AIAA

AEROSPACE MICRO-LESSON

Easily digestible Aerospace Principles revealed for K-12 Students and Educators. These lessons will be sent on a bi-weekly basis and allow grade-level focused learning. - AIAA STEM K-12 Committee.

COMET SHOEMAKER-LEVY 9

Twenty-five years ago this month, a comet slammed into the planet Jupiter in the greatest, most powerful impact ever witnessed by human beings. This lesson describes the comet and its impact, both literal (on Jupiter) and metaphorical (on our thinking about the Solar System).

Next Generation Science Standards (NGSS):

- Discipline: Earth and Space Science
- Crosscutting Concept: Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science & Engineering Practice: Planning and Carrying out Investigations

GRADES K-2

1-ESS1-1. Use observations of the sun, moon, and stars to describe patterns that can be predicted.

Sometimes referred to as “dirty snowballs,” comets are small chunks of dust and ice that orbit the sun. They formed out in the far reaches of the Solar System, far from the heat and light of the Sun, where it was cold enough for the ice not to evaporate. There are billions of comets in the Solar System, but most of them stay out far from the Sun where we cannot see them easily. A few comets come into the inner part of the Solar System near the Earth and we can see them more easily. One which we can see from Earth every 75 years or so is Halley’s Comet.

This is an image of Halley’s Comet recorded by the ESA spacecraft Giotto in 1986. Being about ten miles wide in its largest dimension, it is one of the largest comets. Because the comet is so large and its fly-by of Earth is predictable, and there are documented sightings of it throughout recorded history, it is one of the most

GRADES K-2 (CONTINUED)

famous comets. (Its next visit to the inner Solar System will happen in the summer of 2061; how old will you be then?)

Carolyn Shoemaker, her husband Eugene, and David Levy discovered a comet in March 1993. The comet was named Shoemaker-Levy 9, for the people who discovered it and the fact that it was the ninth such comet they had identified. By tracking its motion backwards using computer simulations, scientists figured out that the comet had been pulled in by Jupiter's gravity; this was the first known instance of a comet orbiting a planet. Scientists calculated that it had been circling Jupiter for some decades before its discovery.

When the comet was discovered, it was found to be in many pieces, strung out in a line. (There is a picture of the comet in the Grades 3-5 lesson.) The largest piece was about a mile across. Scientists figured out that the comet had passed very close to Jupiter a year earlier, in July 1992, and Jupiter's gravity had pulled it apart. (From this, the scientists concluded that the comet didn't have any internal strength, like a rock or an ice cube, to hold it together, but was a loose aggregation like a pile of sand or a snowbank.)

In July 1994 the comet crashed into the planet Jupiter. This was the first time that astronomers actually observed two large objects in the solar system colliding with each other. The force of the impact dredged up darker gases from deeper in Jupiter's atmosphere and brought them to the upper layers where people could see them. Jupiter is a gas giant planet and does not have a solid surface, but the comet's impacts brought the gases up from lower down in the atmosphere to the tops of the clouds.

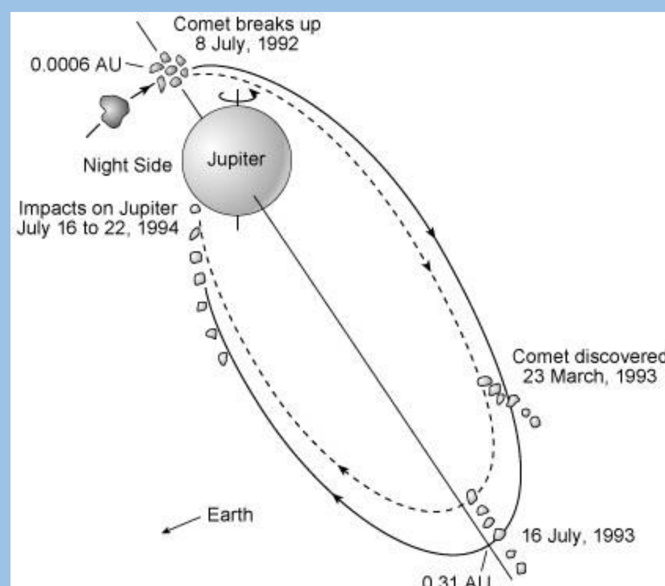
Have you ever skipped a rock across a pond and watched the ripples form at each spot where the rock touched the water? The pieces of the comet made similar marks on the surface of the planet and were visible for months after the crash. Brown spots in the picture mark impact sites on Jupiter's southern hemisphere. As a classroom exercise, you may want to try throwing small pebbles into dry sand and into water. Look at the "craters" and the splashes they make and compare them to the marks that Shoemaker-Levy 9 made on Jupiter.

