot cross the orbit of Jupiter and thus should not be considered members of the Jupiter family. A comet that has $T > 3$ and whose orbit is interior to that of Jupiter is designated a *Encke-type*. This class is named after its best-known member, 2P/Encke. 2P/Encke is a bright, active comet that is decoupled from Jupiter. Its aphelion distance is only 4.2 AU.

A comet that has $T > 3$ and has a semimajor axis larger than that of Jupiter is known as a **Chiron-type**, again named after its best-known member, 95P/Chiron. As we discussed in Section 1.2, Chiron has a semimajor axis of 14 AU and a perihelion distance of 8 AU, putting it well beyond the grasp of Jupiter. Indeed, 95P/Chiron is currently dynamically controlled by Saturn. Although 95P/Chiron has a weak coma and is designated as a comet by the International Astronomical Union (IAU), it is also considered to be part of a population of asteroids known as **Centaurs**, which are found on orbits beyond Jupiter and that cross the orbits of the giant planets. The IAU distinguishes between a comet and an asteroid based on whether an object is active or not. This distinction is therefore not dependent on an object's dynamical history or where it came from. Thus, Chiron is simply a member of the Centaurs, of which there are currently a few dozen known members. For the remainder of this chapter, we will not distinguish between the **Chiron-type** comets and the Centaur asteroids, and will call both Centaurs.

2.3 Orbital Distribution of Comets

Figure 7 shows the location of the comet classes described above as a function of their Tisserand parameter and semimajor axis. Also shown is the location of all comets in the 2003 version of Marsden and Williams' *Catalogue of Cometary Orbits*. The major classes of ecliptic and nearly isotropic comets are defined by T and are independent of a. The ranges of these two classes are thus shown with arrows only. The extent of the subclasses is shown by different shadings. Also shown is the location of all the comets with $1/a > 0$ in the catalog. The white curve shows the relationship of T versus a for a comet with $q = 2.5$ AU and $i = 0$. Comets above and to the left of this line have $q > 2.5$ AU and thus are difficult to detect. By far, most comets in the plot are new or returning NICs. The second largest group consists of the Jupiter-family comets.

We end this section with a short discussion of the robustness of this classification scheme. Long-term orbital integrations show that comets rarely change their primary class (*ecliptic* versus *nearly isotropic*), but do frequently change their subclass (i.e., *new* versus *returning* or *Jupiter-family* versus *Chiron-type*). This result suggests that ecliptic comets and nearly isotropic comets come from different source reservoirs. In particular, as we will now describe, the NICs come from the Oort cloud, while the ecliptic comets are thought to originate in a structure that we call the **scattered disk**.

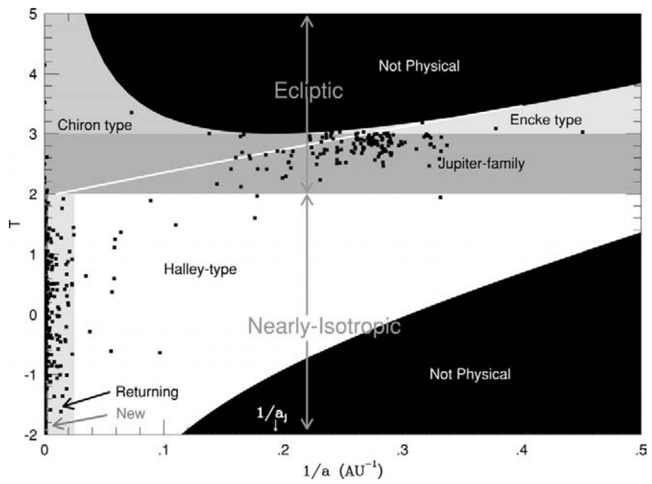

FIGURE 7 The location of the classes in our adopted comet taxonomy as a function of the Tisserand parameter (T) and semimajor axis (a). The major classes of ecliptic and nearly isotropic comets are defined by their values of T. The ranges of these two classes are thus shown with arrows only. The extent of each subclass is shown by different shadings. Also shown is the location of all the comets with $1/a > 0$ in the 2003 version of Marsden and Williams' *Catalogue of Cometary Orbits*. The white curve shows the relationship of T versus a for a comet with $q = 2.5$ AU and $i = 0$. Comets above and to the left of this line have $q > 2.5$ AU and thus are difficult to detect.

