# Mission: Possible

## How Can We Plan an Exploration of Another World?

## Lesson Overview

| Grade Level |
|---|
| 5–8 |

| Duration |
|---|
| Three 45-minute class periods |

| Essential Question |
|---|
| How can we plan an exploration of another world? |

Lesson 2 of the Grades 5-8 Component of the *Mission Design* Education Module

### Lesson Summary

The goal of the lesson is to have the students understand how to plan a mission to explore another world in the Solar System. The students begin by discussing the path of a spacecraft traveling between planets, examining the journey from the Earth to Mars as an example. In Activity 1, students determine the pros and cons for different ways we can explore another world, either by observing from the Earth or by sending a spacecraft to fly by, orbit, or land on the world. In Activity 2, the students plan a complete mission to explore another world in the Solar System. By the end of the lesson, the students come to understand that what scientists want to learn about an object determines how they plan the mission, but real-life constraints such as cost and time determine what actually can be accomplished.

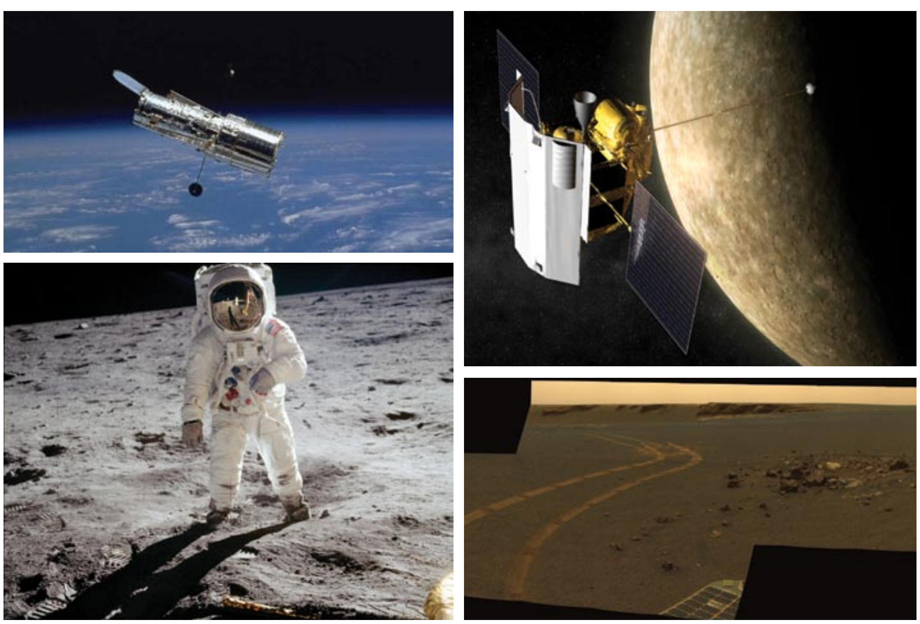


*Figure 1. How do we explore other worlds in the Solar System? Depending on the goals and the constraints of the mission, the exploration can be done through observations with telescopes on (or near) the Earth (e.g., Hubble Space Telescope, top left), by having robotic spacecraft making remote measurements by flying by or orbiting the world (e.g., MESSENGER mission to Mercury, top right), landing on the target world (e.g., Martian rovers, which took photographs of the surface of Mars including its own tracks across the landscape, bottom right), or by sending humans to do the exploration (e.g., Apollo missions to the Moon, bottom left.) (Picture credits: NASA; http://hubblesite.org/gallery/spacecraft/06/;NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/atmercury_br.html; NASA Project Apollo Archive/Apollo Image Gallery, scanned by Kipp Teague, AS11-40-5903; http://www.apolloarchive.com/apollo_gallery.html; NASA/JPL-Caltech/Cornell University; http://photojournal.jpl.nasa.gov/catalog/PIA10213)*

## Objectives

Students will be able to do the following:

- Describe the relationship between the locations of planets as they move around the Sun.
- Make multi-sensory observations.
- Gather data.
- Demonstrate an understanding of real-life constraints on spacecraft missions.

## Concepts

- There are many ways to study other worlds in the Solar System.
- There can be more than one solution to a problem.
- Real-life constraints such as cost and time determine how much can be learned about another world.

## MESSENGER Mission Connection

The MESSENGER spacecraft is one of NASA's Discovery missions, which are meant to do a lot of science within a limited budget. Even with a relatively inexpensive mission, the mission team was able to create an orbiting spacecraft that will tell us more about Mercury than we knew from the only previous mission to Mercury (Mariner 10) and all ground-based observations combined.

## Standards & Benchmarks

### National Science Education Standards

Standard A2: Understandings about scientific inquiry

- Different kinds of questions suggest different kinds of scientific investigations. Some investigations involve observing and describing objects, organisms, or events; some involve collecting specimens; some involve experiments; some involve seeking more information; some involve discovery of new objects and phenomena; and some involve making models.
- Mathematics is important in all aspects of scientific inquiry.
- Scientific investigations sometimes result in new ideas and phenomena for study, generate new methods or procedures for an investigation, or develop new technologies to improve the collection of data. All of these results can lead to new investigations.

Standard E1: Abilities of technological design

- Students should make and compare different proposals in the light of the criteria they have selected. They must consider constraints—such as cost, time, trade-offs, and materials needed—and communicate ideas with drawings and simple models.

Standard E2: Understandings about science and technology

- Perfectly designed solutions do not exist. All technological solutions have trade-offs, such as safety, cost, efficiency, and appearance. Engineers often build in back-up systems to provide safety. Risk is part of living in a highly technological world. Reducing risk often results in new technology.

### AAAS Benchmarks for Science Literacy

Benchmark 3B/M1:

- Design usually requires taking into account not only physical and biological constraints, but also economic, political, social, ethical, and aesthetic ones.

Benchmark 2B/M1:

- Mathematics is helpful in almost every kind of human endeavor—from laying bricks to prescribing medicine or drawing a face.

## SCIENCE OVERVIEW

Before any travel, it is good to plan the trip carefully. What is the best way to get to your destination? What will you do once you reach the destination? What kind of supplies might you need? How much is the trip going to cost? The same is true when planning for an exploration, and especially when planning for space travel to investigate another world in the Solar System. Careful planning makes the mission more likely to succeed.

When planning an exploration of another world, scientists need to consider what kind of information they want to gather. They need to formulate the scientific goals of the mission, and then figure out what is the best way to meet the goals within their budget. If the study cannot be conducted with ground-based observations or telescopes located near the Earth in space, they must consider the extra cost of sending a spacecraft to explore the world by flying by, orbiting, or landing on the target world. The exploration gets more complex and expensive as you progress from ground-based observations to a flyby, an orbital, and a landing spacecraft mission. Most often, the final mission is a compromise between what the scientists want to find out about their target, and what real-world constraints allow.

**Observations from the Earth**

Scientists explored the Universe for thousands of years by using just their unaided eyes to observe phenomena in the sky. While much can be learned about the positions and behavior of the objects in the sky without additional equipment, it is difficult to come to a deeper understanding of the basic nature of the observed phenomena with eyes alone. A significant breakthrough in this regard occurred in about 1608, when the first telescope was constructed; there is some dispute as to exactly who made the first telescope, but the feat is usually attributed to Hans Lippershey. The new tool was soon used by Galileo Galilei to observe objects in the sky no human had ever seen in such great detail before; in effect, this was the beginning of the era of detailed astronomical observations.

Over the last few centuries, astronomical observations have become more advanced not only in the way telescopes are constructed, but also in the way the actual observations are made. At the time of Galileo, astronomers jotted down their observations in notebooks, and the data was only as good as the observer's notes. The development of photographic plates, and, in more recent times, the introduction of advanced image capturing and enhancement technologies, have made ever more complex observations possible. As a result, the last hundred years has revolutionized our understanding of the Universe, and our place in it. Today, ground-based telescopes are still the most commonly used tools in observational astronomy, because they are less expensive to build, maintain, and use when compared with the other options disussed below. Telescope designers race to make new techniques to build, maintain and use ever bigger telescopes. The largest telescopes in the world today use mirrors of about 10 m (394 inches) in size. For example, the Keck Observatory (Fig. 2) on Mauna Kea, Hawaii, has two 10-meter telescopes that can be used either separately or together to enhance the observations even further. The total cost of the Keck telescopes was $231 million to design and build; this includes $48 million for instrumentation (camera systems, etc.) that are mounted on the telescope to make the actual observations. There are plans to build telescopes that have mirrors as big as 30 m (1,181 inches) in diameter over the next decade or so.

There are limits to the effectiveness of ground-based observations, however. Because the telescopes must see through the Earth's atmosphere, which is in constant motion, the clarity of the observations is decreased. There are computer software packages that can overcome some of these problems, but they cannot remove the effect of the moving atmosphere completely. Another way to alleviate the problem is to build telescopes in areas where the atmosphere is naturally calm, or high up in the mountains, where the light arriving from cosmic objects has less atmosphere to pass through. That is why most of the premier observatory sites today are located in high-altitude locations such as Chile and Hawaii. Still, even the best ground-based observations suffer from some atmospheric effects.

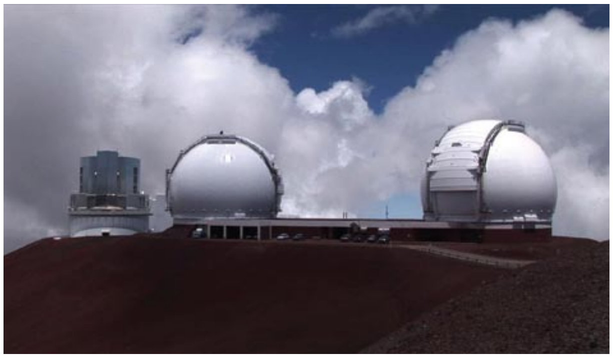


*Figure 2. The Keck Observatory in Mauna Kea, Hawaii, includes two telescopes whose 10-meter mirrors are the largest in the world. The telescopes are located inside the domes seen in the figure; the domes protect the telescopes from the environment and are opened for observations. (Picture credit: NASA; http://www.nasa.gov/centers/jpl/images/content/135066main_Keck-9-29-05-browse.jpg)*

**Observations from Space Near the Earth**

One way to solve the problem of the atmosphere is to place the telescopes in space. This is a popular approach not only because of the limited seeing from the ground, but also because there are many kinds of light that are blocked by the Earth's atmosphere but are observable by telescopes in space. Ground-based telescopes can observe in the visible, radio and some infrared and ultraviolet light, but only telescopes above the Earth's atmosphere can observe gamma rays, X-rays, and most of infrared and ultraviolet light. As a result, space telescopes have become very popular over the last few years.

Probably the best known space telescope is the Hubble Space Telescope (HST; see Fig. 3), which was placed into orbit around the Earth by the Space Shuttle in 1990. While the size of the HST's mirror is small (2.4 m; 94 inches) compared with the large ground-based telescopes, by not having to suffer from atmospheric distortions, HST's observations have revolutionized many aspects of astronomy. The telescope has taken hundreds of thousands of pictures, observing more than 25,000 astronomical targets. There probably are many new discoveries in store before the end of HST's operational lifetime sometime after 2014. The cost of HST at launch was $1.5 billion, which included the design, the building, the testing, and the launch of the telescope. Five additional Shuttle missions have repaired components of the HST and swapped instruments over the years, most recently in 2009. The cost estimates for the Shuttle missions have ranged from $600 million to $2 billion, increasing the cost of the Hubble Space Telescope significantly. There are many other important space-based observatories; for example, NASA's Great Observatories program includes not only the HST, which studies the Universe using visual, ultraviolet and near-infrared light, but also the Compton Gamma Ray Observatory, Chandra X-Ray Observatory, and the Spitzer Space Telescope, which study the Universe using gamma rays, X-rays and infrared light, respectively.

