✧ CHAPTER 1 ✧

Earth's Closest Neighbors

The dinosaurs became extinct because they
didn't have a space program.
—Larry Niven

Michelle Knapp and Her 1980 Chevrolet Malibu

Let me introduce Michelle Knapp of Peekskill, New York, and her 1980 Chevy Malibu sedan. On a rainy Friday night, October 9, 1992, just before 8:00 PM, Michelle, an eighteen-year-old high school senior, heard a loud crash in her driveway and raced outside to discover the rear end of her automobile had been completely destroyed by a football-sized rock. The twenty-seven-pound projectile had punched completely through the trunk, just missing the gas tank.

As unlikely as it sounds, a fragment of a near-Earth asteroid that had collided with Earth destroyed Michelle's car. The fiery trail of the initial, Volkswagen-sized, near-Earth asteroid was first seen over West Virginia appearing with a greenish hue and brighter than the full Moon. Due to the forces of the atmospheric resistance, the asteroid fragmented into more than seventy pieces while traveling northeast for more than forty seconds over Pennsylvania and then New York. The only known surviving fragment came to a full stop underneath Michelle's Chevy Malibu. Countless people, many of whom were watching high school football games that Friday evening, observed the fiery train of fragments in the Pennsylvania and New York skies.

FIGURE 1.1. Michelle Knapp and her 1980 Chevy Malibu. After a small asteroid entered the Earth's atmosphere on October 9, 1992, it caused a spectacular fireball event traveling northeast over parts of West Virginia, Pennsylvania, and New York before coming to rest underneath Michelle's 1980 Chevrolet Malibu sedan.
Source: Courtesy of John E. Bortle, W. R. Brooks Observatory.

Although Michelle's automobile insurance company refused to pay for her car's damages, claiming that it was an act of God, she got the last laugh by selling the so-called Peekskill meteorite and the twelve-year-old Chevy to a consortium of three meteorite collectors for $69,000.

On a daily basis, at least one hundred tons of interplanetary material rain down upon the Earth's atmosphere, but most of it is in the form of very small dust particles or very small stones. Much of this dust and sand grain–sized material, the debris from active comets, can be seen on almost any clear, dark night as meteors or shooting stars. Larger basketball-sized rocks rain down upon the Earth daily and while they can cause impressive fireball events, our atmosphere prevents almost all of them from reaching the ground intact. Volkswagen-sized asteroids, like the one that fragmented and caused the Peekskill meteorite, strike

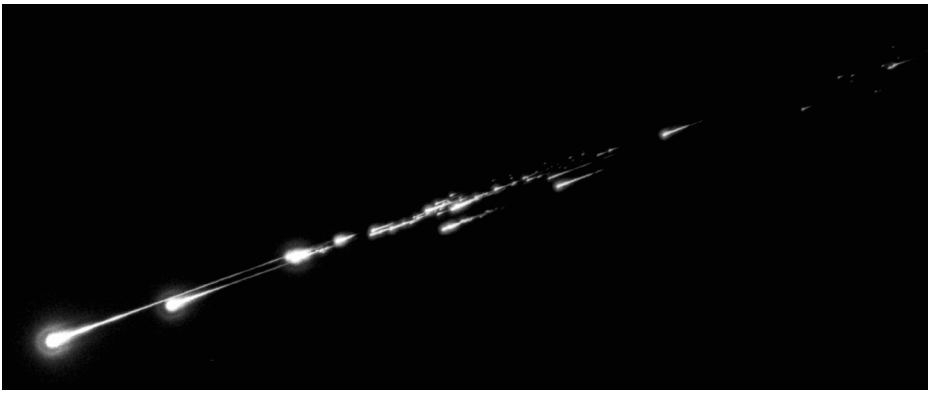


FIGURE 1.2. Because of the atmospheric pressure, the small asteroid that created the Peekskill fireball event fragmented into more than seventy pieces in the Earth's atmosphere. This image was taken from Mansion Park football stadium in Altoona, Pennsylvania. Only a single meteorite was located on the ground.
Source: S. Eichmiller of the *Altoona Mirror*.

the Earth's atmosphere every six months or so on average. At this point, you may be incredulous because you may not have ever seen a fireball and probably not a major fireball like the Peekskill event. But the vast majority of the Earth's surface is either ocean or unpopulated and besides, how often do you monitor the skies all night? Department of Defense satellites do, however, continuously monitor the skies and detect fireballs, as they look downward, twenty-four hours each day, to provide alerts of possible missile launch events and nuclear explosions.