3. Comet Reservoirs

As we discussed above, the active comets that we see are on unstable, short-lived orbits because they cross the orbits of the planets. For example, the median dynamical lifetime of a Jupiter-family comet (defined as the span of time measured from when a comet first evolves onto Jupiter-family comet-type orbit until it is ejected from the Solar System, usually by Jupiter) is only about 300,000 years. So, these comets must have been stored in one or more reservoirs, presumably outside the planetary region, for billions of years before being injected into the inner Solar System where they can be observed. These reservoirs are far from the Sun (and they would have to be in order to store an ice ball for 4 billion years), and thus much of what we know about them has been learned by studying the visible comets and linking them to their reservoirs through a theoretical investigation of the orbital evolution of comets. As we currently understand things, there are two main cometary reservoirs: the Oort cloud and the scattered disk. We discuss each of these separately.

3.1 The Oort Cloud

Nearly isotropic comets originate in the Oort cloud, which is a nearly spherical distribution of comets (at least in the outer regions of the cloud), centered on the Sun. The position of its outer edge is defined by the Solar System's tidal truncation radius at about 100,000–200,000 AU from the Sun. At these distances, the gravitational effect of stars and other material in the Galaxy can strip a comet away from the Solar System. This edge can be seen in the distribution of NICs shown in Figure 6. For reasons described below, we have no direct information about the location of the Oort cloud's inner edge, but models of Oort cloud formation (see Section 3.3) predict that it should be between 2,000 and 5,000 AU.

The orbits of comets stored in the Oort cloud evolve due to the forces from the Galaxy. As shown in Figure 3, the primary role of the Galaxy is to change the angular momentum of the comet's orbit, causing large changes in the inclination and, more importantly, the perihelion distance of the comet. Occasionally, a comet will evolve so that its perihelion distance falls to within a few AU of the Sun, thus making it visible as a new nearly isotropic comet. As we discussed above, the new comets that we see have semimajor axes larger than 20,000 AU, as illustrated by the spike in Figure 6. This led Jan Oort to suggest that the inner edge of the Oort cloud was at this location. However, this turns out not to be the case. In order for us to see a new comet from the Oort cloud, it has to get close to the Sun, which generally means that its perihelion distance, q, must be less than 2 or 3 AU.[1] However, during the perihelion passage before the one on which we see a comet for the first time, its perihelion distance must have been outside the realm of the gas giants ($q \gtrsim 15$ AU), because if the comet had q near either Jupiter or Saturn when it was near perihelion, it would have received a kick from the planets that would have knocked it out of the spike. Thus, new comets can only come from the region in the Oort cloud in which the Galactic tides are strong enough that the change in perihelion in one orbit (Δq) is greater than $\sim$10 AU. It can be shown that the timescale on which a comet's perihelion changes is

$$\tau_q = 6.6 \times 10^{14}\,\text{yr}\,a^{-2}\,\Delta q / \sqrt{q},$$

in the current galactic environment where a, Δq, and q are measured in AU. Thus, only those objects for which τ_q is larger than the orbital period can become a visible new comet. For $\Delta q = 10$ AU and $q = 15$ AU, this occurs when $a \gtrsim 20{,}000$ AU.

The above result does not imply that Oort comets far inside of 20,000 AU do not contribute to the population of nearly isotropic comets. In fact, they do. It is simply that these objects do not become active comets until their orbits have been significantly modified by the giant planets.

[1] Comets are sometimes discovered at larger perihelion distances because the comet is unusually active due to the sublimation of ices, such as carbon monoxide, that are more volatile than water ice. The current record holder, the new comet C/2003 A2 Gleason, had $q = 11$ AU.

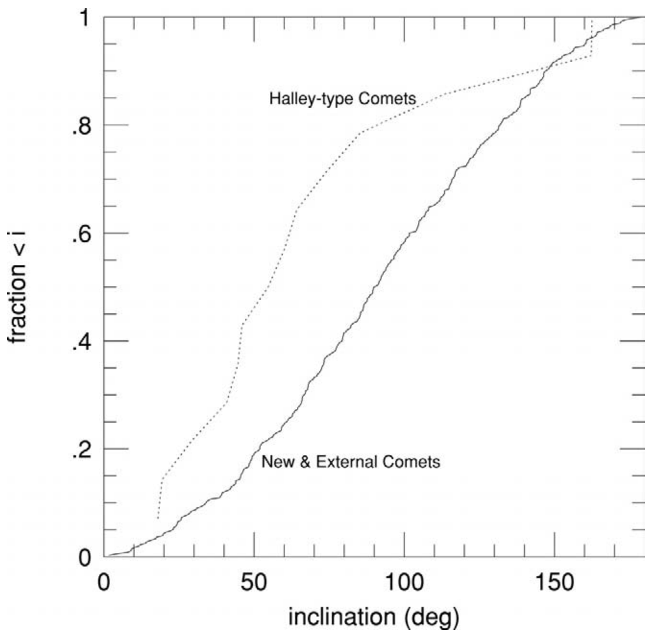

FIGURE 8 The cumulative inclination distribution of the nearly-isotropic comets in Marsden and Williams' catalog. We divide the population into two groups: Halley-types ($a < 40$ AU) and a combination of new and external comets.