One drawback of space telescopes is that they are difficult (if not impossible) to repair and upgrade. For example, the Hubble Space Telescope has many redundant electronic circuits, but the needed repairs and maintenance tasks involved missions using astronauts on a Space Shuttle flight. Most space telescopes are on orbits that are not serviceable by the Shuttle, and so no repairs are possible for these telescopes. Furthermore, while both ground-based and space telescopes can quickly switch between different cameras and point to different parts of the sky, only ground-based telescopes allow an observer to use his or her own instrument packages or other observational devices that may be necessary to make the observations.

*Figure 3. Hubble Space Telescope (HST) was placed into orbit around the Earth by the Space Shuttle in 1990. It has taken hundreds of thousands of pictures since then, observing more than 25,000 astronomical targets, and in so doing has become perhaps the most important telescope in the history of astronomy. (Picture credit: NASA; http://hubble.nasa.gov/hubble/full/img94.jpg)*

**Robotic Exploration of the Solar System**

Almost everything that we know about the Universe beyond the Solar System was discovered through observations made on the Earth or in space near the Earth. However, much of what we know about the Solar System has been discovered by robotic spacecraft sent to make close-up observations of the objects in our planetary system. In fact, we have learned more about the Solar System in the last 50 years using robotic spacecraft than all the previous ground-based observations.

After the launch of Sputnik 1 satellite in 1957 ushered in the Space Age, robotic spacecraft (and in the case of the Moon, human space flight) have been used to study various worlds in the Solar System, with at least one spacecraft visiting each planet. In addition, robotic spacecraft have visited moons, asteroids, and comets. There are spacecraft currently on their way to examine the dwarf planets Ceres and Pluto, and the spacecraft flying by Pluto may also examine at least one of the Kuiper Belt Objects, which are icy worlds beyond the orbit of Neptune discovered in the last few years. Other spacecraft missions are carrying out more detailed observations of the many different worlds in the Solar System, and many more are being planned. While spacecraft are often unique in their detailed design, there are three basic types of missions: flyby, orbital or lander missions.

**Flyby Mission**

The simplest way to explore a world close-up is to have a spacecraft just fly by the body without going into orbit around it or landing on it. A flyby can get much more detailed information on the object than Earth-based observations. However, the spacecraft can only make useful observations of the world while it is nearby, and depending on the trajectory of the spacecraft, the time for observations may be limited and only a small portion of the object facing the spacecraft as it flies by may be viewable. This means that a flyby mission requires a lot of planning to optimize the way the data is gathered. Usually, the details of the planned observations—which instrument to use at each moment, where to point the instrument, what kind of data to take, etc.—are stored in a computer program on the spacecraft before the flyby, and the program begins executing automatically at some distance from the target. The gathered data is then sent back to the Earth for analysis after the flyby is concluded.

The costs of a robotic flyby mission vary depending on the world that is being explored. Typically the costs involve consideration for the following aspects:

- Designing and building the instruments needed to get the desired science data;
- The power needed to run the spacecraft and its instruments;
- Launching the spacecraft;
- The amount of fuel needed to fly to the world;
- Communications needed between the Earth and the spacecraft;
- Human labor for the scientists and engineers working on the mission;
- The length of the mission.

The basic design and structure of the spacecraft is usually done in concert with designing the instrument suite. After all, the spacecraft is really just a vehicle to take the instruments to the target world, create an environment where the instruments can operate properly, and make it possible for gathered data to be returned to the Earth for analysis. There is always a trade-off between the amount and type of science data that is desired and the cost of the instruments to gather this data. If a similar mission has been done before, there can be great cost savings by using similar instruments that were used in the earlier mission. There are also engineering costs associated with incorporating the instrument into the spacecraft, but they are significantly lower. A typical instrument on a spacecraft costs a few million dollars, while the design and construction of the whole spacecraft can vary from a few tens of millions of dollars to $1 billion dollars, depending on the kind of engineering needed to complete the project.

In addition to selecting the instruments, the power needed to operate them must be considered when designing the mission. If the spacecraft is exploring the inner Solar System (Mercury, Venus, or Mars, for example), solar arrays can be used to get power from sunlight. If the mission is to worlds farther out, there is not enough sunlight to produce sufficient power, and the spacecraft will need to rely on nuclear energy. In this case, the power is derived from the natural decay of a radioactive isotope, most often plutonium-238. For example, the Voyager 1 and 2, Galileo, Cassini-Huygens and New Horizons spacecraft use this power source. Future long-duration missions exploring worlds in the outer reaches of the Solar System may need new technology, such as a small nuclear reactor incorporated to the spacecraft.

The cost of launching a spacecraft from the Earth depends on a number of factors, especially on the size and weight of the spacecraft and the amount of propellant aboard. The cost of lifting a spacecraft from the ground to space is about $22,000 per kg ($10,000 per pound); additional costs come from sending the spacecraft toward the target world. The typical cost is around $40 million per launch for spacecraft heading to the inner Solar System and Mars, and roughly $100 million for spacecraft heading to the outer reaches of the Solar System.

The spacecraft carries propellant (mixture of fuel and oxidizer) for course correction maneuvers that may be necessary to adjust the trajectory toward the target world. The spacecraft is usually launched on a trajectory that requires as few course corrections using the spacecraft's engines as possible. The typical spacecraft carries a few hundred kilograms of propellant, at a cost of about $80/kg ($36/lb.) For example, the MESSENGER spacecraft heading to Mercury carried a total of 597 kg (1,316 lbs) of propellant at the start of its journey, with a total cost of approximately $48,000. However, this is only the direct cost and does not include the cost of lifting the propellant to space (which is included in the launch cost mentioned above.) For example, in the case of MESSENGER, the cost of lifting the propellant to space cost $13 million, much more than the cost of the propellant itself.

Communications with spacecraft studying other worlds are done using radio waves, which travel at the speed of light. As a result, the time between sending a signal to the spacecraft and receiving the response varies from a couple of seconds (for missions exploring the Moon) to several hours (for missions investigating the outer reaches of the Solar System.) This delay makes it necessary for the spacecraft to be able to execute many commands on their own, without direct input from ground control on the Earth. Therefore, the computer programs operating robotic spacecraft must be designed carefully. For example, before firing the spacecraft's engines to make a course correction maneuver, a signal is sent from the ground control to the spacecraft to have the computer execute a series of commands to complete the necessary operations, but providing additional commands is usually not possible before the maneuver is completed. Communication with spacecraft is done using large radio antennas on Earth, such as NASA's Deep Space Network, which includes three radio antenna facilities located around the world. The time to use the network must be planned in advance. The cost for using these communication facilities can be several million dollars, depending on the frequency of communications and the amount of data transmitted.

An important cost item is to reserve sufficient funds to pay for the scientists and engineers working on the mission. The mission team spends considerable time designing and testing the spacecraft and the instruments, making sure that the mission events from launch to the end of the mission occur smoothly, monitoring the spacecraft during its entire mission, and, of course, analyzing and interpreting the gathered data.

The length of the mission increases the total cost, since a longer duration results in not only continued communications with the spacecraft, but also additional human labor on the Earth to monitor and communicate with the spacecraft, as well as to analyze the larger amount of data returned by the spacecraft. Mission length depends on many factors, such as the distance to the target world, the way the spacecraft travels there, the power available to operate the spacecraft, and the scientific goals of the mission. The mission also becomes longer if the spacecraft is directed to fly by multiple targets. For example, after flying by Jupiter in 1979, the Voyager 2 spacecraft flew by Saturn in 1981, Uranus in 1986, and Neptune in 1989.

Designing a spacecraft mission often involves making compromises with the different aspects of the program to keep the total costs within budget. This may require changes in the spacecraft or instrument design, or in the amount of data that can be returned back to the Earth. On the other hand, a successful spacecraft may also earn an extended mission, which allows the spacecraft to continue its exploration with additional funds even after the original mission is completed.

**Orbital Mission**

While a flyby mission is the simplest, and therefore the most likely to be successful, spacecraft mission to explore another world, it usually only offers a snapshot of one part of the world. A more complicated mission, but also one that can offer a more comprehensive science investigation, is an orbital mission, in which the spacecraft goes into an orbit around the target world (e.g., Fig. 4.) The main complication in this kind of mission compared with the flyby is the orbit insertion maneuver: firing the spacecraft's engines to change the trajectory so that the gravity of the target world can "capture" the spacecraft into an orbit around the object. An orbital mission can obtain more detailed information than a flyby since it not only will be able to see much more of (if not the entire) world, but it also can spend a longer time making repeated observations of the same area.

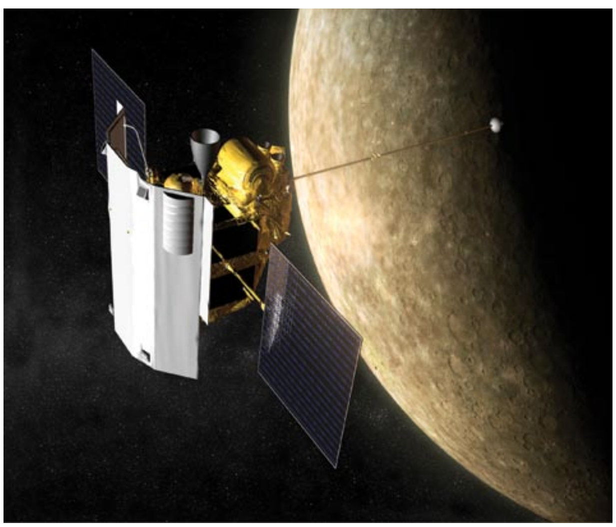


*Figure 4. An artist's impression of the MESSENGER spacecraft exploring Mercury. MESSENGER is the first spacecraft to explore the innermost planet in our Solar System since the 1970s, and the first ever to investigate the planet from orbit. (Picture credit: NASA/JHU-APL/CIW; http://messenger.jhuapl.edu/the_mission/artistimpression/atmercury_br.html)*

In addition to the costs described in the context of a flyby mission, the following additional aspects must be considered for a robotic orbital mission:

- Propellant required for the orbit insertion maneuver and for possible orbit correction maneuvers needed later;
- Hardware and software engineering necessary to prepare the spacecraft for the orbit insertion maneuver and for orbital operations;
- Additional instruments that may be desired for a more comprehensive science investigation;
- More involved communications with ground control on the Earth.

**Lander Mission**

The landing of a spacecraft, or the landing of a probe launched from a flyby or orbiting spacecraft, to another world entails additional complexity over an orbital mission. In addition to flying to the world, the mission must plan for a safe landing of the probe. In some cases, the probe is designed to just crash on the world and provide as much information as possible before the crash, but in most cases careful planning is required to ensure a soft, safe landing on the target world's surface. Spacecraft can be slowed down during descent by firing the engines at precise moments for a pre-determined duration, or by using parachutes if the target world has a substantial atmosphere. The spacecraft may also include cushioning (such as air bags) to prevent a jarring landing on the surface. Often, these options are combined to ensure a safe landing. A lander mission is riskier than a flyby or an orbital mission, since there are more chances for something to go wrong. For example, about half of all lander missions sent to Mars have failed for one reason or another. On the other hand, a lander mission can provide much more detailed information on the world than the other kinds of missions, often making the higher risk acceptable. A lander can examine the world's surface features close-up and use tools to burrow underground, drill into rocks, or take samples for analysis within the spacecraft. While most landers are stationary, some have been designed to move around the surface, providing detailed information over a larger area (see Fig. 5.)

