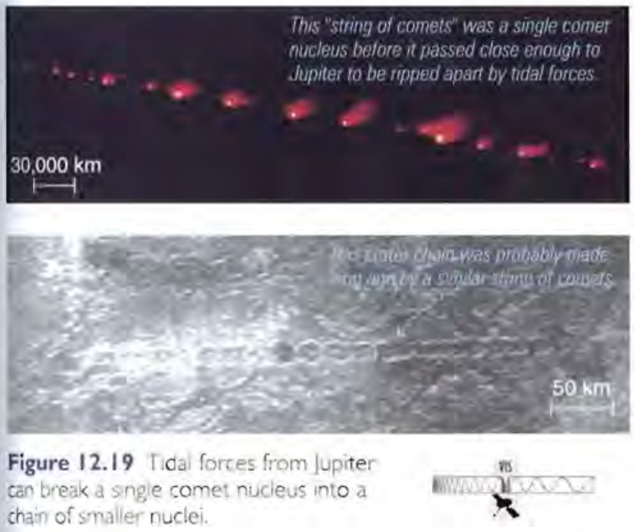


Figure 12.19 Tidal forces from Jupiter can break a single comet nucleus into a chain of smaller nuclei.

12.4 Cosmic Collisions: Small Bodies Versus the Planets

The hordes of small bodies orbiting the Sun are slowly shrinking in number through collisions with the planets and ejection from the solar system. Many more must have roamed the solar system in the days of the heavy bombardment, when most impact craters formed [Section 8.4]. Plenty of small bodies still remain, however, and cosmic collisions still occur on occasion. These collisions have had important effects on Earth and other planets.

• Have we ever witnessed a major impact?

Modern scientists have never witnessed a major impact on a solid world, but in 1994 we were privileged to witness one on Jupiter. The event was likely a rare one: Astronomers estimate that a major impact occurs on Jupiter about once every 1,000 years. The dramatic event was the impact of a comet named *Shoemaker-Levy 9*, or *SL9* for short.

Rather than having a single nucleus, SL9 consisted of a string of comet nuclei lined up in a row (Figure 12.19a). Apparently, tidal forces from Jupiter ripped apart a single comet nucleus during a previous close pass near the planet. Crater chains on Jupiter's moons are evidence that similar breakups of comets near Jupiter have occurred in the past. For example, Figure 12.19b shows a chain of craters on Callisto, presumably formed when a string of comet nuclei crashed into its icy surface.

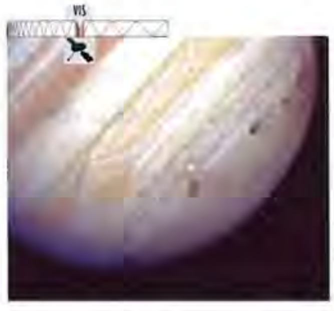
Comet SL9 was discovered more than a year before its impact on Jupiter, and orbital calculations had told astronomers precisely when the impact would occur. Thus, when the impacts finally began, they were observed with nearly every major telescope in existence, as well as by spacecraft that were in a position to get a view. The images were astonishing (Figure 12.20). Each of the individual nuclei in comet SL9 crashed into Jupiter with an energy equivalent to that of a million hydrogen bombs. Comet nuclei barely a kilometer across left scars larger than the entire Earth. The scars lasted for months before Jupiter's strong winds finally made them fade from view.

The SL9 impacts allowed us to study both the impact process and material splashed out from deep inside Jupiter. They also provided two important sociological lessons. First, "Comet Crash Week" proved to be one of the best examples of international collaboration in history. With the aid of the Internet, scientists quickly and effectively shared data from observatories around the world. Second, extensive media coverage helped the event capture the public imagination, leading to awareness that impacts are not merely relegated to ancient geological history. If such violent impacts can happen on other planets in our lifetime, could they also happen on Earth?

• Did an impact kill the dinosaurs?

There's little doubt that major impacts have occurred on Earth in the past. Meteor Crater in Arizona (see the photo that opens this chapter, p. 359) formed about 50,000 years ago when a metallic asteroid roughly 50 meters across

a This infrared photo shows the brilliant glow of a rising fireball from one of the impacts. Jupiter is the round disk, with the impact occuring near the lower left of the disk.



b Each of the black dots in this Hubble Space Telescope photo is a scar from the impact of one of the SL9 nuclei.

c This painting shows how the impacts might have looked from the surface of Io. The impacts occurred on Jupiter's night side.