Some become returning comets. Indeed, from modeling the inclination distribution of the Halley-type comets, we think that some objects from the inner regions of the Oort cloud eventually become NICs.

Figure 8 shows the cumulative inclination distribution for a combination of new and external comets (solid curve) and Halley-type comets (dotted curve). The solid curve is what would be expected from an isotropic Oort cloud. The curve follows a roughly sin (i) distribution, which has a median inclination of 90° and thus has equal numbers of prograde and retrograde orbits. It is these data that astronomers use to argue that the outer Oort cloud is basically spherical.

The inclination distribution of the Halley-type comets is quite different from that of the rest of the NICs. Almost 80% of Halley-type comets are on prograde orbits ($i < 90°$); the median inclination is only 55°. Numerical simulations of the evolution of comets from the Oort cloud to Halley-type orbits show that the inclination distribution of the comets is approximately conserved during the capture process. This means that the source region for these comets should have the same inclinations, on average, as the dotted curve in Figure 8. The only way to reconcile this with the roughly spherical shape of the outer Oort cloud is if the inner regions of the Oort cloud are flattened into a disk-like structure. Indeed, simulations suggest that the inner Oort cloud must have a median inclination of between 10 and 50° for it to match the observed inclination distribution of Halley-type comets. Figure 9 shows an artist's conception of what the Oort cloud may look like in cross-section.

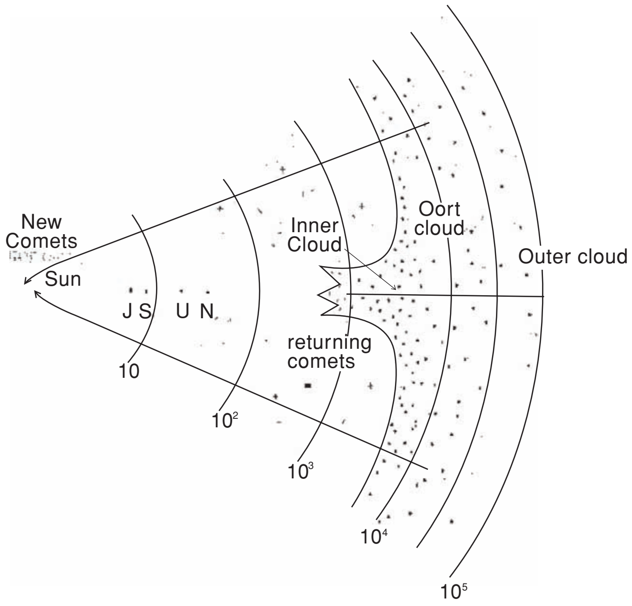

FIGURE 9 An artist's conception of the structure of the Oort cloud. In particular, the locations of the inner and outer edges of the Oort cloud, and where the cloud is flattened, are shown with respect to the location of the giant planets. Note that the radial distance from the Sun is spaced logarithmically. The location of the returning comets and the source for the new comets are also illustrated.

3.2 The Scattered Disk

To start the discussion of the scattered disk, we turn our attention back to Figure 5, which shows the semimajor axis–inclination distribution of the known comets. There is a clear concentration of comets on low-inclination orbits near $a \sim 4$ AU. Indeed, 27% of all the comets in the catalog lie within this concentration. As we described above, we call these objects ecliptic comets, and most are Jupiter-family comets.

Until the 1980s, the origin of these objects was a mystery. Even at that time it was recognized that the inclination distribution of comets does not change significantly as they evolve from long-period orbits inward. This is a problem for a model in which these comets originate in the Oort cloud, as most astronomers believed, because the median inclination of the Jupiter family is only 11°. So, dynamicists argued that Jupiter-family comets could not come from the Oort cloud, but must have originated in a flattened structure. Indeed, it was suggested that these objects originated in a disk of comets that extends outward from the orbit of Neptune. Spurred on by this argument, observers discovered the first trans-Neptunian object in 1992. Although this object is about a million times more massive then the typical ecliptic comet (it needs to be much larger than a typical comet, or we would not have seen it that far away), it was soon recognized that it was part of a population of objects both large and small—mainly small.