In addition to the costs of a flyby mission, as well as those of the orbital mission (if the mission includes an orbiting component), a lander mission involves the following additional cost considerations:

- Fuel to slow down the spacecraft for landing;
- Engineering and additional hardware for landing (e.g., parachute, cushioning);

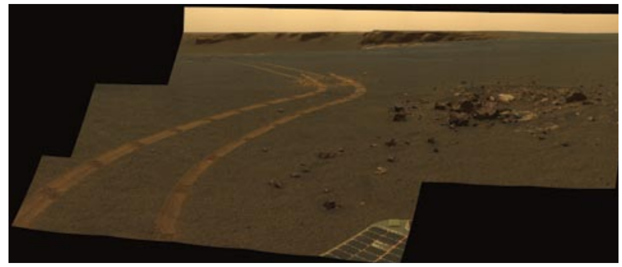


*Figure 5. This image taken by the Martian Exploration Rover Opportunity shows not only natural features of the surface of Mars, but also the tracks the rover has left behind. On the lower part of the picture, a section of the rover itself is visible. (Picture credit: NASA/JPL-Caltech/Cornell University; http://photojournal.jpl.nasa.gov/catalog/PIA10213)*

- Software engineering to prepare the spacecraft for landing;
- Engineering necessary to make communications from the surface back to the Earth reliable;
- Additional instruments that may be desired for a more comprehensive science investigation.

**Spacecraft Instruments**

The instruments used by spacecraft exploring other worlds depend on the kind of science the mission designers want to gather about the world. Typically, spacecraft include one or more of the following:

*Camera:* Cameras provide images not only to astonish us with views from another world, but also to give basic information on the target world for scientists to analyze. Cameras aboard spacecraft are in many ways similar to the digital cameras in wide use today in the way they capture images, though they usually have additional tools as part of the image capturing system, such as a (small) telescope to take more detailed images, a microscope to allow for detailed analysis of sampled material, or color filters to take images sensitive to different colors, which can then be combined to provide color pictures. Depending on how wide a view needs to be captured, the spacecraft may have a narrow angle (small field of view but more detailed images) or a wide angle (wider field of view but less detailed images) camera. A device with an exceptionally wide field of view is called a panoramic camera. A stereo camera has two lenses that make it possible to take three-dimensional images of a target, in this way mimicking human binocular vision. Cameras may also be sensitive to different kinds of light, producing images using infrared light, for example.

*Spectrometer:* An optical instrument that is used to measure properties of different colors, a spectrometer is often used to provide information on the composition of the object that is emitting or reflecting the light captured by the instrument. Spectrometers are sensitive to different kinds of light, and the exact kind of device placed aboard the spacecraft depends on what kind of information the scientists want to gather. Because spectrometers sensitive to different kinds of light can provide different information on the same targets, spacecraft often carry several spectrometers aboard, ranging from infrared and visible to ultraviolet, x-ray and gamma ray spectrometers. Spectrometers can also be designed to measure the properties of particle radiation, such as cosmic rays or neutrons, or the properties of geologic or atmospheric samples. Spectrometers are essential in providing information on the composition of the target world's atmosphere, rocks, and soil, as well as providing information on the space environment near the world.

*Magnetometer:* A magnetometer measures properties of the magnetic field near the spacecraft. The data gathered by a magnetometer can be used to provide information on the target world's magnetic field, the solar wind, and the behavior of the Sun's magnetic field in space near the world.

*Laser altimeter:* A laser altimeter uses a laser beam bounced off the surface of the world to determine the distance to various points on the body. It is used on orbital missions to map the heights or depths of the geologic features on the world.

*Radar:* A radar can be used like a camera to take images of the target world, but instead of capturing reflected or emitted light, it uses microwaves bounced off the surface of the world. Advanced radar systems can also be used to analyze the properties of the world's atmosphere, or features below the surface.

*Seismometer:* Just like similar devices on the Earth, seismometers can be used on a lander spacecraft to see if there are seismic quakes on the world (e.g., marsquakes or moonquakes.)

*Meteorology instrument:* To monitor weather on the target world, the spacecraft may be equipped with a suite of meteorology instruments to measure the temperature, air pressure, humidity and wind properties, for example.

*Geologic exploration tool:* For a more comprehensive analysis of the surface of the world, a lander may include an arm designed to take soil samples from the surface or dig underground. The lander may also be equipped with drills that can bore into rocks for a more detailed analysis of their properties. In this case, the lander becomes a robotic geologist.

*Life experiment suite:* If there is a chance of living beings existing on the target world, a package of laboratory experiments may be included. The experiments may look for life in different ways, such as searching for organic molecules or for chemical signs of microbial feeding or respiration.

The instruments described above are the most common types carried by spacecraft exploring other worlds in the Solar System, but there are many other tools that can be used, as well. More information on the instruments used by past and current spacecraft can be found on the mission Web pages.

**The Total Cost of a Spacecraft Mission**

While the design of the mission becomes more complicated as the type changes from a flyby to an orbital or a lander mission, there is sufficient variance in the costs discussed above for each type of mission that a lander mission is not always more expensive than a flyby mission, for example. Many factors can change the total cost of a mission, and it is often the overall budget that sets limits on how much science can be done with what kind of mission, and not vice versa. For a few examples of the total costs of various types of mission exploring different worlds in the Solar System, see Table 1.

Table 1: Examples of past and current spacecraft missions exploring other worlds in the Solar System.

| World | Mission | Timeline | Type | Total Cost |
|---|---|---|---|---|
| Mercury | MESSENGER | 2004 – | Orbiter | $446 million |
| Venus | Magellan | 1989 – 1994 | Orbiter | $680 million |
| Mars | Mars Express | 2003 – | Orbiter | $150 million |
| | Mars Reconnaissance Orbiter | 2005 – | Orbiter | $720 million |
| | Viking 1 and 2 | 1975 – 1982 | Landers and orbiters | $3.5 billion ($935 million in 1974 dollars) |

*(continued on the next page)*

Table 1 (continued): Examples of past and current spacecraft missions exploring other worlds in the Solar System..

| World | Mission | Timeline | Type | Total Cost |
|---|---|---|---|---|
| Mars, *continued* | Mars Exploration Rovers (Spirit and Opportunity) | 2003 – | Lander / rover | $820 million |
| | Phoenix Mars | 2007 – | Lander | $417 million |
| Jupiter | Pioneer 10 | Flyby in 1973 | Flyby | $350 million |
| | Voyager 1 | Flyby in 1979 | Flyby | $905 million[1] |
| | Galileo | 1989 – 2003 | Orbiter, atmosphere probe | $1.5 billion |
| Saturn | Pioneer 11 | Flyby in 1979 | Flyby | $350 million |
| | Cassini-Huygens | 1997 – | Orbiter, lander to Titan | $3.4 billion |
| Uranus | Voyager 2 | Flyby in 1986 | Flyby | $905 million[1] |
| Neptune | Voyager 2 | Flyby in 1989 | Flyby | $905 million[1] |
| Dwarf planet (Pluto) | New Horizons | 2006 – | Flyby | $550 million |
| Kuiper Belt Object | New Horizons | 2006 – | Flyby | $550 million |
| Dwarf planet (Ceres); asteroid (Vesta) | Dawn | 2007 – | Flyby | $446 million |
| Asteroid (433 Eros) | NEAR Shoemaker | 1996 – 2001 | Flyby, orbiter, lander | $220.5 million |
| Comet (9P/Tempel 1) | Deep Impact[2] | 2005 – | Flyby; probe crashed on comet | $240 million |
| Comet (67 P/ Churyumov-Gerasimenko) | Rosetta | 2004 – | Orbiter, lander | $980 million |

*Notes on Table 1*:

[1] Voyager 1 and 2 costs are the combined cost of the twin spacecraft.

[2] Deep Impact flyby spacecraft was granted an extended mission (under the name EPOXI) to study another comet and extrasolar planets.

Note that many of the missions listed in the table were designed to have the spacecraft fly by multiple targets, in some cases to perform gravity assist maneuvers to modify the spacecraft's trajectory toward other targets. For example, Voyager 2 flew by Jupiter, Saturn, Uranus and Neptune, and Cassini-Huygens flew by Venus and Jupiter before arriving at Saturn.

*Data in Table 1 from NASA National Space Science Data Center Spacecraft Project Page (http://nssdc.gsfc.nasa.gov/planetary/projects.html) and references therein.*

While the mission costs listed in Table 1 may look extravagant, especially considering that there are many problems right here on the Earth that could benefit from additional funding, it is good to remember that there are benefits from space exploration that go well beyond learning more about the target of the mission. For example, the bulk of the money given to a space mission goes into funding people and companies that design, construct, and conduct the mission. In this way, space exploration creates jobs which drive our economy and help create a financial environment in which additional funds can be assigned to other causes, as well. Furthermore, there are often technological solutions which are developed to make a spacecraft mission possible and which may be spun off for more Earth-bound applications. Therefore, while the primary goal of space exploration missions is to answer scientific questions about the target world, they often provide benefits that reach into our daily lives.

**Journey to the Target World**

How does a spacecraft travel from the Earth to another planet? Your first guess might be to launch a rocket from the Earth directly toward the planet in a straight line. However, because the planets move in their orbits around the Sun, that method does not work. If the spacecraft heads toward the location where the other planet is when the spacecraft is launched, the planet would have moved along on its orbit by the time the spacecraft reaches the location, and the spacecraft would miss its target. Consider the following analogy. You and a friend are playing catch with a football in a large open field. Your friend runs away from you, and you throw the football to your friend's current location. By the time the football gets there, your friend will be farther away and the football will just fall to the ground. Instead, you need to estimate where your friend will be in a few seconds and throw the ball to that point. If you have guessed correctly, your friend and the football will get to the same point at the same time, and the ball will be caught. You would also notice that the football does not travel in a straight line. This is because once the football leaves your hand, the motion of the ball is controlled mainly by the Earth's gravity, which is pulling the ball toward the ground as it flies through the air, causing the ball to fly in an arc.

Now consider sending a spacecraft from the Earth to Mars. When the spacecraft is launched, it does not fly in a straight line, but rather in a curve bending around the Sun. This is because the force of the Sun's gravity is pulling it toward the Sun, just like the same force is pulling the Earth toward the Sun. And just like this causes the Earth to orbit the Sun in an elliptical orbit, the spacecraft at the time it leaves the Earth is on a similar orbit around the Sun. The properties of the initial orbit are determined by the launch details, and they can be modified later with course correction or gravity assist maneuvers.

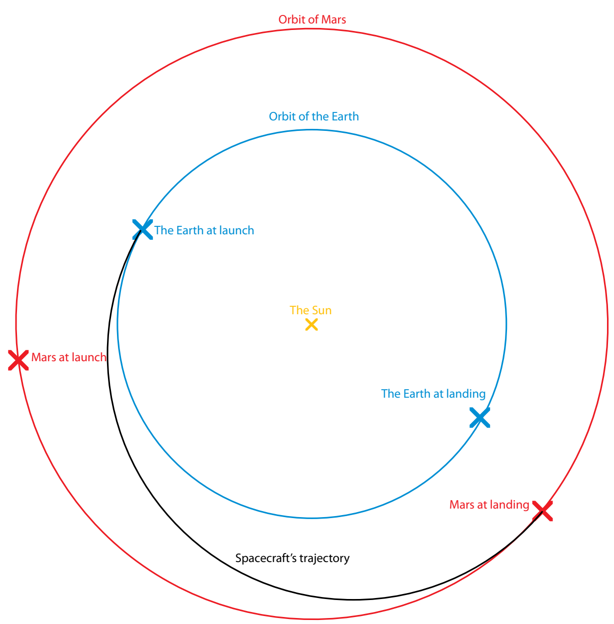



*Figure 6. The trajectory of a spacecraft traveling from the Earth to Mars.*

If the spacecraft had enough fuel, it could use its engines to overcome the gravitational pull of the Sun and fly in a more straightforward manner toward its target. However, to carry enough fuel, the spacecraft would need to be larger, it would be much heavier and, therefore, it would be much more expensive to launch. This is one of the basic problems to consider when launching a spacecraft. Mission designers want spacecraft to get from the Earth to Mars (or any other planet) using the least amount of fuel. It turns out that the best way to send a spacecraft to Mars using the least amount of fuel is to have the spacecraft travel in a trajectory that is an orbit around the Sun where the orbit's closest approach to the Sun is at the Earth's distance (at launch) and the farthest distance from the Sun the same as Mars's distance (at arrival; see Figure 6.) In this case, the spacecraft does not need to use any fuel while traveling from one planet to the other after being set on the so-called transfer orbit: the spacecraft can cruise through space toward its target.