Figure 12.20 The impacts of comet Shoemaker-Levy 9 on Jupiter allowed astronomers their first direct view of a cosmic collision.

crashed to Earth with the explosive power of a 20-megaton hydrogen bomb. Although the crater is only a bit more than 1 kilometer across, the blast and ejecta probably battered an area covering hundreds of square kilometers. Meteor Crater is relatively small and recent. Despite the fact that erosion and other geological processes have erased most of Earth's impact craters, geologists have identified more than 100 impact craters on our planet. So before we consider whether an impact might occur in our lifetimes, it's worth examining the potential consequences if it did. Clearly, an impact could cause widespread physical damage. But a growing body of evidence, accumulated over the past three decades, suggests that an impact can do much more—in some cases, large impacts may have altered the entire course of evolution.

In 1978, while analyzing geological samples collected in Italy, a scientific team led by Luis and Walter Alvarez (father and son) made a startling discovery. They found that a thin layer of dark sediments deposited about 65 million years ago—about the time the dinosaurs went extinct—was unusually rich in the element iridium. Iridium is a metal that is common in meteorites but rare on Earth's surface (because it sunk to Earth's core when our planet underwent differentiation). Subsequent studies found the same iridium-rich layer in 65-million-year-old sediments around the world (Figure 12.21).* The Alvarez team suggested a stunning hypothesis: The extinction of the dinosaurs was caused by the impact of an asteroid or comet.

In fact, the death of the dinosaurs was only a small part of the biological devastation that seems to have occurred 65 million years ago. The fossil record suggests that up to 99% of all living organisms died around that time and that up to 75% of all existing *species* were driven to extinction. This makes the event a clear example of a **mass extinction**—the rapid extinction of a large fraction of all living species. Could it really have been caused by an impact?

Evidence for the Impact There's still some scientific controversy about whether the impact was the sole cause of the mass extinction or just one of many causes, but there's little doubt that a major impact coincided with the death of the dinosaurs. Key evidence comes from further analysis of the sediment layer. Besides being unusually rich in iridium, this layer contains four other features: (1) unusually high abundances of several other metals, including osmium, gold, and platinum; (2) grains of "shocked quartz," quartz crystals with a distinctive structure that indicates they experienced the high-pressure conditions of an impact; (3) spherical rock "droplets" of a type known to form when drops of molten rock cool and solidify in the air; and (4) soot (at some sites) that appears to have been produced by widespread forest fires.

All these features point to an impact. The metal abundances look much like what we commonly find in meteorites rather than what we find elsewhere on Earth's surface. Shocked quartz is also found at other impact sites, such as Meteor Crater in Arizona. The rock "droplets" presumably were made from molten rock splashed into the air by the force and heat of the impact. The soot probably came from vast forest fires ignited by impact debris. Some debris would have been blasted so high that it rose above the atmosphere, spreading worldwide before falling back to Earth. On their downward plunge, friction would have heated the debris particles until they became a hot, glowing rain of rock.

In addition to the evidence within the sediments, scientists have identified a large impact crater that appears to match the age of the sediment layer. The crater, about 200 kilometers across, is located on the coast of Mexico's Yucatán Peninsula, about half on land and half underwater (Figure 12.22). Its size indicates that it was created by the impact of an asteroid or a comet measuring about 10 kilometers across. (It is named the *Chicxulub crater,* after a nearby fishing village.)

The Mass Extinction If the impact was indeed the cause of the mass extinction, here's how it probably happened: On that fateful day some 65 million years ago, the asteroid or comet slammed into Mexico with the force of a hundred million hydrogen bombs (Figure 12.23). It apparently hit at a slight angle, sending a shower of red-hot debris across the continent of North America. A huge tsunami sloshed more than 1,000 kilometers inland. Much of North American life may have been wiped out almost immediately. Not long after, the hot debris raining around the rest of the world ignited fires that killed many other living organisms.

The longer-term effects were even more severe. Dust and smoke remained in the atmosphere for weeks or months, blocking sunlight and causing temperatures to fall as if Earth were experiencing a global and extremely harsh winter. The reduced sunlight would have stopped photosynthesis for up to a year, killing large numbers of species throughout the food chain. This period of cold may have been followed by a period of unusual warmth. Some evidence suggests that the impact site was rich in carbonate rocks, so the impact may have released large amounts of carbon dioxide into the atmosphere. The added carbon dioxide would have strengthened the greenhouse effect, and the months of global winter may have been followed by decades or longer of global summer.

Figure 12.21 Around the world, sedimentary rock layers dating to 65 million years ago share the evidence of the impact of a comet or asteroid. Fossils of dinosaurs and many other species appear only in rocks below the iridium-rich layer.