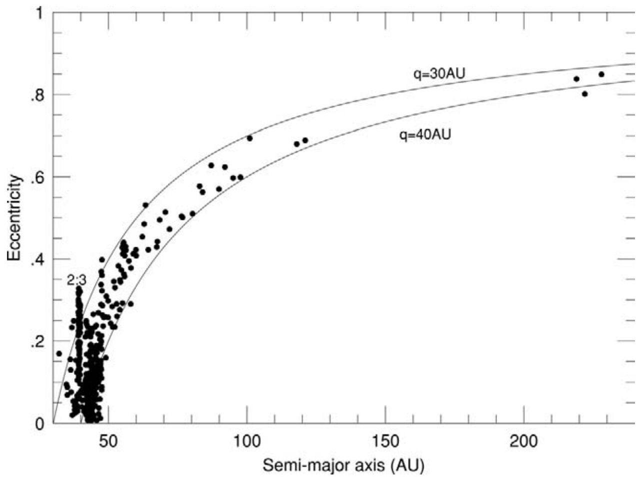

FIGURE 10 The eccentricity–semimajor axis distribution for the known trans-Neptunian objects with good orbits as of November 2005. We truncated the plot at 250 AU in order to resolve the inner regions better. Two curves of constant perihelion distance (q) are shown. In addition, the location of Neptune's 2:3 mean motion resonance is marked.

Since 1992, the trans-Neptunian region has been the focus of intense research, and over a thousand objects are now known to reside there. The diversity (both physical and dynamical) of its objects make it one of the most puzzling and fascinating places in the Solar System. As such, a complete discussion is beyond the scope of this chapter and, indeed, chapters on the Kuiper Belt are dedicated to this topic [*See* KUIPER BELT: DYNAMICS; KUIPER BELT OBJECTS: PHYSICAL STUDIES]. For our purposes, it suffices to say that the trans-Neptunian region is inhabited by at least two populations of objects that roughly lie in the same region of physical space, but have very different dynamical properties. These are illustrated in Figure 10, which shows the semimajor axis and eccentricity of all known trans-Neptunian objects with good orbits as of November 2005.

The first population of interest consists of those objects which are on orbits that are stable for the age of the Solar System. These objects mostly have perihelion distances (q) larger than 40 AU, or are in mean motion resonances with Neptune. Of particular note are the bodies in Neptune's 2:3 mean motion resonance, which are marked in the figure. Pluto is a member of this group. Even though some objects in the resonances are on orbits that cross the orbit of Neptune, they are stable because the resonance protects them from close encounters with that planet. All in all, we call this population the **Kuiper Belt**.[2]

The second population is mainly made up of objects with small enough perihelion distances that Neptune can push

[2] There are two meanings of the phrase "Kuiper Belt" in the literature. There is the one employed above. In addition, some researchers use the phrase to describe the entire trans-Neptunian region. In this case the term "classical Kuiper Belt" is used to distinguish the stable regions. We prefer the former definition.

them around as they go through perihelion. Because of this characteristic, we call this population the **scattered disk**. These are mainly nonresonant objects with $q < 40$ AU. [*See* KUIPER BELT: DYNAMICS for a more detailed definition.] Although most of the trans-Neptunian objects thus far discovered are members of the Kuiper Belt as defined here, it turns out that this is due to observational bias, and the Kuiper Belt and scattered disk contain roughly the same amount of material. In particular, the scattered disk contains about a billion objects that are comet-sized (roughly kilometer-sized) or larger.

Since the scattered disk is a dynamically active region, objects are slowly leaking out of it with time. Indeed, models of the evolution of scattered disk objects show that the scattered disk contained about 100 times more objects when it was formed roughly 4 billion years ago than it does today (see below). Objects can leave the scattered disk in two ways. First, they can slowly evolve outward in semimajor axis until they get far enough from the Sun that Galactic tides become important. These objects then become part of the Oort cloud. However, most of the objects evolve inward onto Neptune-crossing orbits. Close encounters with Neptune can then knock an object out of the scattered disk. Roughly one comet in three that becomes Neptune-crossing, in turn, evolves through the outer planetary system to become a Jupiter-family comet for a small fraction of its lifetime.

Figure 11 shows what we believe to be the evolution of a typical scattered disk object as it follows its trek from the scattered disk to the Jupiter family and out again. The figure shows this evolution in the perihelion distance (q) – aphelion distance (Q) plane. The positions are joined by blue lines until the object first became "visible" (which we take to be $q < 2.5$ *AU*) and are linked in red thereafter. Initially, the object spent considerable time in the scattered disk, i.e., with perihelion near the orbit of Neptune (30 AU) and aphelion well beyond the planetary system. However, once an object evolves inward, it tends to be under the dynamical control of just one planet. That planet will scatter it inward and outward in a random walk, typically handing it off to the planet directly interior or exterior to it. Because of the roughly geometric spacing of the giant planets, comets tend to have eccentricities of about 25% between "handoffs" and spend a considerable amount of time with perihelion or aphelion near the semimajor axis of Saturn, Uranus, or Neptune.