**Mission Length and Gravity Assists**

How long does it take to go from the Earth to different places in the Solar System? There were six landings on the Moon during the Apollo era (Apollo 11, 12, 14, 15, 16, 17 in 1969-1972); it took just over three days for the spacecraft to get to the Moon. For a quick estimate for the travel times to other worlds in the Solar System, let's assume that a spacecraft is flying at 11.2 kilometers per second (25,000 miles/hour); this is the escape velocity from the Earth; that is, the speed which an object (such as a spacecraft) needs to have to overcome the gravitational pull of the Earth and travel into space. We can then make a quick estimate that it would take 95 days to travel to Mercury, 43 days to Venus, 81 days to Mars, 2 years to Jupiter, and 16 years to Pluto! Note that this quick "back-of-the-envelope" calculation is based on the differences in the target worlds' and the Earth's average distances from the Sun, and it does not include the more realistic curved trajectories discussed earlier; for example, the real travel time to Mars is typically about six months instead of the 81 days calculated above. However, the calculation does give a basic order-of-magnitude idea of how long it takes to travel to the different worlds in the Solar System.

One way to shorten the travel time is to use more fuel to boost the speed of the spacecraft. However, extra fuel raises the cost of the mission significantly and is rarely worth the cost. Another way to boost the speed without using more fuel is through a method known as gravity assist where a spacecraft can use a planet's gravity to change its speed and direction in a similar way as a tennis ball thrown at a moving train causes the ball to change direction and speed when bouncing off the train (though with the difference that the spacecraft does not actually strike the planet.) Using this method can aid the mission significantly. For example, the New Horizons spacecraft, launched in 2006, left the Earth at a speed of 16 km/s (36,000 mph.) After flying by Jupiter in 2006, the spacecraft sped up to the speed of 23 km/s (51,000 mph) relative to the Sun. As a result, New Horizons will reach Pluto in 2015, only 9 years after launch. In some cases, a mission might not be even possible without gravity assist maneuvers. For example, without the complicated gravity assist trajectory, the MESSENGER spacecraft would not be able to go into orbit around Mercury. In this case, the complicated trajectory actually increases the travel time, but the requirement to perform an orbital mission makes the extra travel time worthwhile.

**Human Exploration versus Robotic Missions**

Space is a dangerous environment for humans to operate, with hazards ranging from the airless vacuum to temperatures that are either scorching hot or freezing cold, depending on whether one is in sunlight or in shade, or close to or far away from the Sun. As a result, humankind has never sent astronauts anywhere other than the orbit around the Earth and to our Moon, and no human has been on the Moon since the Apollo 17 crew returned from their three-day visit in 1972. There are plans to build a permanent settlement on the Moon and send humans to Mars in the next few decades, but these kinds of missions require extensive planning and are very expensive. This is due to many reasons. The mission must be self-sufficient all the way to the target world and back; the astronauts cannot depend on getting more supplies from the Earth. For example, establishing a settlement on the Moon or Mars would require that the astronauts grow their own food and have a system to recycle water. They would have to have equipment to generate oxygen and remove carbon dioxide from the air. They may also need to produce fuel at their landing location or settlement, making locating and securing resources on the target world necessary. Additional thought must be given to secure the health of the astronauts in other ways, from combating muscle weakness caused by lower gravity to making sure the dangerous forms of radiation coming from the Sun and elsewhere in the Universe does not cause severe harm to the astronauts. On the Earth, we are protected from this kind of hazardous radiation by the atmosphere, but the astronauts would not have this protection on a long journey through space, or while on a world without as substantial an atmosphere as the Earth. While designing robotic spacecraft missions require taking into account many of the same issues (cold and/or hot temperatures, radiation, vacuum), the concern is nowhere near on the same level as it would be for humans performing the same functions. As a result, robotic exploration of the Solar System remains more cost-effective than human spaceflight.

**Proposing Exploration of Other Worlds**

An exploration of another world typically begins with a proposal to a funding agency (such as NASA) providing details for the proposed mission. The science team must explain why their target is worth studying, identify science goals, and explain how the goals can be met with their particular mission design. A detailed budget for each aspect of the mission must be provided, and the total budget must be within specified limits. The proposal must also consider the risks associated with the mission and estimate how likely it is to succeed. Often, the proposing team has to modify their initial idea for the mission based on budgetary constraints. Sometimes science goals may have to be scoped down, or some investigations may have to be abandoned to keep the proposal within constrains. For example, NASA Discovery Program allows scientists to propose highly focused planetary science investigations. The program solicits proposals from the planetary science community every so often, and after careful review of all received proposals, the winning missions are announced. The selected missions are cost-capped; that is, the mission teams are given a maximum allowed budget within which they must plan the mission, construct the spacecraft, launch it, monitor its journey, and receive and analyze the data. A lot of work goes into making a winning proposal, but once selected, the mission design team can use the proposal as a blueprint to guide their mission to a successful completion.

# Lesson Plan

## Warm-Up & Pre-Assessment

1. Make an overhead transparency of each of the three *Earth and Mars Orbit Transparencies* found in the back of the lesson.

2. Have the students share experiences that require reacting to a moving target. Examples might be passing a football, catching a fly ball, driving vehicles to avoid being hit, or playing dodge ball. Lead the students to discuss the how and why of the necessary movements to complete the tasks.

3. Display the first transparency with the locations of the Earth and Mars. Ask the students to imagine that NASA wants to launch a spacecraft from the Earth to Mars, and it will take about six months to get there. What would happen if they aimed directly to where Mars is at that moment? *(Desired answer: Mars would have moved on its orbit and the spacecraft would miss it!)*

4. Remind the students how planets move in their orbits: planets closer to the Sun move in their orbits faster than those farther away from the Sun. Ask the students where the Earth would be when the spacecraft lands on Mars, if the journey takes six months. *(Desired answer: since the Earth takes one year to orbit the Sun, it will be exactly on the other side of the Sun in six months.)* Make a dot on the transparency where the Earth would be in six months. Ask the students where Mars would be in its orbit. *(Desired answer: since Mars is slower in its orbit, it will not be on the other side of its orbit, and would not have moved as far as the Earth had moved.)* Display the second *Mars and Earth Orbit Transparency*, which shows the locations of the planets six months later.

5. Ask the students to imagine the trajectory (path) of the spacecraft as it leaves Earth and meets up with Mars six months later. Have a discussion about what the path may look like.

**Materials**

*Per class*:

- *Earth and Mars Orbit Transparency 1, 2, 3*

**Teaching Tip**

You can make class copies of the second transparency and have the students draw on their copy their guess of the trajectory rather than leaving it an open discussion.

6. Place the third transparency on top of the second, and line up the transparencies so that students can see the trajectory of the spacecraft. Discuss why it would be difficult to have the spacecraft travel in a straight line from the Earth to Mars. *(Desired answer: to travel in a straight line, the spacecraft would have to fight the gravitational pull of the Sun, which tries to make the spacecraft move on a curved orbit around the Sun, all the way to Mars, while this trajectory allows the spacecraft to cruise most of its journey without using additional fuel. It is more energy-efficient and, therefore, more fuel- and cost-efficient, to use this kind of trajectory.)*

7. Discuss with the students issues that scientists and engineers have to consider when planning a robotic spacecraft exploration of another world, such as what they want to learn of the world, how to travel to the world, whether to land on the world, or just observe it from a distance, how to send data back to Earth, etc.

## ACTIVITY 1: STRANGE NEW PLANET

In this activity, students explore the advantages and disadvantages of different kinds of explorations of another world, such as Earth-based observations, or flyby, orbital, and lander missions to the world. Students use an object such as a plastic ball or round fruit to represent a planet, and decorate it with stickers to simulate landforms, create clouds using cotton and glue, carve channels, apply scents, place moons around it, etc. The students simulate four different types of missions and list the strengths and weaknesses of each. They also discuss the advantages and disadvantages of planning a human spaceflight versus a robotic spacecraft mission.

**Materials**

*Per class*:

- Roll of masking tape
- Yard or meter stick
- Stopwatch or clock

*Per group of 3 or 4*:

- Plastic ball, Styrofoam© ball, or round fruit (cantaloupe, pumpkin, orange, etc.)
- Modeling clay, e.g., Playdoh©
- Vinegar, perfume, or other scents
- Small stickers, sequins, candy, marbles; anything small and interesting
- A few cotton balls
- A few toothpicks
- Glue
- Towel or a large sheet of opaque paper (to drape over the model planet)
- Push-pin
- Pen, pencil, or marker
- Index card
- Sheet of colored cellophane; large enough to cover the model planet (optional)
- Knife (optional)

*(continued on the next page)*

## PREPARATION

1. Make one copy of Student Worksheet 1 per student.
2. Gather group materials to pass out or lay out materials for groups to take as needed.
3. Divide students into groups of three or four.
4. Pair up each group with another. Each group will study the planet designed by their partner team.

## PROCEDURES

*A. Class discussion*

1. Ask the students to describe the planet Earth. What are some of its characteristic features? How does the Moon look different from the Earth? What do the students know about the Moon by just looking at it? How would their observations change if they got closer to the Moon? If they landed on it?
2. Ask the students to come up with different ways they can explore another planet in the Solar System. Make sure the students come up with all the mission possibilities discussed in this activity.
3. Pass out Student Worksheet 1. Explain that the groups will investigate the differences between the various ways to explore another planet.

*B. Creating a model planet*

1. Have each group choose an object such as a plastic ball or fruit (e.g., a cantaloupe) that allows for multi-sensory observations. Instruct the students to decorate the object with stickers, toothpicks, scents, etc., to make the object interesting to observe. Some of the materials should be placed discreetly so that they are not obvious upon distant or brief inspection. Some suggestions for features are:

   - Carve channels with a toothpick or a knife;
   - Attach small stickers or embed other objects onto the ball or fruit (to represent different kinds of landforms);
   - Apply scent sparingly to a small area;
   - Use a sheet of clear or colored cellophane to wrap up the model planet (to represent different kinds of atmosphere);
   - Create clouds by using cotton and glue;
   - Attach a toothpick with a piece of modeling clay at the end (to represent a moon).

2. Make sure the students record on Student Worksheet 1 what each feature is and what it represents in their model planet. Their partner team will explore the planet later, and there needs to be a record of what the features are versus what the other team sees.

3. When the teams are finished, place the model planets on a desk in one side of the room. Make sure the students place an index card next to each planet identifying the team whose model it is. Cover each model planet with a towel (or a large sheet of opaque paper.)

4. Hand out to the students their Viewers – paper towel rolls or rolled-up sheets of paper.

**Materials**

*(continued from page 21)*

*Per student*:

- Student Worksheet 1
- Paper towel roll or a sheet of letter-size paper rolled up and taped on the side to form a tube
- 5″x5″ square of clear cellophane (optional)
- 6″ piece of tape or a rubber band (optional)

*C. Mission 1: Earth-based observations (simulating observations made from observatories on the Earth or with space telescopes near the Earth)*

1. Have the students gather in teams in the opposite side of the room from where the model planets are located. This space will act as the Mission Control for each team.