Mr. S. B. Semenov Gets Blown off His Porch

Allow me to introduce Mr. S. B. Semenov, who was an eyewitness to a larger Earth-impacting near-Earth asteroid on June 30, 1908, in a remote region of Russian Siberia called Tunguska.

Mr. Semenov, a farmer, was sitting at a trading post when he noticed what appeared to be a fire high and wide over the local forest. A loud and strong shock ensued, blowing him a few meters off the trading post

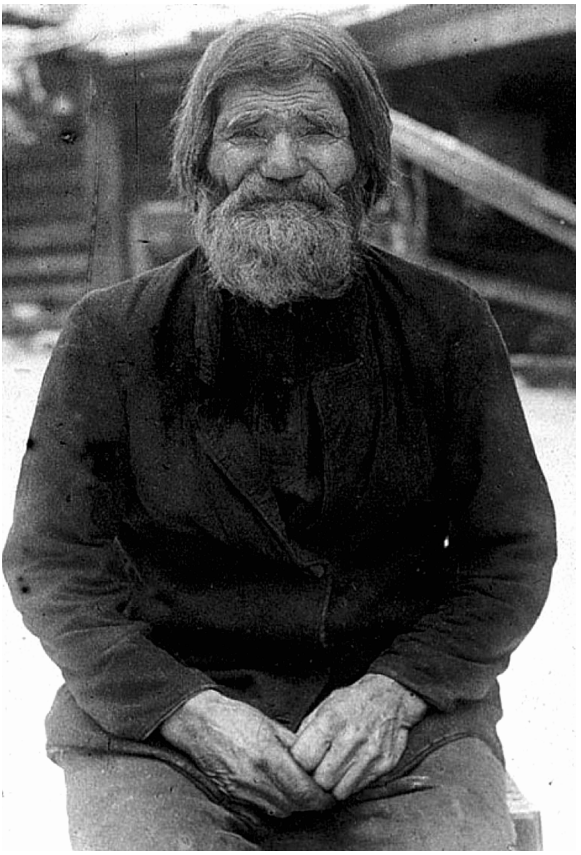


FIGURE 1.3. Mr. S. B. Semenov, eyewitness to the Tunguska blast of June 30, 1908. Although he was sixty-five kilometers distant from the blast site, he was thrown off a porch and related that his shirt felt like it was on fire.
Source: Courtesy of E. L. Krinov.

porch. He noted that the heat from the blast felt like his shirt was on fire, even though he was located about sixty-five kilometers south of ground zero. Although a wide variety of suggestions have been made to explain the Tunguska event, including the absurd notions that the blast was due to a UFO crash or an overzealous signal greeting by aliens, by far the most likely cause of the Tunguska blast was an atmospheric impact by a near-Earth asteroid. Most likely, a thirty-meter-sized asteroid entered the Earth's atmosphere and reached an altitude

of about eight kilometers before the atmospheric pressure in front of the stony object "pancaked" the rock, causing it to explode above the forest floor. A tremendous blast wave then continued to the surface, and an area that spanned some two thousand square kilometers of forest, involving millions of trees, was leveled. But since the stony asteroid itself disintegrated in the air blast explosion and did not reach the ground, no crater was evident on the forest floor and no sizable meteorites were left near ground zero. Current estimates place the energy of the event at about four million tons (four megatons) of TNT high explosives.[1] Considering there are more than a million of these asteroids, thirty meters and larger, in the Earth's neighborhood, one would expect an asteroid of this size or larger to strike the Earth every few hundred years. Thirty meters, or Tunguska-sized, is about the minimum diameter of an Earth impactor that could cause significant ground damage. In general, smaller stony objects would not be expected to survive passage through the Earth's atmosphere.