However, once comets have been scattered into the inner Solar System by Jupiter, they can have much larger eccentricities as they evolve back outward. The postvisibility phase of the object in Figure 11 is reasonably typical of Jupiter-family comets, with much larger eccentricities than the previsibility comets and perihelion distances near Jupiter or Saturn. This object was eventually ejected from the Solar System by a close encounter with Saturn.

Numerical models, like the one used to create Figure 11, show that most of the ecliptic comets and Centaurs most likely originated in the scattered disk. Figure 12 shows the distribution of the ecliptic comets derived from these simulations. The figure is a contour plot of the relative number of comets per square AU in perihelion-aphelion ($q - Q$) space. Also shown are the locations of 95P/Chiron and 2P/Encke (big dots marked "C" and "E", respectively), and the known Jupiter-family comets (small gray dots).

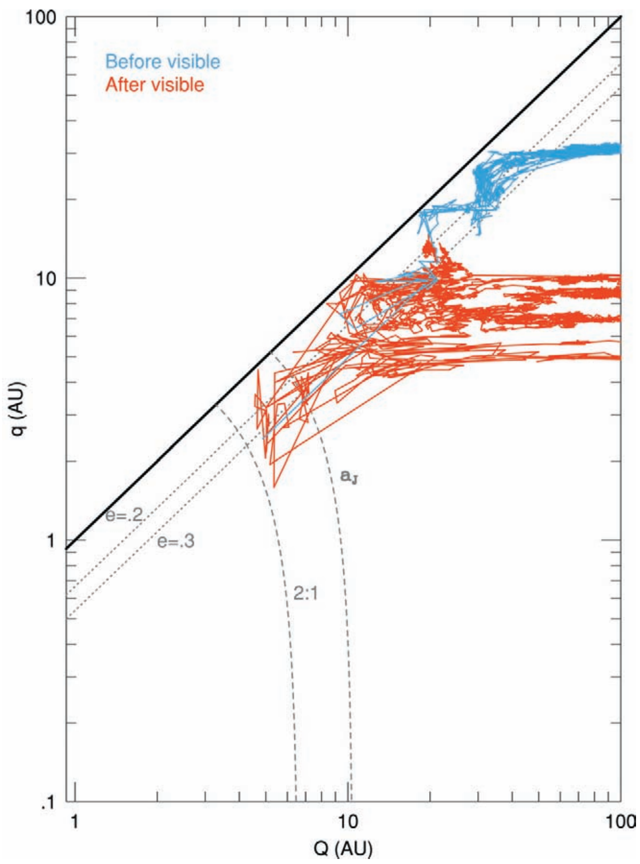

FIGURE 11 The orbital evolution of a representative object originating in the scattered disk. In particular, the locations of the object's orbit in the $q - Q$(perihelion-aphelion) plane are joined by blue lines until the object became "visible" ($q < 2.5$ AU) and are linked in red thereafter. The sampling interval was every 10,000 years in the previsibility phase and every 1000 years thereafter. Also shown in the figure are three lines of constant eccentricity at $e = 0$, 0.2, and 0.3. In addition, we plot two dashed curves of constant semimajor axis, one at Jupiter's orbit and one at its 2:1 mean motion resonance. Note that it is impossible for an object to have $q > Q$, so objects cannot move into the region above and to the right of the solid diagonal line.

There are two well defined regions in Figure 12. Beyond approximately $Q = 7$ AU, there is a ridge of high density extending diagonally from the upper right to the center of the plot, near $e \approx 0.25$. The peak density in this ridge drops by almost a factor of 100 as it moves inward, having a minimum where the semimajor axes of the comets are the same as Jupiter's (shown by a dotted curve and marked with a_J). This region of the plot is inhabited mainly by the Centaurs. Inside of $Q \approx 7$ AU, the character of the distribution is quite different. Here there is a ridge of high density extending vertically in the figure at $Q \sim$ 5–6 AU that extends over a wide range of perihelion distances. Objects in this region are the Jupiter-family comets. This characteristic of a very narrow distribution in Q is seen in the real Jupiter-family comets and is a result of the narrow range in T which, in turn, comes from the low to moderate inclinations and eccentricities of bodies in the scattered disk.

Figure 12 shows the relationship between the Centaurs and the Jupiter-family comets and illustrates the distribution of objects throughout the outer Solar System. The simulations predict that the inclinations of this population should be small everywhere, which is consistent with observations.