GRADES 3-5

5-ESS1-2. Represent data in graphical displays to reveal patterns of daily changes in length and direction of shadows, day and night, and the seasonal appearance of some stars in the night sky.

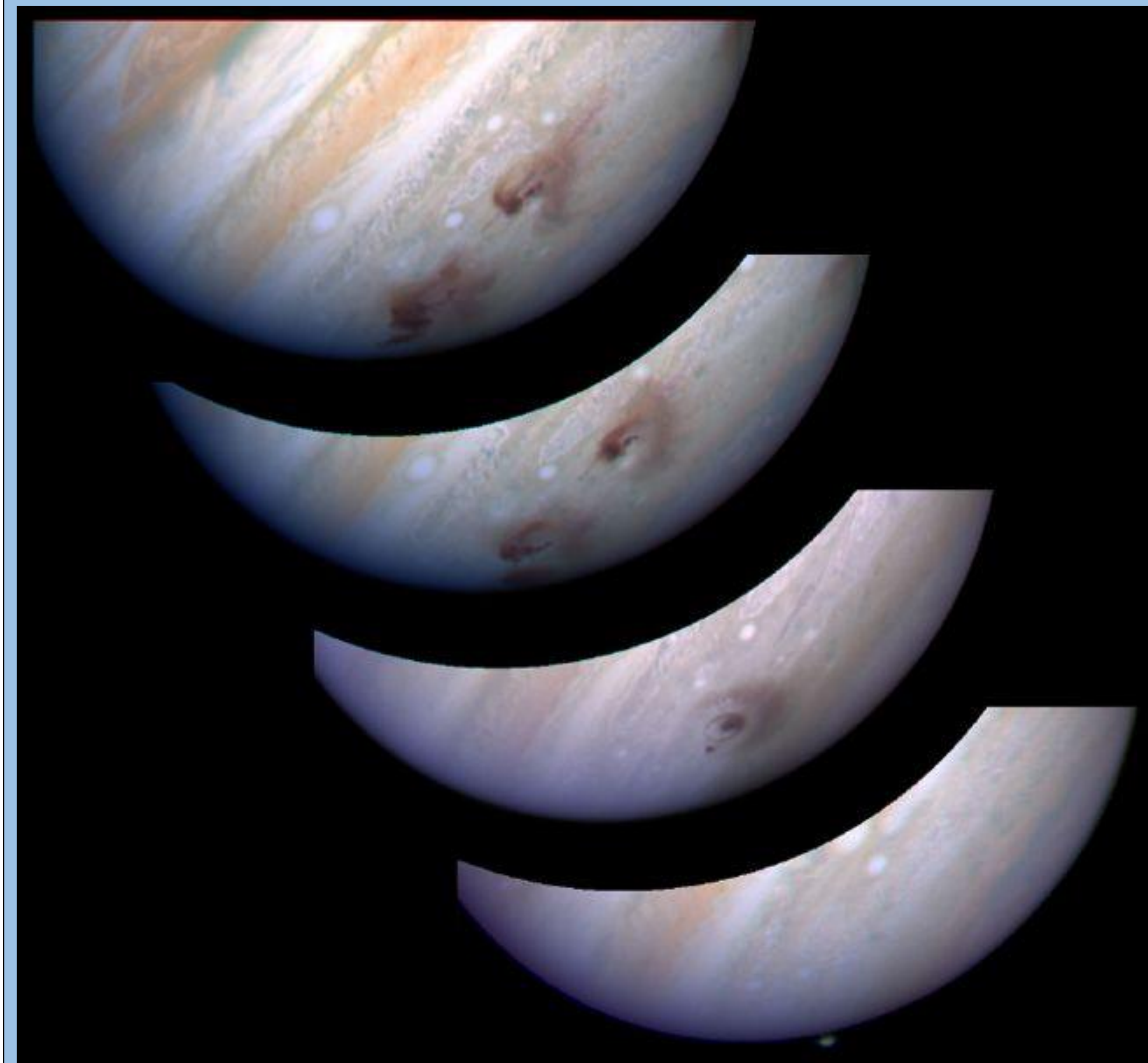
Before Shoemaker-Levy 9 was discovered, all comets were thought to orbit the sun. But studies of its orbital pattern surprised astronomers when they realized that Jupiter's gravity had captured the comet. The gravitational forces of the planet had also broken the comet into fragments when it had passed very close in July 1992. Here is a panoramic image of the comet taken by the Hubble Space Telescope in January 1994.