The Dinosaurs Check Out Early

At the upper end of the near-Earth object sizes are about one thousand asteroids larger than one kilometer in diameter, and an Earth impact by one of these asteroids would be capable of causing global devastation. Fortunately asteroids of this size would not be expected to strike Earth but every seven hundred thousand years on average, and NASA's ongoing search programs have already found more than 90 percent of this population. None of them represents a credible threat during the next century. The very largest near-Earth objects are as large as ten kilometers in diameter. Sixty-five million years ago, one of them killed much of the land and sea flora and fauna along with almost all of the large vertebrates on land and at sea. Most species were exterminated. Crater evidence for this major extinction event has been found near Chicxulub on the edge of the Mexican Yucatán peninsula. A ten-kilometer impactor could cause a so-called extinction event because it

[1] Chapter 8 goes into more detail on the Tunguska event of 1908.

would subject the Earth to global firestorms, severe acid rain, and the darkening of the skies with soot and impact-created debris. The resultant loss of photosynthesis would cause plants to die along with the animals and marine life that depend upon these plants for food. After more than a 160-million-year run, the large land dinosaurs could not survive this impact event because of the complete disruption of their food chain. An Earth impact by a ten-kilometer-sized near-Earth object would create an impact of unimaginable energy—equivalent to some fifty million megatons of TNT. To put that in perspective, that amount of energy would be equivalent to a Hiroshima-type nuclear blast every second for about 120 years! This underscores the statement that while large near-Earth object impacts are very rare, they are extremely high-consequence events capable of ending civilization as we know it.[2]

One of NASA's goals is to discover and track the vast majority of the relatively large near-Earth asteroids and comets that would be capable of threatening Earth or causing a local or regional disaster. If we find them early enough, we now have the technology to deal with them. For example, a massive spacecraft could be directed to purposely run into an Earth-threatening asteroid of modest size to slow it down and alter its trajectory just enough so that it would no longer threaten Earth. As it turns out, the dinosaurs became extinct because they didn't have a space program.

Just What Are Comets, Asteroids, Meteoroids, Meteors, and Meteorites?

In interplanetary space, a large rocky body in orbit about the Sun is referred to as an asteroid or sometimes a minor planet. They are inactive and, unless struck by another nearby asteroid, they do not shed material like their cousins the comets. Comets differ from most asteroids in that they are icy dirtballs. When they approach the Sun, their ices (mostly water ice) are warmed by the Sun so they begin to

[2] Chapter 4 goes into more detail on the extinction event that took place sixty-five million years ago.

vaporize and release the dust particles that were once embedded in their ices. Inactive comets that have exhausted their supply of ices near the surface or have their ices covered and insulated by more rocky material are no longer termed comets but asteroids. The only real difference between a comet and an asteroid is that comets, when near the Sun, are actively losing their ices and dust, often causing a highly visible trail of dust and gas, and asteroids are not. Even objects that are icy, like some asteroids and other bodies in the outer solar system, are just classified as asteroids since they do not get close enough to the Sun for their ices to vaporize. They are not active and hence they are not comets. Since the physical makeup of an active icy body (comet) near the Sun can be identical to an inactive icy body (asteroid) that is farther from the Sun, the line between comets and asteroids cannot be clearly drawn.

Small collision fragments of inactive asteroids or the dusty debris from active comets in orbit about the Sun are called meteoroids if their sizes are between ten microns, the width of a cotton fiber, and one meter in diameter. Once a tiny meteoroid enters the Earth's atmosphere and vaporizes due to atmospheric friction, it emits light that causes a meteor or "shooting star." Almost all meteors are due to cometary sand- or pebble-sized particles while small asteroids or large meteoroids can cause much brighter fireball events in the Earth's atmosphere. Fireball events can range in brightness from just brighter than the brightest planets to events that briefly rival the Sun. If a fragment of the impacting body survives its passage through the Earth's atmosphere and lands upon the Earth's surface, it is then called a meteorite.

The Near-Earth and Potentially Hazardous Objects

Astronomers refer to the approximate average distance between the Sun and Earth as an astronomical unit (AU), which is a distance of about 150 million kilometers or 93 million miles. Near-Earth objects are simply defined as comets and asteroids that approach the Sun to within 1.3 AU so therefore they can also approach the Earth's orbit to within 0.3 AU if their orbits are close to the same plane as that of the

Earth. The so-called potentially hazardous objects are a subset of the near-Earth objects that approach the Earth's orbit to within 0.05 AU, which is roughly the distance that a near-Earth object's trajectory can be gravitationally altered by a single planetary encounter. These objects would have to be about 30 meters in size or larger to cause significant damage at the Earth's surface.