*The layer marks what geologists call the *K-T boundary,* because it separates sediments deposited in the Cretaceous and Tertiary periods (the "K" comes from the German word for Cretaceous, *Kreide*). The mass extinction that occurred 65 million years ago therefore is often called the *K-T event.*

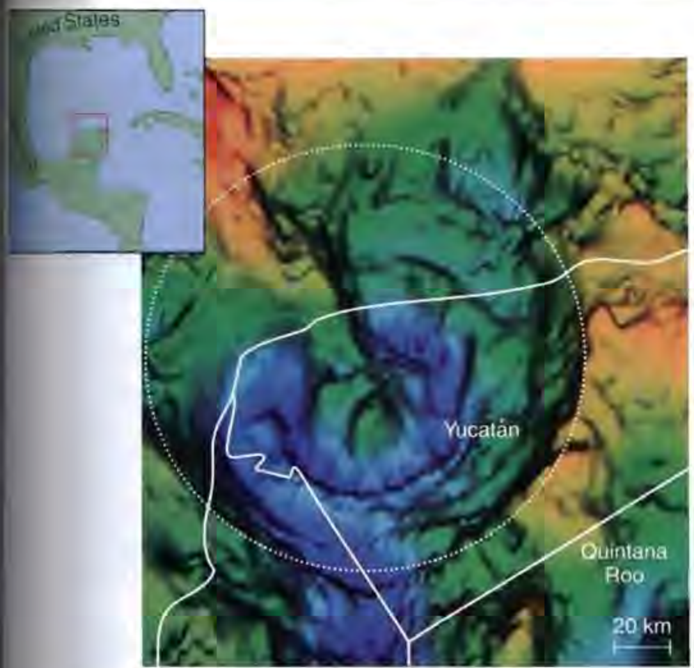


Figure 12.22 This computer-generated image, based on measurements of small local variations in the strength of gravity, shows an impact crater (dashed circle) in the northwest corner of Mexico's Yucatán Peninsula. The crater measures about 200 kilometers across, and about half of it lies underwater off the coast. (The solid white lines show the coastline and borders of Mexican states.)

The impact probably also caused chemical reactions in the atmosphere that produced large quantities of harmful compounds, such as nitrous oxides. These compounds dissolved in the oceans, where they probably were responsible for killing vast numbers of marine organisms. Acid rain may have been another by-product, killing vegetation and acidifying lakes around the world.

Perhaps the most astonishing fact is not that 75% of all species died but that 25% survived. Among the survivors were a few small mammals. These mammals may have survived in part because they lived in underground burrows and managed to store enough food to outlast the global winter that immediately followed the impact.

The evolutionary impact of the extinctions was profound. For 180 million years, dinosaurs had diversified into a great many species large and small, while mammals (which had arisen at almost the same time as the dinosaurs) had generally remained small and rodentlike. With the dinosaurs gone, mammals became the new kings of the planet. Over the next 65 million years, the small mammals rapidly evolved into an assortment of much larger mammals—ultimately including us.

Controversies and Other Mass Extinctions There seems little doubt that a major impact coincided with the mass extinction of 65 million years ago, but does it tell the entire story? The jury is still out. The fossil record can be difficult to read when we are trying to understand events that happened over just a few years rather than a few million years. Some scientists suspect that the dinosaurs were already in decline and the impact was only the last straw. Others suggest that major volcanic eruptions also may have played a role.

Figure 12.23 This painting shows an asteroid or comet moments before its impact on Earth, some 65 million years ago. The impact probably caused the extinction of the dinosaurs, and if it hadn't occurred the dinosaurs might still rule Earth today.

Was the dinosaur extinction a unique event? Measuring precise extinction rates becomes more difficult as we look to older fossils, but there appear to have been at least four other mass extinctions during the past 500 million years. None of the other mass extinctions is as closely tied to an impact as the dinosaur extinction, but impacts almost certainly played a role. Sediments from the times of other mass extinctions reveal evidence similar to that found in the iridium-rich layer tied to the death of the dinosaurs. In some cases, impact craters have been found that date to about the right times. Much more research is needed, but impacts appear to have played a major role in shaping the history of life on Earth.

• Is the impact threat a real danger or media hype?

On June 14, 2002, the 100-meter-wide asteroid 2002MN passed within 120,000 kilometers of Earth (less than a third of the Earth-Moon distance). There was no advance warning; in fact, the asteroid wasn't discovered until after it had passed by. Although an asteroid of this size would not cause global devastation, it might kill millions of people in the unlikely event that it struck a large city. How concerned should we be about the possibility of objects like this striking Earth—or, worse yet, even larger objects such as those that may have caused past mass extinctions? We can analyze the threat by examining both the frequency of past impacts and the number of objects in space that pose a potential future threat.

No large impacts have left craters in modern times, but we know of at least one smaller impact that devastated a fairly large area. In 1908, a tremendous explosion occurred over Tunguska, Siberia (Figure 12.24). Entire forests were flattened and set on fire, and air blasts knocked over people, tents, and furniture up to 200 kilometers away. Seismic disturbances were recorded at distances of up to 1,000 kilometers, and atmospheric pressure fluctuations were detected almost 4,000 kilometers away. The explosion, now estimated to have released energy equivalent to that of