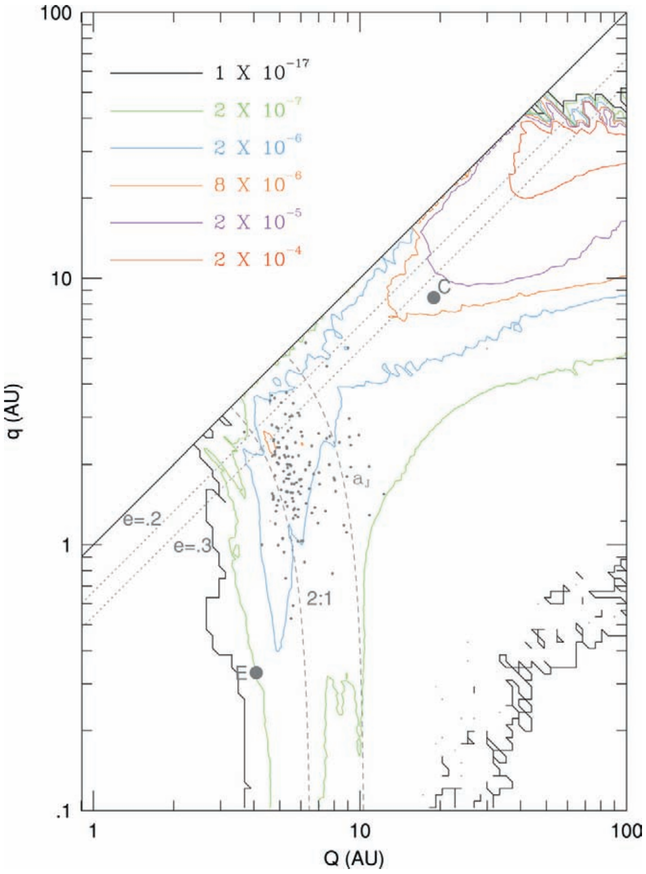

FIGURE 12 A contour plot of the relative distribution of ecliptic comets in the solar system as a function of aphelion (Q) and perihelion (q). The units are the fraction of comets per square AU in $q - Q$ space. Also shown in the figure are three lines of constant eccentricity at $e = 0$ (solid), 0.2, and 0.3 (both dotted). In addition, we plot two dashed curves of constant semimajor axis, one at Jupiter's orbit and one at its 2:1 mean motion resonance. They gray dots labeled "E" and "C" show the locations of comets 2P/Encke and 95P/Chiron. The small gray dots show the orbits of the Jupiter-family comets.

3.3 Formation of the Oort Cloud and Scattered Disk

Let us take stock of where we have come thus far. Active comets can be divided into two groups based on the value of the Tisserand parameter, T. The nearly isotropic comets have $T < 2$ and originate in the Oort cloud. The ecliptic comets have $T > 2$ and originate in the scattered disk. The Oort cloud is a population of comets that lie very far from the Sun, with semimajor axes extending from tens of thousands of AU down to thousands of AU. It also is roughly spherical in shape. The scattered disk, on the other hand, lies mainly interior to ~1000 AU and is flattened. It may be surprising, therefore, that modern theories suggest that both of these structures formed as a result of the same process and therefore the objects in them formed in the same region of the Solar System.

First, we must address why we think that these structures did not form where they are. The answer has to do with the comets' eccentricities and inclinations. Although comets are much smaller than planets, they probably formed in a similar way. The Solar System formed from a huge cloud of gas and dust that initially collapsed to a protostar surrounded by a disk. The comets, asteroids, and planets formed in this disk. However, initially the disk only contained very small solid objects, similar in size to particles of smoke, and much smaller than comets. Although it is not clear how these objects grew to become comet-sized, all the processes thus far suggested require that the relative velocity between the dust particles was small. This, in turn, requires the dust particles to be on nearly circular, coplanar orbits. So, the eccentric and inclined orbits of bodies in the cometary reservoirs must have arisen because they were dynamically processed from the orbits in which they were formed to the orbits in which they are found today.

Astronomers generally agree that comets originally formed in the region of the Solar System now inhabited by the giant planets. Although comets formed in nearly circular orbits, their orbits were perturbed by the giant planets as the planets grew and/or the planets' orbits evolved. Figure 13 shows the behavior of a typical comet as it evolves into the Oort cloud. At first, the comet is handed off from planet to planet, remaining in a nearly circular orbit (Region 1 in the figure). However, eventually Neptune scatters the body outward. It then goes through a period of time when its semimajor axis is changing due to encounters with Neptune (Region 2). During this time its perihelion distance is near the orbit of Neptune, but its semimajor axis can become quite large. (If this reminds you of the scattered disk, it should.) When the object gets into the region beyond 10,000 AU, galactic perturbations lift its perihelion out of the planetary system, and it is then stored in the Oort cloud for billions of years (Region 3).