Careful study of the comet revealed that it actually had multiple cores, rather than one "nucleus" at its center. Eventually, scientists were able to label 21 separate fragments and, from analyzing their movements, calculate when the comet had been broken up. Astronomers were even more excited when they analyzed the orbit and realized that the comet would be entering the planet's atmosphere and that they could predict the date of the collision.



Space agencies and astronomers from all over the world focused their telescopes and instruments on this remarkable event. The Hubble Space Telescope, the ESA's Giotto, and NASA's Galileo spacecraft (which was already en route to Jupiter), were some of the technology used to capture images and other information about the comet and its impact with Jupiter. After the collision, astronomers continued to gather images and information, watching the effects of the event on the planet. The impact scars slowly faded, as seen in the series of images from NASA on the next page. Studying the rate at which the marks disappeared gave new data on atmospheric conditions on Jupiter which scientists could use to make new predictions and formulate new questions to pursue.

GRADES 3-5 (CONTINUED)



There are many web sites geared towards children that give information about Comet Shoemaker-Levy 9.

GRADES 6-8

ESS1.B: Earth and the Solar System. The solar system consists of the sun and a collection of objects, including planets, their moons, and asteroids that are held in orbit around the sun by its gravitational pull on them. (MS-ESS1-2),(MS-ESS1-3)

GRADES 6-8 (CONTINUED)

We presume that Comet Shoemaker-Levy 9 began its existence as a typical comet, far out in the outer reaches of the Solar System. (Nobody was there to see it form, but all the other comets that we know about were formed out there and we have no reason to think Shoemaker-Levy 9 was any different.) It orbited the Sun, as other comets do, and at some point it started coming into the inner Solar System where the planets are.

During one of its trips into the inner Solar System, Comet Shoemaker-Levy 9 passed near the planet Jupiter and was captured by Jupiter's gravity. While this is a very easy thing to say, it is very unusual in practice. The reason it is unusual is that out in space, if something had enough energy to come towards a planet from interplanetary space and pass it by, then it almost always has enough energy to leave the planet behind and go back into interplanetary space. There is no friction to slow it down and bring it into orbit around the planet. (You can see something like this effect if you pour water from a tap into a shallow cup: if you run the water down the inside of one side of the cup at a high flow rate, it can flow up the other side and spill out. If you try this at home, be sure to do it over the sink! Also, make sure you use a cup with a rounded bottom and not a mug.) For the planet to "capture" the object so that it goes into orbit around the planet instead of around the Sun, something else needs to slow the object down relative to the planet.