2. If you want to include a representation of the Earth's atmosphere, you can have the students crumple up a piece of clear cellophane, then straighten it out and place it on the end of their Viewers, taped or held in place by a rubber band. This helps to simulate the variation that occurs when viewing objects through the Earth's atmosphere. You can also leave out the piece of cellophane, in which case the observations would be similar to those made by space telescopes near the Earth.

3. Uncover the model planets. Have the teams observe the model planet of their partner team using their Viewers for two minutes. Rotate each model planet so that the other side can be observed (to simulate the rotation of a real planet.) Allow another two minutes for new observations. Cover the model planets with towels.

4. Have the teams discuss and record their observations in Student Worksheet 1. At this point, most of the observations will be visual and will include color, shape, texture, and position. The teams should also discuss and write down questions to be explored in future missions to the planet before moving on to the next section.

*D. Mission 2: Flyby*

1. Use masking tape to mark a distance of about five feet from the desk holding the model planets.

2. Partially uncover the model planets so that one side of each planet is in sight, but the rest is still covered by the towel.

2. Have the teams quickly walk by their target planet and use their Viewers to make their observations. Make sure no-one approaches the planet closer than the distance marked on the floor.

3. Place the towels back over the model planets.

4. Have the teams reconvene at the Mission Control to record and discuss their observations. The teams should also discuss what they will be looking for in their orbiter mission.

*E. Mission 3: Orbiter*

1. Use masking tape to mark a distance of two feet from the desk holding the model planets all around the table. If the desk is large, you may want to move the planets to individual desks to make sure all sides of the target planets can be observed from roughly the same distance.

2. Uncover the model planets.

3. Give each team two minutes to orbit (circle) their target planet at the marked distance and to look at the features on the model planet through their Viewer. Remind the students that they have to move around their target planet the whole time; they cannot stop and look closer at any point. Have the students reconvene at their Mission Control to record and discuss their observations. The teams should also develop a plan for their landing expedition onto the planet's surface. Plans should include the landing spot and a list of features to be examined.

*F. Mission 4: Lander*

1. If pieces of cellophane were wrapped around the model planets to simulate atmospheres, remove them carefully and make sure no other features are disturbed. Removing the model atmosphere simulates the effect of making observations from the ground, without having to look through the atmosphere when making observations from a distance. Have the teams mark their landing sites on their target planets with a push-pin (or a piece of masking tape if the model planet will not accommodate a push-pin.) Have the team place their Viewer around the push-pin, draw a circle on the model planet's surface around the Viewer, and then remove the Viewer and the push-pin. The circle marks the maximum area around the landing site which can be explored with this mission. Remind the students that they are not to make any observations of features beyond the circle.

2. Have the team members observe the area around the landing site close-up for five minutes.

3. Have the students reconvene at their Mission Control to record and discuss their observations. The teams should also discuss additional features they might want to investigate with a follow-up mission.

## DISCUSSION & REFLECTION

1. Have the students compare their observations with the list of features placed on the model planet by their partner team. Did they see all features with all missions? Were there any they did not observe at all?

2. Discuss with the students, and make a class list, of the pros and cons of each type of exploration. Your table might look something like the following:

| Mission 1: Earth-based observations | | Mission 2: Flyby | | Mission 3: Orbiter | | Mission 4: Lander | |
|---|---|---|---|---|---|---|---|
| Pros | Cons | Pros | Cons | Pros | Cons | Pros | Cons |
| | | | | | | | |

3. Discuss with the students other differences besides just the kind of observations one can make with the different missions, such as: Which mission is the easiest to do? Which ones are most likely to require complicated tools and machinery? Which one would be the most likely to succeed? What kinds of hazards could each mission face? Which ones would be most expensive? See the *Science Overview* for a more detailed discussion.

4. Ask the students what kind of mission they would design to explore an object in the Solar System that has never been visited by a spacecraft before. An example could be Pluto, a dwarf planet in the outer parts of the planetary realm of the Solar System (note that the New Horizons spacecraft will fly by Pluto in 2015, so after that Pluto will no longer be a good example.) What do the students know about Pluto already? What would they want to learn with the new mission? Would they want to do a flyby, orbiter, or a lander mission? The total cost of the flyby New Horizons mission is $550 million, and it will fly by Pluto nine years after launch. What if the cost of the orbiter mission is two times more, and it takes five years

longer to do it? What if the lander is five times more expensive and takes another five years longer? Would the additional cost and time influence the students' decision?

5. Discuss with the students how what scientists want to learn about a world determines how a mission is initially planned, but real-world constraints such as available funding can influence mission design significantly. In the next activity, students will plan a mission to explore another world, and they must take into account not only what they want to learn about the world to decide if it will be a flyby, an orbiter, or a lander mission, but also consider the costs involved with the different kinds of missions.

6. Ask the students what additional problems mission designers might face when planning a human spaceflight mission instead of using robotic spacecraft. *(Desired answers include: equipment and supplies necessary to sustain the life of the astronauts, such as food, water, air, and ways to recycle the resources; shielding from the dangers of the harsh space environment, such as vacuum, extreme temperatures, and damaging radiation. See the* Science Overview *for more details.)* Discuss with the students how these considerations have limited human spaceflight so far to the space near the Earth and to the Moon, and why only robotic spacecraft have journeyed further into space.

## Activity 2: Mission Design

Students create a plan for a spacecraft exploration of another world. They will consider different aspects of mission planning, including science goals, engineering constraints, and financial considerations. They have to consider how their exploration would be affected in terms of whether the spacecraft would land, orbit, or just fly by the target. Students will come to understand that what one wants to learn about a world determines how one plans a mission, but real-world constraints such as cost and time determine what actually can be accomplished.

**Materials**

*Per group of 3 or 4*:

- Student Worksheet 2
- *Mission Log*
- Presentation materials, such as access to PowerPoint or poster board and markers, depending on how you decide to have the groups present their mission proposal

### Preparation

1. Students will design a mission to explore another world in the Solar System. You can have the students plan their mission without budgetary limits, or you could make the activity a NASA Discovery Program mission design process, for example, with a cost cap of $450 million. Examples of past and current Discovery Program missions include Deep Impact, which studied the comet 9P/Tempel 1, and the MESSENGER mission to Mercury. The cost restriction makes the mission design more challenging, because the students have to meet their mission goals with limited funding. However, the restriction also makes the decision of which mission to fund more balanced, since all missions would cost roughly the same.

2. Reserve appropriate materials for the students to present their final mission proposals: access to PowerPoint or materials to create a poster.

3. Make copies of Student Worksheet 2 and *Mission Log* (found at the back of the lesson), one per group of three or four students.

### Procedures

1. Divide students into groups of three or four.

2. Ask each group to choose a world in the Solar System (such as a planet or a moon) that they would like to explore. Tell the students that they will be designing a spacecraft mission to this world using one of the methods they investigated in Activity 1.

3. Pass out copies of the *Mission Log*, which is a description of some of the different worlds in the Solar System, including a list of missions that have explored these worlds to date. Have the groups take a few minutes to examine the whole *Log* to understand the history of investigating other worlds in the Solar System, and then focus on the description of the world of their choice. Science builds on previous studies, so the students need to design a mission to investigate unknown aspects of the world and not just repeat something that has been done before (unless something new could be learned from a repeat experiment.) Be sure to point out that even though each *Log* page mentions the likelihood of life existing on the different worlds, the search for life is by no means the only, or in many cases even a very important, reason to explore other worlds in the Solar System. There are open science questions about all worlds discussed in the *Log*, making them well worth exploring.

4. Pass out Student Worksheet 2. Have the students follow the instructions to plan a mission to the world of their choice.

**Teaching Tips**

- The dollar figures given for the costs of spacecraft missions can be put to a better perspective by relating them to more familiar matters, such as the population of the United States and common expenses. For example, funding a $450 million spacecraft mission would be equivalent to every person in the U.S. skipping buying a $1.50 soda bottle.

- You may want to have the students conduct more research into what is known about their target world, open questions about it, and the past missions that have explored their world. The Web sites listed in the *Internet Resources & References* section are good places to look for more information.

- In Student Worksheet 2, the students are asked to re-think their mission designs due to constraints introduced during the planning process. This is an important part of creating a mission. Encourage students to re-design their mission in order to come up with the most complete and comprehensive mission possible.

- If you have completed the first lesson in the *Mission Design* Education Module, "Exploring Exploring", you can have students form the same groups that they had in that lesson and plan the mission to the world that they chose to investigate there.

## Discussion & Reflection

1. Ask the students to identify any difficulties in completing this assignment. Ask the students to relate these difficulties to real-world constraints. How do they think this relates to what scientists and engineers go through when designing a real mission?

2. Discuss how financial considerations introduced constraints on the students' missions. How do they think space exploration would be different if these constraints did not exist?

3. Have the students present their mission proposal to the rest of the class, which can act as a NASA review panel. These kinds of panels are charged with reviewing mission proposals and selecting one or more for funding. In their proposal, the students must include an explanation for why they decided to go with a flyby, an orbiter, or a lander mission, and they must defend their exploration in terms of the science that can be accomplished, the risk, and the total cost of the mission. The class can vote for which missions they would fund and why. Perhaps you can offer extra credit to the winning proposal teams.

## Curriculum Connections

- *Technology*: Have the students explore further the differences between the technology needed for human spaceflight versus robotic spacecraft missions.

- *Social Studies*: Remind the students how financial considerations introduced many constraints on the students' missions. You can take this opportunity to discuss how NASA is funded with federal tax dollars. Have the students research how NASA funding compares with other federal programs. Do the students think the allocation of funds to NASA is appropriate? If NASA were to receive more money to fund more missions to explore other worlds, funding for other programs would have to be reduced, or federal taxes would have to be raised. Discuss how the government must be able to allocate its resources in a reasonable manner, and that there is not an unlimited supply of funding available for any one agency.

## Closing Discussion

1. Discuss with the students how the kinds of questions we want to answer about a specific world may dictate the kind of mission we want to perform. Stress that understanding the similarities between different worlds in the Solar System allows scientists to plan their missions better, for example by using similar instruments to study different worlds.

2. Discuss with the students how designing new missions to study other worlds builds on previous explorations, from defining science questions to providing instrument designs that are used to answer those questions.

3. Discuss with the students how available technology sets constraints on the kinds of missions that are possible at present time, while sometimes it is necessary to develop new technologies to answer particularly important science questions. Therefore, it is possible for science to drive technology, or for the available technology to define the kind of science that is possible, but the two always go hand-in-hand.

4. Hand out copies of the *Mission Information Sheet* located at the back of the lesson. Discuss with the students how the mission designers had to consider the same kinds of issues that the students faced in planning their missions.

## Assessment

4 points

- ▼ Student listed pros and cons for each type of mission in Student Worksheet 1.
- ▼ Student completed Student Worksheet 1.
- ▼ Student used reasoning to support the mission design in Student Worksheet 2.
- ▼ Student presented his/her team's mission proposal to the class and used evidence and reasoning to support the mission design.

3 points

- ▼ Three of the four above criteria were met.

2 points

- ▼ Two of the four above criteria were met.

1 point

- ▼ One of the four above criteria was met.

0 points

- ▼ No work completed.