Figure 14 shows the result of a numerical model of the formation of the Oort cloud and scattered disk. The simulation followed the orbital evolution of a large number of

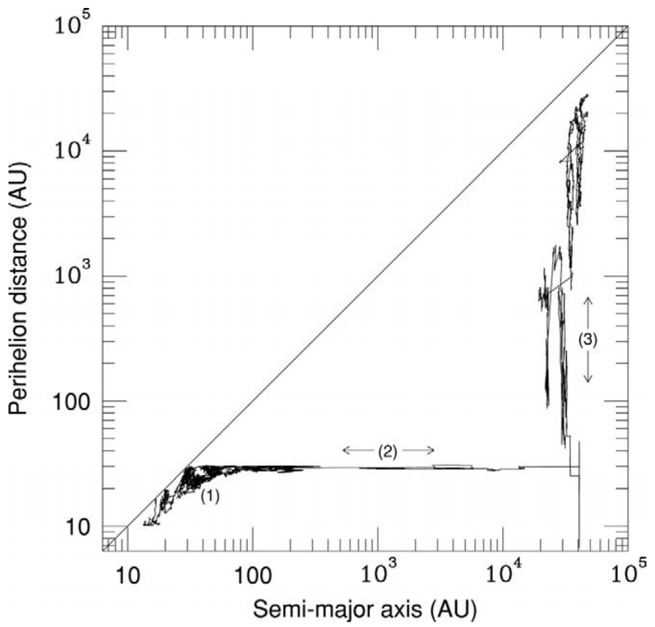

FIGURE 13 The dynamical evolution of an object as it evolves into the Oort cloud. The object was initially in a nearly circular orbit between the giant planets. Its evolution follows three distinct phases. During Phase 1 the object remains in a relatively low eccentricity orbit between the giant planets. Neptune eventually scatters it outward, after which the object undergoes a random walk in semimajor axis (Phase 2). When it reaches a large enough semimajor axis, galactic perturbations lift its perihelion distance to large values (Phase 3).

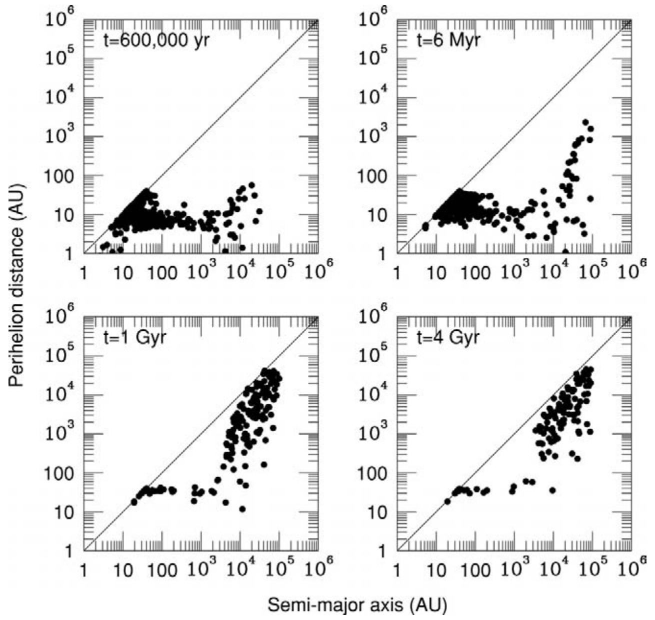

FIGURE 14 Four snapshots of comets in a simulation of the formation of the scattered disk and the Oort cloud.

comets initially placed on nearly-circular, low-inclination orbits between the giant planets, under the gravitational influence of the Sun, the four giant planets, and the Galaxy. The major steps of Oort cloud formation can be seen in this figure. Initially the giant planets start scattering objects to large semimajor axes. By 600,000 years, a massive scattered disk has formed, but only a few objects have evolved far enough outward that Galactic perturbations are important.

At $t = 6$ million years the Oort cloud is beginning to form. The Galactic perturbations have started to raise the perihelion distances of the most distant comets, but a complete cycle in q has yet to occur (see Fig. 3). Note that the scattered disk is still massive. By 1 billion years, the Oort cloud beyond 10,000 AU is inhabited by objects on moderate-eccentricity orbits (i.e., where $a \sim q$). Note also that a scattered disk still exists. There is also a transition region between ~2,000 AU and ~ 5,000 AU, where objects are beginning to have their perihelia lifted by the Galaxy, but have not yet undergone a complete cycle in perihelion distance. By 4 billion years, the Oort cloud is fully formed and extends from 3000 AU to 100,000 AU. The scattered disk can easily be seen extending from Neptune's orbit outward. If our current understanding of comet reservoirs is correct, these are the two source reservoirs of all the known visible comets.