In the case of Comet Shoemaker-Levy 9, what seems to have happened—nobody knows for sure—is that it was in an orbit around the Sun with an aphelion (farthest distance from the Sun) a few tens of millions of miles inside Jupiter's orbit. This was within Jupiter's "Hill Sphere," which is the region of space within which Jupiter's gravity predominates over the Sun's gravity. Because the comet was near its aphelion, it was moving more slowly than at other points in its orbit, and its speed almost matched the speed of Jupiter in its orbit around the Sun. (Jupiter's orbit was farther from the Sun than the comet's orbit, giving Jupiter a lower average speed as it goes around the Sun.) This match in speed made the comet fall almost straight "down" toward Jupiter, giving it a very elongated orbit around Jupiter that took about two (of Earth's) years to go around once. By the time the comet reached apojove (farthest distance from Jupiter) again, Jupiter had gone farther around the Sun and the radius of its Hill Sphere (which is not a true sphere) in the direction of the comet's apojove was larger. The size of Jupiter's Hill Sphere also depends on its distance from the Sun, and if it captured the comet while it was near perihelion (closest distance from the Sun), its greater distances from the Sun when the comet reached apojove would also have worked against the comet's escaping its gravity.

GRADES 6-8 (CONTINUED)

We think of an orbit as being stable and unchanging. As long as nothing comes along to perturb the orbit, it tends to be stable—especially if it is nearly circular, as the planets' orbits are. An orbit like Shoemaker-Levy 9's around Jupiter, though, is very unstable. When the comet was at its farthest point from Jupiter, it was moving extremely slowly relative to the planet. Any tiny perturbation would have a major effect on the inner part of its orbit. And in fact this is what happened. Some perturbing force—possibly the gravitational attraction of distant planets, possibly something else—caused the comet to slow down and the perijove of its orbit to decrease. Finally, in 1992, the comet passed close enough to Jupiter for the planet's gravity to break the comet apart into separate pieces. On its next orbit, the orbit's perijove was inside Jupiter itself, and the comet smashed into the planet.

The impact of Comet Shoemaker-Levy 9 onto Jupiter took place over a period of six days. The comet had broken up into pieces two years earlier, and the different pieces had spread apart from each other. A sequence of twenty-one major comet fragments (and untold numbers of smaller pieces) smashed into Jupiter with a total energy of 300 million atomic bombs. The impact threw plumes of gas from Jupiter's atmosphere some 1,500 miles high and stirred up chemicals from the lower layers of the atmosphere. The result was a string of black spots at a specific latitude in Jupiter's southern hemisphere. (You may want to ask the students, why were the spots all at one latitude? And why were they strung out in a line instead of all being in the same place on Jupiter? The answer is that Jupiter rotated under the impact point as the individual fragments came in. Between each impact and the next, the planet rotated some tens of degrees.) Seen in infrared, the spots glowed with the heat from the energy of impact. (Here is a video with several pictures.) After several months, Jupiter's winds dissipated the spots.

GRADES 9-12

HS-ESS1-4. Use mathematical or computational representations to predict the motion of orbiting objects in the solar system.

One of many things that made Comet Shoemaker-Levy 9 unique was its "string of pearls" configuration, caused by its encounter with the planet Jupiter in July 1992. It is all very well to say that tidal forces broke the comet apart, but what exactly does that mean?

GRADES 9-12 (CONTINUED)

Tides are most familiar as the (usually) twice-daily rise and fall of the sea level at any given point on the Earth's surface. They are caused by the gravitational attraction of the Moon on the Earth: the water on the side of the Earth facing the Moon is closer to the Moon than the Earth's center is, and so the Moon's gravity pulls harder on it than it pulls on the center. Conversely, the water on the side of the Earth facing away from the Moon is farther away from the Moon and the Moon's gravity does not pull as hard. The gravitational forces exerted by the Moon on one-kilogram masses the near and far sides of the Earth are given by the formulas

$$F_{near} = \frac{GM_{moon}(1\ kg)}{R_{near}{}^2} \qquad F_{far} = \frac{GM_{moon}(1\ kg)}{R_{far}{}^2}$$