## INTERNET RESOURCES & REFERENCES

*MESSENGER web site*

http://messenger.jhuapl.edu/

*American Association for the Advancement of Science, Project 2061, Benchmarks for Science Literacy*

http://www.project2061.org/publications/bsl/online/bolintro.htm

*National Science Education Standards*

http://www.nap.edu/html/nses/

*Cassini-Huygens Mission to Saturn*

http://saturn.jpl.nasa.gov/

*Dawn Mission to Asteroids*

http://dawn.jpl.nasa.gov/

*Deep Impact Mission to a Comet*

http://deepimpact.umd.edu/

*Galileo Mission to Jupiter*

http://solarsystem.nasa.gov/galileo/

*Hubble Space Telescope*

http://hubblesite.org/

*Keck Observatory*

http://www.keckobservatory.org/

*Magellan Mission to Venus*

http://www2.jpl.nasa.gov/magellan/

*Mars Express Mission*

http://www.esa.int/SPECIALS/Mars_Express/

*Mars Exploration Rover Mission*

http://marsrovers.jpl.nasa.gov/home/

*NASA: Discovery Program*

http://discovery.nasa.gov/

*NASA: Gravity Assist Primer*

http://www2.jpl.nasa.gov/basics/grav/primer.html

*NASA: Human Space Fight*

http://spaceflight.nasa.gov/station/

*NASA: Mars Exploration Program*

http://mpfwww.jpl.nasa.gov/

*NASA National Space Science Data Center Spacecraft Project Page*

http://nssdc.gsfc.nasa.gov/planetary/projects.html

*NASA: Planetary Photojournal*

http://photojournal.jpl.nasa.gov/

*NASA Solar System Exploration*

http://solarsystem.nasa.gov/

*NEAR-Shoemaker Mission to Asteroids*

http://near.jhuapl.edu/

*New Horizons Mission to Pluto and the Kuiper Belt*

http://pluto.jhuapl.edu/

*Phoenix Mars Mission*

http://phoenix.lpl.arizona.edu/

*Pioneer 10 and 11 Missions to Jupiter and Saturn*

http://www.nasa.gov/centers/ames/missions/archive/pioneer10-11.html

*The Nine Planets*

http://nineplanets.org/

*The Nine Planets – Planetary Science Spacecraft*

http://nineplanets.org/spacecraft.html

*Rosetta Mission to a Comet*

http://sci.esa.int/rosetta/

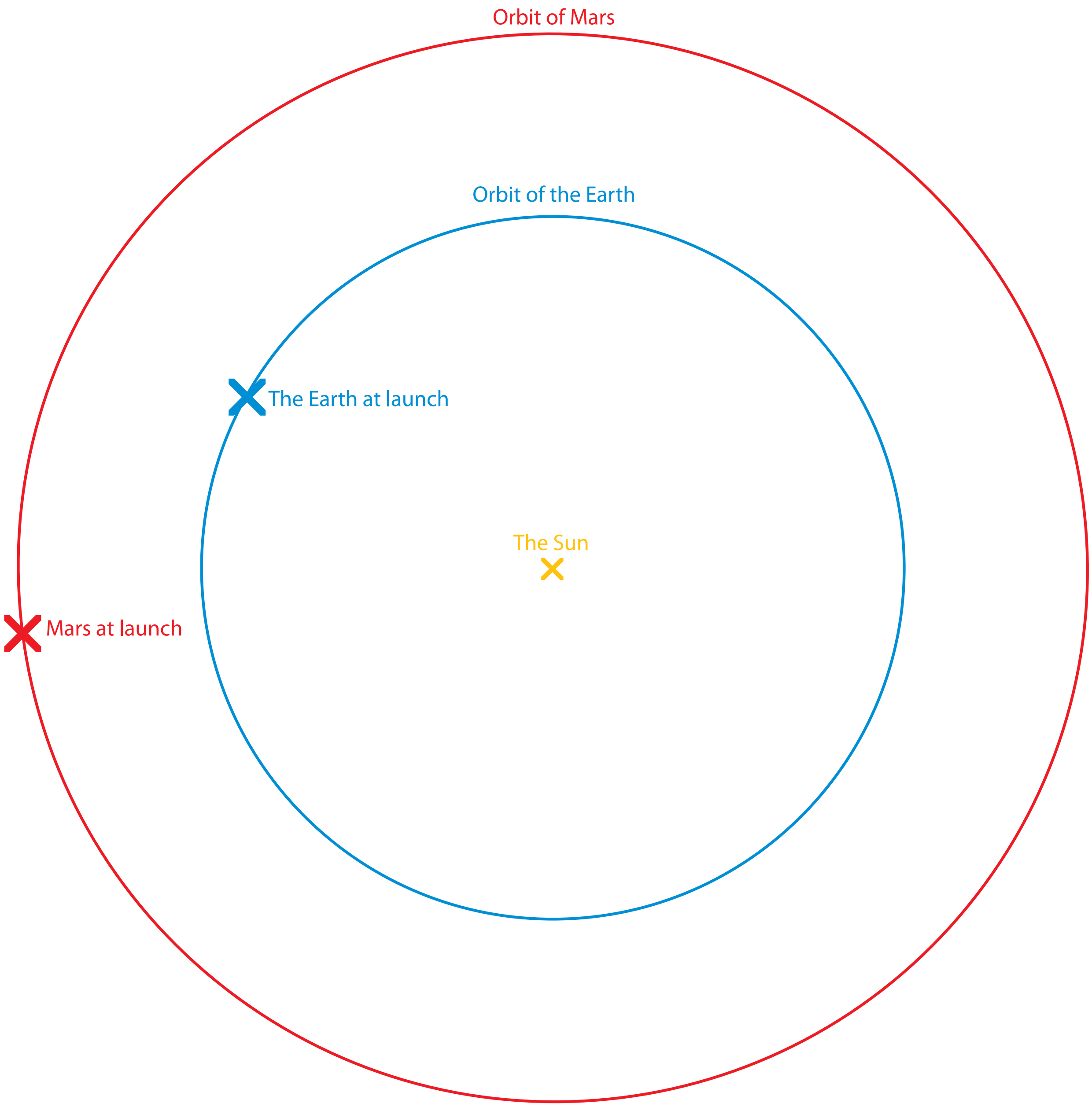
*Voyager 1 and 2 Missions to Jupiter, Saturn, Uranus, and Neptune*

http://voyager.jpl.nasa.gov/

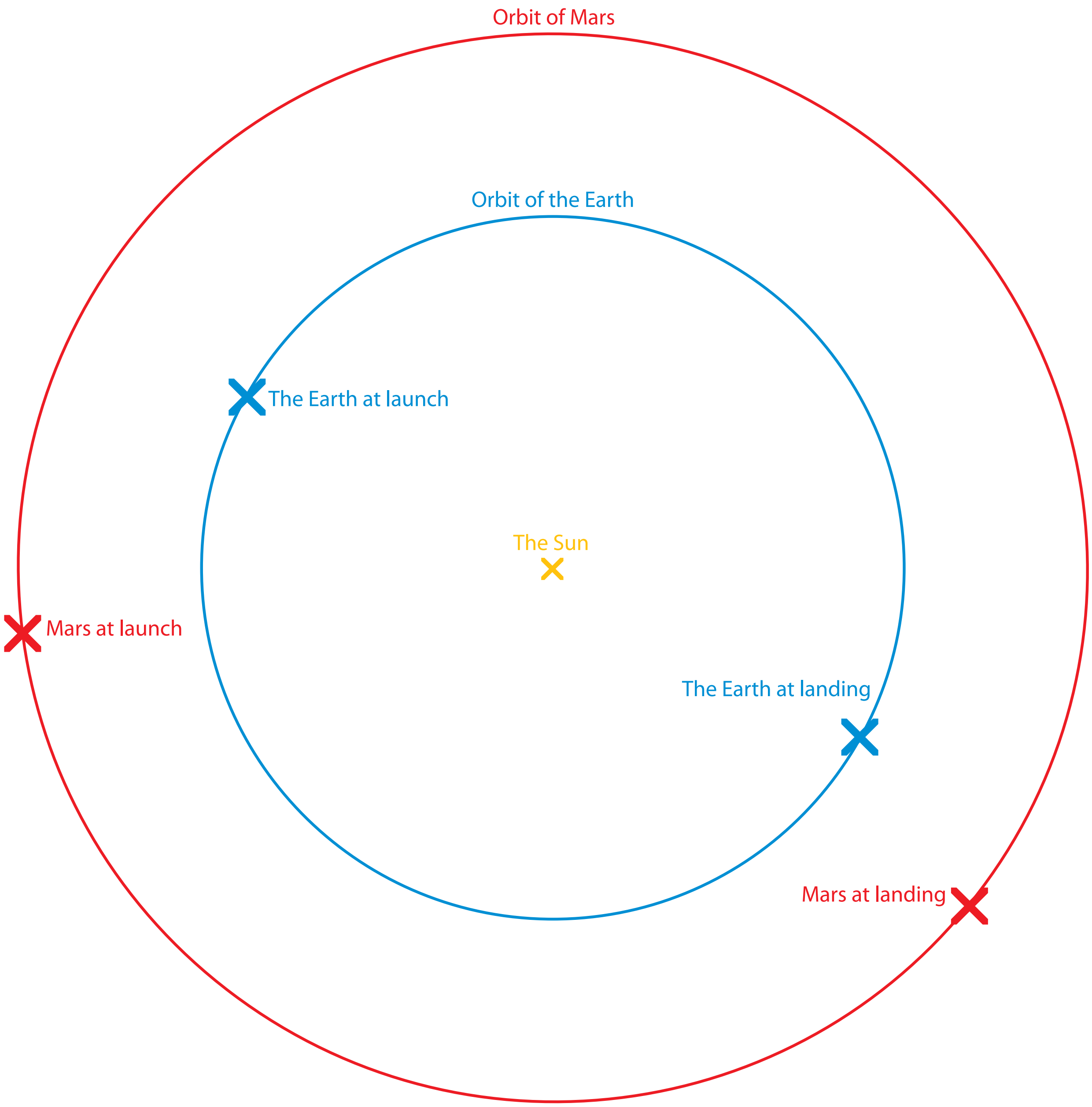
## Acknowledgements

Activity 1 was adapted from "Strange New Planet" from the ASU Mars K-12 Education Program 6/99 (http://quilt.jpl.nasa.gov/docs/Strange_New_Planet.pdf), which in turn was adapted from NASA Education Brief "EB-112: How to Explore a Planet" 5/93..