The above calculations assume that the Sun has always occupied its current Galactic environment, i.e., it is isolated and not a member of a star cluster. However, almost all stars form in dense clusters. The gravitational effects of such a star cluster on a growing Oort cloud is similar to that of the Galaxy except that the torques are much stronger. This would lead to an Oort cloud that is much more compact if the Sun had been in such an environment at the time that the cloud was forming. However, models of the dynamical evolution of star clusters show that the average star spends less than 5 million years in such an environment and the giant planets might take that long to form. Additionally, even if the planets formed very quickly, Figure 14 shows that the Oort cloud is only partially formed after a few million years. In particular, only those objects that originated in the Jupiter-Saturn region have evolved much in semimajor axis. Therefore, the Oort cloud probably formed in two stages. Before ~5 Myr a dense *first generation* Oort cloud formed from Jupiter-Saturn planetesimals at roughly $a \sim 1{,}000$ AU due to the effects of the star cluster. After the Sun left the cluster, a normal Oort cloud formed at $a \sim 10{,}000$ AU from objects that originated beyond Saturn. Figure 15 shows an example of such an Oort cloud as determined from numerical experiments. There is some observational evidence that the Solar System contains a first generation Oort cloud. In 2004, the object known as Sedna was discovered. Sedna has $a = 468\,AU$ and $q = 76\,AU$, placing it well beyond the planetary region. Numerical experiments have shown that the most likely way to get objects with perihelion distances as large as Sedna is through external torques (as in Fig. 15).

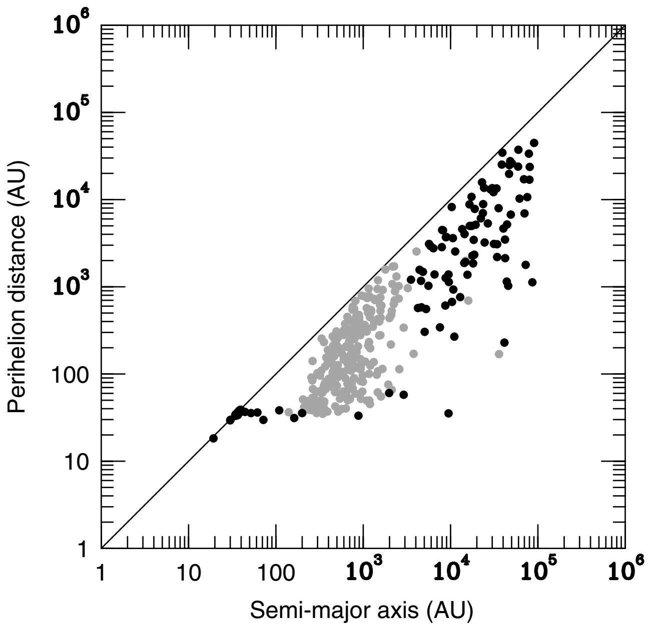

FIGURE 15 The final distribution of comets in the scattered disk and the Oort cloud according to a numerical experiment where the Sun spent 3 Myr in a star cluster. The grey and black dots refer to objects that formed interior to or exterior to 14 AU.

And, since the current Galactic environment is too weak to place Sedna on its current orbit, Sedna's orbit probably formed when the Sun was in its birth star cluster. If true, Sedna's orbit represents the first observational constraint we have concerning the nature of this star cluster. If such a structure really exists, it does not contribute to the population of observed comets because it is in a part of the Solar System which is currently stable: objects in this region do not get close to the planets and the Galactic tides are too weak.

4. Conclusions

Comets are only active when they get close to the Sun. However, they must come from more distant regions of the Solar System where it is cold enough for them to survive the age of the Solar System without sublimating away. Dynamical simulations of cometary orbits argue that there are two main source regions in the Solar System. One, known as the Oort cloud, is a roughly spherical structure located at heliocentric distances of thousands to tens of thousands of AU. The nearly isotropic comets come from this reservoir. The scattered disk is the other important cometary reservoir. It is a disk-shaped structure that extends outward from the orbit of Neptune. The ecliptic comets come from the scattered disk.

However, there are substantial reasons to believe that these two cometary reservoirs are not primordial structures and that their constituent members formed elsewhere and were dynamically transported to their current locations. Indeed, current models suggest that objects in both the Oort cloud and scattered disk formed in the region between the giant planets and were delivered to their current locations by the action of the giant planets as these planets formed and evolved. Comets, therefore, represent the leftovers of planet formation and contain vital clues to the origin of the Solar System.

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