where G is the universal gravitational constant, M_{moon} is the mass of the Moon, and R_{near} and R_{far} are the distances from the center of the Moon to the near and far sides of the Earth respectively. The difference in force between the two masses is the tidal force of the Moon pulling the two masses apart:

$$F_{near} - F_{far} = GM_{moon}(1\ kg)\left[\frac{1}{R_{near}{}^2} - \frac{1}{R_{far}{}^2}\right]$$

or, with a little algebra,

$$F_{near} - F_{far} = \frac{GM_{moon}(1\ kg)[R_{far} + R_{near}][R_{far} - R_{near}]}{R_{near}{}^2 R_{far}{}^2}$$

In this equation, the sum "[R_{far} + R_{near}]" is twice the distance from the center of the Earth to the center of the Moon while the difference "[R_{far} – R_{near}]" is simply the diameter of the Earth. If we substitute in 6.67430×10^{-11} $m^3/Kg\text{-}s^2$ for G, 7.342×10^{22} Kg for M_{moon}, anywhere from 356,400 Km to 406,700 Km for the distance from the center of the Earth to the center of the Moon (let us use 384,402 Km or 3.84402×10^8 meters as an average value), and 12,756.2 Km (1.27562×10^7 meters) for the diameter of the Earth, we find that the tidal force from the Moon is pulling those two kilogram masses apart with a force of 2.202×10^{-6} Newtons. Earth's gravity overcomes this force easily.

Now consider the case of Comet Shoemaker-Levy 9 on its close pass by Jupiter the last time before it hit. This is the point at which the tidal forces from Jupiter's gravity caused it to break up. Jupiter's mass is 1.8982×10^{27} Kg. The comet's perijove (the closest point in its orbit to Jupiter) for that pass was about 25,000-120,000 Km above the cloud tops, or 96,000-

GRADES 9-12 (CONTINUED)

191,000 Km (let us call it 1.5×10^8 meters) from Jupiter's center. The comet's diameter before it was disrupted is not known, but given 21 fragments, the largest of which was about 1.5 Km in diameter, we can estimate a value of about five kilometers (5,000 meters). Given these values, the force pulling two one-kilogram masses on the near and far sides of the comet is about 3.8×10^{-4} Newtons. (The tidal force depends on the cube of the distance from Jupiter, so the differing estimates of the distance result in force estimates from 1.8×10^{-4} to 1.4×10^{-3} Newtons.)

A force of 3.8×10^{-4} Newtons, or about the weight of a large mosquito, does not sound like much. If there is something holding the comet together, it is not much. But if the comet is just a loose collection of sand grains and ice crystals held together by its self-gravity, then 3.8×10^{-4} Newtons is about enough to pull it apart. The gravitational force on a one-kilogram mass on the surface of the un-disrupted comet (radius of 2,500 meters, volume of 6.5×10^{10} m^3, and mass of about 6.5×10^{13} Kg) will be 7×10^{-4} Newtons. A difference of a factor of two between the tidal and gravitational forces may seem like a lot, but it is within the uncertainty of the calculations.

An indirect effect that Shoemaker-Levy 9 had on people was that it brought home to them the effects of a large impact. A decade and a half earlier, two geologists named Walter and Luis Alvarez had proposed the idea that an asteroid impact had caused the extinction of the dinosaurs, but this had not been widely accepted yet. After seeing photographs of the Earth-sized blemishes on Jupiter that the comet impact had created, the general public—and government policy-makers—began to take the danger from space seriously. Hollywood made movies with plots centered around large asteroids hitting the Earth; Congress ordered NASA to catalog all the near-Earth asteroids that could pose an impact threat and to come up with ways to protect against it. A science fiction writer went so far to say that "[t]he dinosaurs became extinct because they didn't have a space program."

Sixty Years Ago in the Space Race:

July 7: The first American four-stage rocket, the Javelin, was launched to an altitude of 750 miles.