Although sizable near-Earth asteroids outnumber near-Earth comets by more than one hundred to one, the solid nuclei of comets may provide the very largest impactors like the one that took out the dinosaurs. Cometary debris is also the source of most tiny meteoroid particles and meteors. Many comets generate meteoroid streams when their icy cometary nuclei pass near the Sun, begin to vaporize, and release the dust, sand-sized particles, and fragile clumps that were once embedded in the cometary ices. These meteoroid particles then follow in the wake of the parent comet. When the Earth, in its orbit about the Sun, runs into this dusty debris from active comets, meteor showers can be observed. Sometimes hundreds and even thousands of meteors, or shooting stars, can be seen within an hour when the Earth collides with a particularly dense band of meteoroids. The annual August Perseid showers occur when the Earth runs into small particles from comet Swift-Tuttle while the November Leonid showers are caused by the debris from comet Tempel-Tuttle.

Occasional collisions between asteroids in the main asteroid belt located between the orbits of Mars and Jupiter create asteroid fragments, and it is these fragments that are the sources of most near-Earth objects. These fragments are also the source of most Earth-impact events and the meteorites that have survived these violent collisions with Earth. As time goes by, asteroids colliding with one another in the inner planetary region produce more and more smaller fragments while reducing the number of larger ones. As a result, we are fortunate that the vast majority of near-Earth objects that collide with Earth are far too small to survive the Earth's atmosphere and there are relatively few objects in near-Earth space that are large enough to cause global consequences upon impact with the Earth.

Because they are readily available for study, many meteorites have already been subjected to detailed chemical and physical analyses in

laboratories. If particular asteroids can be identified as the sources for some of the well-studied meteorites, a detailed knowledge of the meteorite's composition and structure will provide important information on the chemical mixture and conditions from which the parent asteroid formed 4.6 billion years ago.

The Orbits of Near-Earth Objects

There are four orbital classes of near-Earth asteroids with membership in each class being determined by a particular asteroid's orbital characteristics compared to the Earth's orbit. The Earth's orbit about the Sun is nearly circular—but not quite. An orbit's eccentricity (e) is a measure of the orbit's departure from a circle. For a circular orbit, e = 0, and as the orbit gets more and more elongated, or eccentric, the eccentricity increases toward one. An open parabolic orbit has an eccentricity of one and a hyperbolic orbit greater than one. Earth's orbital eccentricity is 0.0167. Earth reaches its closest point to the Sun (perihelion) in early January at a heliocentric distance of about 0.983 AU while it

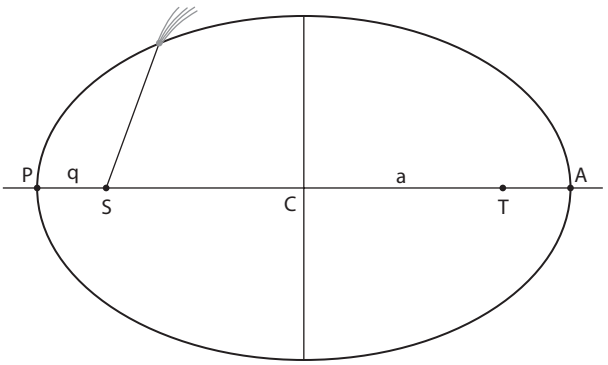


FIGURE 1.4. Some orbital characteristics. The Sun (S) is located at one of the two foci of the asteroid's elliptical orbit. Half the long, or major, axis of the ellipse is termed the semi-major axis (CP). The ratio of the distances CS to CP is the orbital eccentricity. The perihelion distance (SP) is usually denoted as "q" while the aphelion distance (SA) is denoted "Q."