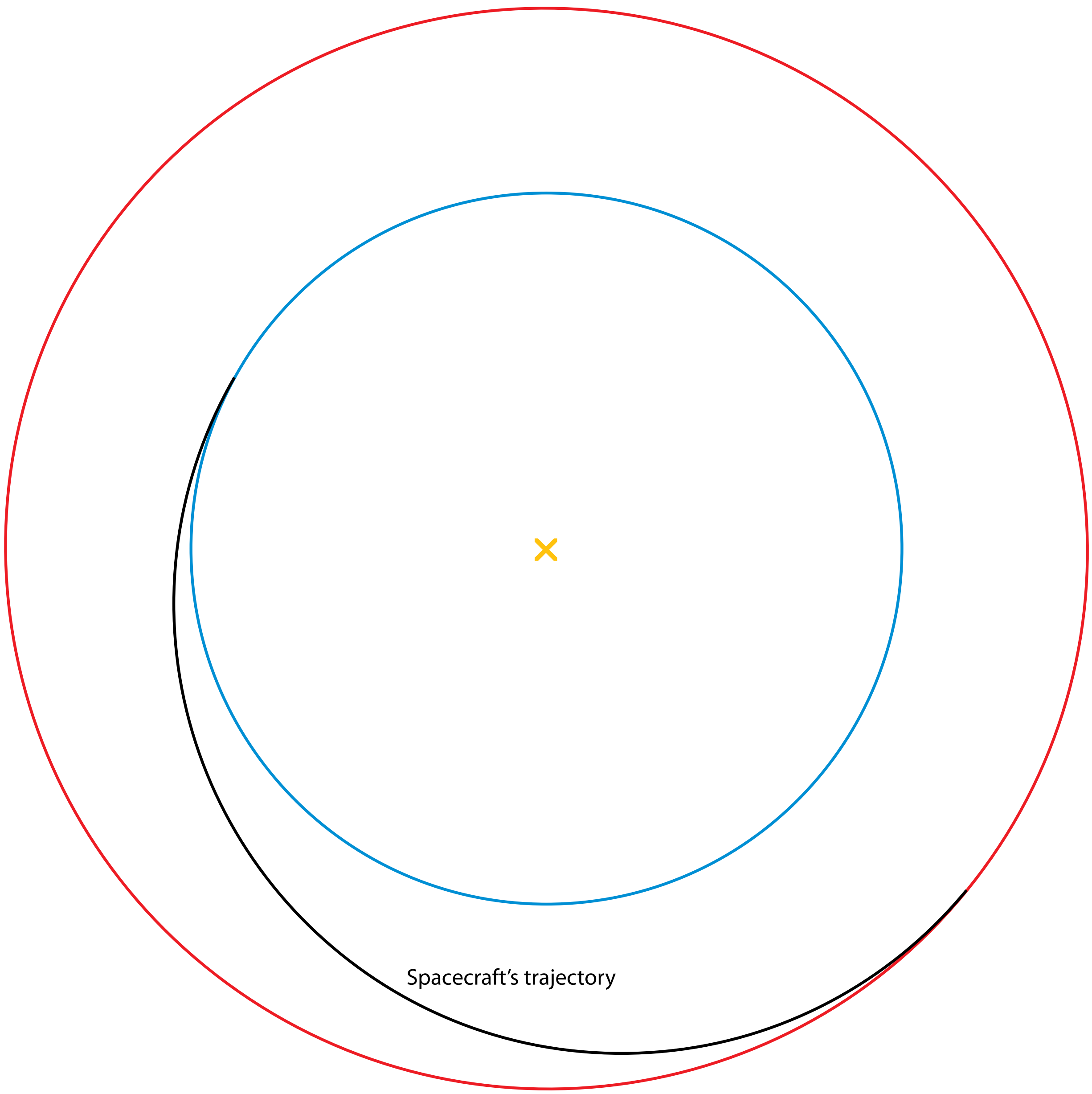
# Earth and Mars Orbit Transparency #1



# Earth and Mars Orbit Transparency #2

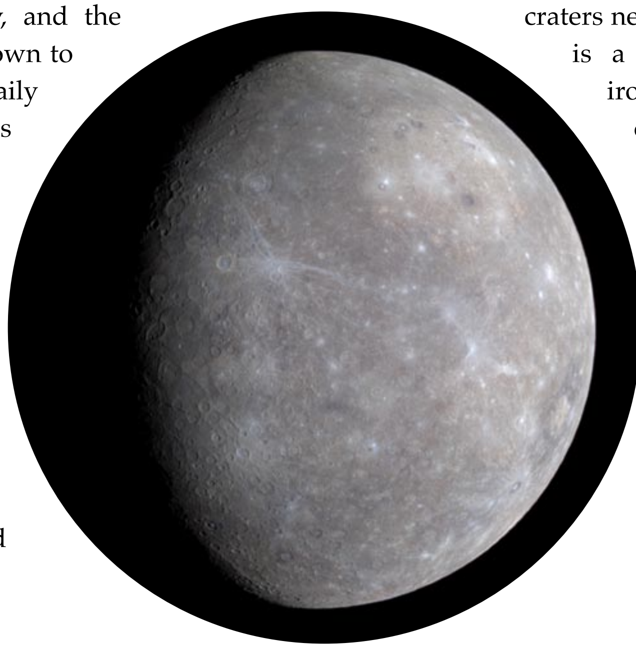


# Earth and Mars Orbit Transparency #3



# Mission Log: Mercury

Mercury is the closest planet to the Sun. Its diameter is only a little more than a third of the Earth. It has a very thin atmosphere, which is only a little more substantial than a vacuum. Sunlight heats up the surface of the planet to high temperatures during the day, up to 450ºC (840ºF). At night, the surface cools off rapidly, and the temperatures can drop down to –180ºC (–300ºF). This daily temperature variation is the largest of all planets. Mercury orbits the Sun once every 88 Earth days; that is, its year is 88 Earth days long. Mercury's day is much longer than the Earth's. It rotates once around its axis every 59 Earth days; the slow rotation rate, combined with the planet's fast orbital period around the Sun, makes the the length of one day on Mercury is equal to 176 Earth days; that is, the time from one sunrise to another is 176 Earth days. There is no liquid water on Mercury, although it is possible that water ice could exist in the permanently shadowed craters near Mercury's poles. Mercury is a planet with a very large iron core and a thin mantle compared with the Earth. Mercury is bombarded by intense solar radiation since its atmosphere is not sufficiently thick to provide much protection (unlike the atmosphere of the Earth), and it is so close to the Sun. It is unlikely that any life forms could live on Mercury.



### Spacecraft Missions to Mercury:

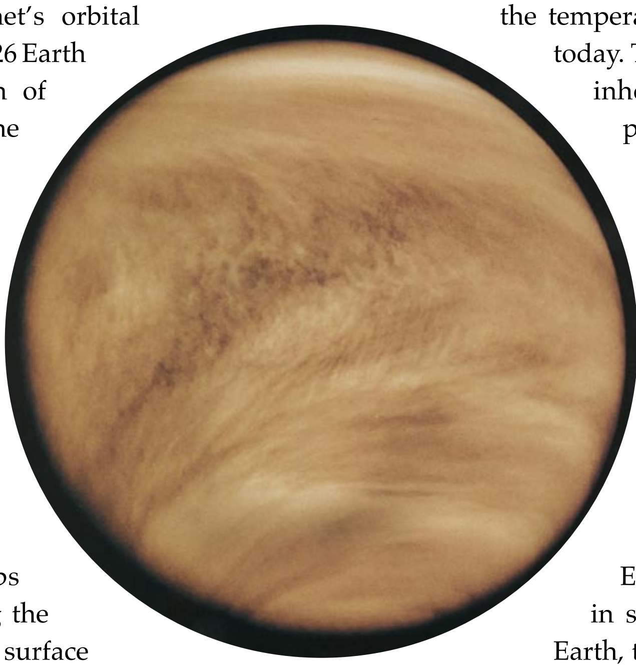
- Mariner 10 (1974-1975): The spacecraft flew by the planet three times, took images of 45% of the surface and revealed that Mercury had greater mass than previously thought.
- MESSENGER (launched in 2004): This orbiter mission flew by Mercury three times in 2008 and 2009 and will go into orbit around the planet in 2011. During its year-long orbital mission, the spacecraft will map the entire surface and conduct a comprehensive study of the planet and its space environment.

For a complete list of past, current, and future missions to Mercury, see http://nssdc.gsfc.nasa.gov/planetary/planets/mercurypage.html

*(Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington; http://solarsystem.nasa.gov/multimedia/gallery/messenger_new_big.jpg)*

# Mission Log: Venus

Venus is the second planet from the Sun. It is a near twin in size to the Earth but otherwise very different. Venus's rotates around its axis very slowly, once every 244 Earth days. The slow rotation rate, combined with the planet's orbital period around the Sun—226 Earth days—makes the length of one day on Venus (from one sunrise to another) equal to 117 Earth days. In addition, Venus rotates in a clockwise direction as viewed from above the north pole of the Sun; this is opposite to the rotation of the Earth and most other planets. Venus has a very thick carbon dioxide atmosphere that traps heat from the Sun during the day and does not let the surface cool at night. As a result, the temperatures on the surface of Venus are over 464ºC (867ºF). Similar greenhouse effect operates also on the Earth, but on Venus the process went to extremes and raised the temperature to the high value seen today. To make the planet even more inhospitable, the atmospheric pressure on the surface of Venus is about 90 times as high as the air pressure at sea level on Earth. Any water that might have existed on the surface of Venus in the past has long since evaporated, and finding life on the planet is not likely (though not entirely impossible.) We may learn a lot about the Earth by learning why Venus, in so many ways similar to the Earth, turned out so differently.



### Some of the Most Successful Spacecraft Missions to Venus:

- Mariner 2 (1962): This flyby mission confirmed that Venus is a very hot planet with a cloud-covered atmosphere composed primarily of carbon dioxide.
- Venera 7 (1972): This lander was the first human-made probe to send back data from the surface of another planet.
- Venera 9 (1975): The mission featured an orbiter, as well as a lander, which sent back the first images of the surface of Venus.
- Pioneer Venus (1978-1992): Consisted of an orbiter, which used radar to make the first high-quality map of the surface of Venus, and atmosphere probes, which descended into the atmosphere to analyze it in greater detail.
- Magellan (1990-1994): This orbiting mission mapped 98% of the surface of Venus. Most of what we know of the surface features of Venus is due to the work of this spacecraft.
- Venus Express (Arrived in 2006): This orbiter mission is studying the atmosphere to understand its greenhouse effect better; also looking for volcanic and seismic activity.

For a complete list of past, current, and future missions to Venus, see http://nssdc.gsfc.nasa.gov/planetary/planets/venuspage.html

*(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Venus_Clouds.jpg)*

# Mission Log: The Moon

The Moon is Earth's celestial neighbor. It is 384,000 km (239,000 miles) from the Earth, and its diameter is about one quarter of the Earth's. It takes the Moon 27 1/3 days to go once around the Earth. The Moon's composition is very similar to those of the Earth and the other rocky, Earth-like planets in the Solar System. In fact, its similar composition to the Earth's crust material was a crucial clue in developing an understanding of its origin. The Moon is thought to have formed when a Mars-sized object smashed into the forming Earth billions of years ago. Material was blasted into orbit around the Earth by this collision and later collected together to become the Moon. The surface of the Moon is heavily cratered as a result of meteoroid bombardment in the past. There are two main types of terrain on the Moon: the old, light-colored, heavily cratered highlands, and the younger, dark, smooth areas called maria. About 382 kg (842 lbs) of rock samples from the surface of the Moon have been returned for laboratory studies, which have revealed lots of information about the composition, the structure, and the history of the Moon. Recent spacecraft have revealed the presence of water ice in the permanently shadowed craters near the Moon's poles. There are currently plans to send humans back to the Moon and even establish a permanent colony.

### Some of the Most Successful Spacecraft Missions to the Moon:

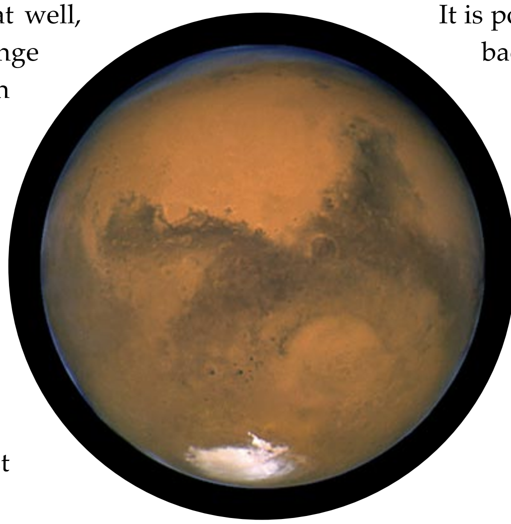
- Luna 1 (1959): This flyby mission was the first spacecraft to reach the Moon.
- Luna 2 (1959): This lander mission was the first spacecraft to reach the surface of another world: it crashed on the surface (as planned) and provided data on the conditions near the surface
- Luna 3 (1959): This flyby mission took the first pictures of the far side of the Moon.
- Luna 9 (1966): This lander mission was the first to make a soft landing on another world and return data from the surface.
- Lunar Orbiter 1-5 (1966-1967): These orbiter missions mapped the surface of the Moon and looked for landing sites for future missions.
- Apollo 11,12,14,15,16,17 (1969-1972): These orbiter/lander missions were the first to take humans to the surface of another world. The astronauts made close-up observations of the surface and brought back samples for analysis.
- Clementine (1994): This orbiter discovered that there might be water ice under the surface.
- Lunar Reconnaissance Orbiter (Launched in 2009): Maps the surface of the Moon in great detail and will help identify possible landing sites and resources for future missions.
- Lunar Crater Observation and Sensing Satellite (2009): Crashed on the surface (as planned) and confirmed the presence of water ice in the permanently shadowed craters.