TABLE 1.1. *Definitions of near-Earth objects*

Asteroid	A relatively small, inactive, (usually) rocky body orbiting the Sun
Comet	A relatively small, at times active object whose ices can vaporize in sunlight, forming an atmosphere (coma) of dust and gas and, sometimes, tails of dust and gas
Meteoroid	A small particle from a comet or asteroid that is orbiting the Sun and is less than one meter in extent
Meteor	The atmospheric light phenomenon that results when a meteoroid enters the Earth's atmosphere and vaporizes
Fireball	An event that is brighter than a meteor ranging in brightness from just brighter than the brightest planets to approaching the brightness of the Sun
Meteorite	A meteoroid that survives its passage through the Earth's atmosphere and lands upon the Earth's surface
Near-Earth Object	A comet or asteroid that can approach the Sun to within 1.3 AU. In order for a body to be classified as a near-Earth object, it must have an orbital period less than 200 years
Potentially Hazardous Object	A comet or asteroid that can approach the Earth's orbit within 0.05 AU or about 7.5 million kilometers and is large enough to cause impact damage

reaches its farthest point from the Sun (aphelion) in early July at a distance of about 1.017 AU.[3] An object's perihelion and aphelion distances are usually denoted with the letters "q" and "Q," respectively. The distance of the longest axis of a celestial object's orbit is termed its major axis and, not surprisingly, the semi-major axis (a) is one-half this

[3] The Earth is closest to the sun when it is winter in the northern hemisphere and farthest from the sun when it is summer there. This underscores the fact that the seasons have more to do with the orientation of the Earth's rotation pole than its distance from the sun. During summer in the northern hemisphere, the Earth's rotation pole is oriented more toward the sun than in winter so the sun is more nearly overhead with more concentrated sunlight than in the winter months.

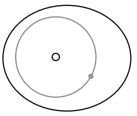
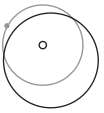
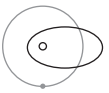
Near Earth Object Orbit Classes	Orbit Criteria	
Amors	Earth approaching asteroids with orbits exterior to Earth's but interior to the orbit of Mars. Hence their semi-major axes are larger than 1.0 AU and their perihelia are between 1.017 and 1.3 AU.	
Apollos	Earth orbit crossing asteroids with semi-major axes larger than Earth's (a is larger than 1.0 AU) and with perihelia less than 1.017 AU.	
Atens	Earth orbit crossing asteroids with their semi-major axes smaller than Earth's and their aphelia larger than 0.983 AU.	
Atiras	Asteroids with their orbits contained entirely within that of the Earth. Hence their semi-major axes are less than 1 AU and their aphelia are less than 0.983 AU.	

FIGURE 1.5. The four heliocentric orbit classifications for the near-Earth asteroids.

distance. These terms are mathematically related to one another and for closed elliptical orbits, the perihelion distance $q=a(1-e)$ and the aphelion distance $Q=a(1+e)$.

In 1619, the German astronomer Johannes Kepler put forward a fundamental law of planetary motion, which can be expressed as the square of the orbital period (P), in years, is equal to the orbital semi-major axis (a) in AU raised to the power of three. For example, a near-Earth object with a semi-major axis of 2 AU would have an orbital period of 2.8 years (i.e., $2.8 \times 2.8 = 2 \times 2 \times 2$). Some near-Earth asteroids and many comets have orbits that are highly inclined to the plane of the Earth's orbit about the Sun, the plane called the ecliptic. The highest orbital inclination for a planet is seven degrees for Mercury.

The four groups of near-Earth asteroid orbits have real bodies as their namesakes. There is the Earth orbit crossing Apollo group named after asteroid (1862) Apollo, the Earth orbit approaching Amor group named after (1221) Amor, the Earth orbit crossing Aten group, named after (2062) Aten, whose semi-major axes are smaller than that of the Earth's

orbit, and finally the Atira group, named after (163693) Atira, whose orbits lie entirely within the Earth's orbit. It is some members of the Aten and Atira orbit groups that are most similar to the Earth's orbit and hence they are, at the same time, the most easily reached asteroids using spacecraft and the ones most likely to run into the Earth.

Rock Stars: Naming Asteroids

There are more than half a million known asteroids in the region between the orbits of Mars and Jupiter and several thousand known near-Earth objects of various sizes in the Earth's neighborhood. These numbers are rapidly growing as more and more of them are discovered. Currently, more than three thousand asteroids a month are being discovered and dozens of these monthly discoveries are in the near-Earth object population.

When a comet is discovered, it is usually named for the discoverer or the discovery program and given a temporary designation to indicate the year and time of year of the discovery. The year of discovery is followed by a letter to denote the half-month during which the discovery took place (I and Z are not used, reducing the alphabet to twenty-four letters). A comet designated 2011 A2 would indicate the comet was the second comet (2) discovered during the first half of January (A) in 2011. Periodic comet Swift-Tuttle was discovered on July 16 by Lewis Swift in Marathon, New York, and independently three days later by Horace Tuttle at Harvard College.[4] Its designation is then P/1862 O1 because it was the first comet discovered in the second half of July 1862. The "P" designates it as a periodic comet that returns on a regular basis. Once there are a sufficient number of observations to allow a secure orbit to be determined, then periodic comets are permanently numbered sequentially (e.g., 1P/Halley, 109P/Swift-Tuttle).

[4] Horace Tuttle (1837–1923), a co-discoverer on both of these comets, was during his checkered career a successful astronomer and a Civil War hero; he was also convicted of embezzlement by the U.S. Navy and dismissed for "scandalous conduct tending to the destruction of good morals." See D. K. Yeomans, *Comets: A Chronological History of Observation, Science, Myth and Folklore* (New York: John Wiley and Sons, 1991), 238–39.

In a similar fashion, asteroids are first given preliminary designations according to the year, half-month, and discovery number within that particular half-month. Then, once the asteroid has been well observed and its orbit is secure, the asteroid is given a sequential number. Once an asteroid is given a permanent number, the discoverer has the privilege to name it after a person, place, or thing of his or her choice. Politicians and military figures who have not been dead for one hundred years are ground-ruled out. So are pets and attempts to sell an asteroid name.[5] These "rules" have not been in place that long and sometimes they are not enforced too rigorously, so there are, in fact, asteroids named after three dogs and a cat. With so many asteroid names, there are ample opportunities for unabashed silliness. For example, one could string together the names of the asteroids whose numbers are 9007, 673, 449, 848, and 1136 and arrive at "James Bond Edda Hamburga Inna Mercedes."

There is a certain amount of immortality associated with having your name on an asteroid because it will outlast you by millions of years. Asteroid 2956 Yeomans, a nine-kilometer-sized silicate rock, will be circling the Sun between the orbits of Mars and Jupiter long after this author is dead and gone. Asteroid names are often associated with important scientists, significant artists, adored musicians, and classical composers like (2001) Einstein, (6701) Warhol, (8749) Beatles, and (1814) Bach.

The Importance of Near-Earth Objects

The relatively small comets and asteroids that make up the near-Earth object population are not just poor cousins to the much larger planets. They are the remnants of the planetary formation process itself, and as

[5] Asteroid names are approved by the Committee for Small Body Nomenclature of the International Astronomical Union. They are official and permanent. However, for a fee, a number of companies will sell you a fancy certificate that claims to somehow associate your name with a star, but these names are not official and not recognized by any international scientific organization. Apart from a few bright, historic stars that carry official names like Sirius, Betelgeuse, and Rigel, no stars have names, just numerical designations.

the least changed bodies from that process they offer clues to the chemical and thermal conditions under which the planets formed some 4.6 billion years ago. They also likely laid down a veneer of the carbon-based materials and water to the early Earth, thus allowing life to form. Subsequent collisions punctuated evolution, allowing only the most adaptable species, including the mammals, to evolve further. In some sense we owe our very existence and our position atop the food chain to these objects that are, from time to time, our very closest neighbors.

Near-Earth objects also represent potential targets for future human exploration and resources for interplanetary habitats. They are rich in metals and minerals that can be used to build interplanetary shelters and habitats. Their hydrated, or clay, minerals and ices can be used to provide life-giving water and the water can be broken down into hydrogen and oxygen, the most efficient form of rocket fuel. These near-Earth objects may one day act as interplanetary watering holes and fueling stations.

In April 2010 President Obama asked NASA to identify a human exploration mission to a near-Earth asteroid as a stepping-stone mission for the human exploration of Mars. The necessary space technologies and mission risks associated with a several-year human mission to Mars could be tested with a much safer and relatively quick visit to a nearby asteroid. Ironically, the easiest near-Earth asteroids to reach for human exploration are also in orbits that make them the most dangerous in terms of potential future Earth close approaches. The knowledge gained on the asteroid's structure and composition resulting from the human exploration of a near-Earth asteroid could be put to good use, not only for a future human exploration of Mars but also if one of these asteroids were found to be on an Earth-impact threatening trajectory.