For a complete list of past, current, and future missions to the Moon, see http://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html

*(Picture credit: NASA/JPL; http://solarsystem.nasa.gov/multimedia/gallery/PIA00405.jpg)*

# Mission Log: Mars

Mars is the fourth planet from the Sun. It is about half the size of the Earth in diameter. The Martian day is about 43 minutes longer than the Earth day, and its year is 686 Earth days. Mars has a carbon dioxide atmosphere, but it is extremely thin, only about 1/100 as thick as the Earth's atmosphere. The thin air does not retain heat well, and surface temperatures range from a frigid –130ºC (–200ºF) on a winter night to 27ºC (80ºF) at the equator on a summer day. Mars appears red because the iron contained in the rocks and the sand has combined with the oxygen in the atmosphere through the same process that produces rust on the Earth. Mars occasionally has dust storms that can cover almost the whole planet for months. Mars has polar ice caps made of carbon dioxide ice ("dry ice") and water ice. The size of the polar ice caps changes significantly during the planet's seasons. While Mars is very dry today, it used to have lots of liquid water in the form of rivers and seas on its surface in the past. It is possible that living beings (such as bacteria) could have existed on the planet then. Or, perhaps there are simple life forms still on Mars similar to bacteria on the Earth that can survive in frigid conditions by creating anti-freeze chemicals that keep the water in their cells from freezing. In any case, Mars looks like the likeliest place for life to exist outside of the Earth.



### Some of the Most Successful Spacecraft Missions to Mars:

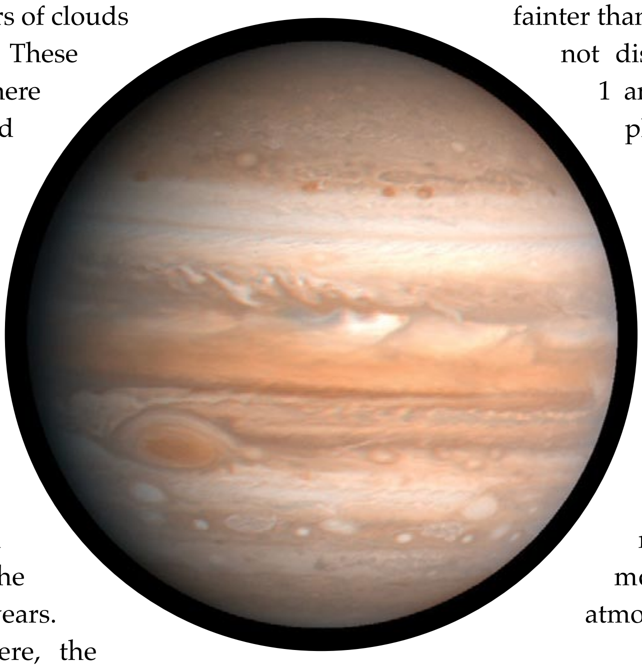
- Mariner 4 (1964-1965): This flyby mission took the first close-up images of the Martian surface.
- Mariner 9 (1971-1972): This orbiter mission provided detailed views of the huge volcanoes on the Martian surface, the giant canyon systems, the polar ice caps and Mars's two moons, Phobos and Deimos.
- Viking 1 and 2 (1976-1982): These combined orbiter/lander missions sent back the first images from the surface, made life-detection experiments (with inconclusive results), recorded a marsquake, and monitored weather.
- Mars Pathfinder (1997): Included a stationary lander and the first robotic surface rover that successfully operated on another planet.
- 2001 Mars Odyssey (2001-2006): This orbiter found evidence for large amounts of water ice under the surface near the south pole of Mars.
- Mars Exploration Rovers (Arrived in 2004): These roving landers confirmed that Mars had a lot of water on its surface in the past.
- Mars Express (Arrived in 2003): This orbiter mission has gathered detailed information on the surface features and minerals, as well as the atmosphere.
- Phoenix Mas (2008): The lander mission to the north polar regions confirmed the presence of ice just under the surface, looked for potential nutrients in the soil, and observed snow falling in the Martian atmosphere.

For a complete list of past, current, and future missions to Mars, see http://nssdc.gsfc.nasa.gov/planetary/planets/marspage.html

*(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Hubble_Mars.jpg)*

# Mission Log: Jupiter

Jupiter is the fifth planet from the Sun and the largest planet in the Solar System. Its mass is 318 times the mass of the Earth, and over 1,300 Earths could fit inside it. Jupiter is a gas giant mostly made of hydrogen and helium. Jupiter has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its massive atmosphere. These upper layers of the atmosphere show complicated wind patterns. The winds blow in opposite directions in the light-colored zones and dark belts. Perhaps the most recognizable feature on Jupiter's visible surface is the Great Red Spot, a huge storm, more than twice the diameter of the Earth, which has been seen by observers on the Earth for more than 300 years. Deeper in the atmosphere, the gases become thicker until they eventually turn into a liquid. At its center, Jupiter may have a solid, rocky core a few times the size of Earth, though based on current data, it is also possible that it does not have a solid core at all. Jupiter has at least 63 moons and a faint ring system. The ring system is much fainter than the rings of Saturn and was not discovered until the Voyager 1 and 2 spacecraft flew by the planet in 1979. Jupiter's day is about 10 hours long, and its year is about 12 Earth years. Jupiter radiates more energy into space than it receives from the Sun. This excess energy, produced by the massive planet being compressed under its own gravity, is thought to be ultimately responsible for the complex motions in the planet's atmosphere.



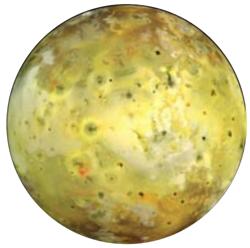
## Some of the Most Successful Spacecraft Missions to Jupiter:

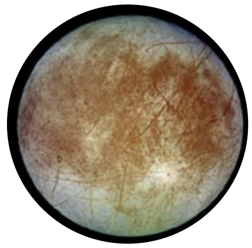
- Pioneer 10 (1973): This flyby mission provided the first close-up images of Jupiter.
- Pioneer 11 (1974): This flyby mission took dramatic images of the Great Red Spot and made the first observations of the planet's polar regions.
- Voyager 1 and 2 (1979): These flyby missions discovered that Jupiter features complicated atmospheric phenomena, as well as lightning and aurora. They also made observations of the planet's moons and discovered that Jupiter has rings.
- Galileo (1995-2003): There were two components to the mission: the orbiter was the first spacecraft to orbit Jupiter and provide information on the giant planet for a long period of time; the probe plunged into the planet's atmosphere and provided the first measurements of the properties of a giant planet underneath the surface clouds.

For a complete list of past, current, and future missions to Jupiter, see http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html

*(Picture credit: NASA; http://nssdc.gsfc.nasa.gov/imgcat/hires/vg2_usgs_1990.jpg)*

# Mission Log: Galilean Moons
# Io, Europa, Ganymede, Callisto





The four largest moons of Jupiter are known as the Galilean moons, since they were discovered by Galileo Galilei in 1610. Jupiter's immense gravity exerts strong tidal forces on the moons. The tides bend and flex the rock of the crust and core of the moons, creating heat. The level of this heating depends on the moons' distances from Jupiter. The tidal forces on Io (pictured top left), the innermost of the Galilean moons, generate enough heat to produce volcanoes and evaporate any ice the moon may have once had. With at least 180—and possibly as many as 400—active volcanoes, Io is the most volcanically active object in the Solar System, with a surface covered by brightly colored sulfur. Europa (second from top), the smallest of the Galilean moons and slightly smaller than the Earth's Moon, has a very smooth surface with few craters. The moon is covered by water ice that is probably a few kilometers thick, and underneath the ice there probably is a liquid water ocean. Ganymede (third from top) is the largest moon in the Solar System, larger than the planet Mercury. It is the only moon known to have an internal magnetic field, created probably in a manner similar to the magnetic field of the Earth. Ganymede is thought to have an underground ocean, though the evidence is not quite clear as for Europa. Callisto (bottom) is the second largest of the Galilean moons, and the third largest moon in the Solar System (after Ganymede and Saturn's Titan). Its surface is heavily cratered and ancient, and it does not appear to experience as much tidal heating as the other moons. However, it still may have a liquid water ocean under the surface. Since liquid water is thought to be one of the requirements for living beings, could life exist in the underground oceans? This question remains currently unanswered, but the Galilean moons will undoubtedly see new missions exploring this possibility in the future.

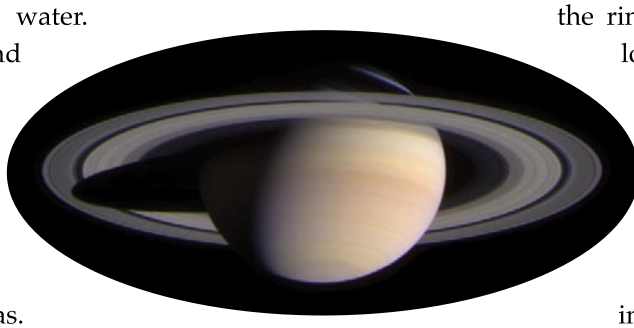
### Spacecraft Missions to the Galilean Moons:

- Voyager 1 & 2 (1979): These flyby missions mapped parts of the Galilean moons' surfaces as they passed through the Jupiter system.
- Galileo (1995-2003): This mission, while orbiting Jupiter, flew by the Galilean moons several times. Much of what we know of the moons, especially of their internal structure, comes from the observations made by this spacecraft.

For a complete list of past, current, and future missions to the Jupiter system, including Europa, see http://nssdc.gsfc.nasa.gov/planetary/planets/jupiterpage.html

*(Picture credits: Io: NASA/JPL/University of Arizona, http://photojournal.jpl.nasa.gov/catalog/PIA02308; Europa: NASA, http://nssdc.gsfc.nasa.gov/imgcat/hires/gal_p48040.jpg; Ganymede: NASA/JPL, http://photojournal.jpl.nasa.gov/catalog/PIA00716; Callisto: NASA/JPL/DLR, http://photojournal.jpl.nasa.gov/catalog/PIA03456)*

# Mission Log: Saturn



Saturn is the sixth planet from the Sun and the second largest planet in the Solar System after Jupiter. Its diameter is about 85% of Jupiter's but it is a lot lighter: its mass is about a third of Jupiter's. This means that it has a very low density. In fact, its density is the lowest of all the planets and less than the density of water. Still, in composition and internal structure, the planet is thought to be fairly similar to its larger sibling. Like Jupiter, Saturn is a gas giant mostly made of hydrogen and helium gas. Saturn has no solid surface we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light-colored zones and dark belts, where the winds blow in opposite directions, but the bands are not as prominent as on Jupiter. Deeper in the atmosphere, the gases get thicker, until finally they turn into a liquid. At its center Saturn may have a solid, rocky core a few times the size of Earth, though based on current data, it is also possible that it does not have a solid core at all. Saturn's day is about 10.5 hours long, and its year is about 29.5 Earth years. Saturn has at least 61 moons, and perhaps many more that are yet to be discovered. Saturn's most striking property may be its exquisite ring system. The rings are surprisingly thin: they are 250,000 km (155,000 miles) in diameter, but their thickness is typically less than 10 meters (30 feet), though this varies somewhat within the ring system depending on the location and the size of the ring particles. Even though the rings look solid when viewed from the Earth, they are actually composed of millions of small icy particles varying in size from a centimeter (less than an inch) to a few meters (yards), and perhaps even to a size of a kilometer (half a mile). Scientists are still trying to determine the origin of the ring particles; the most commonly accepted suggestions are that they are particles blown off the planets' moons by asteroid or meteoroid impacts, or leftovers from the breakup of larger moons. Saturn radiates more energy into space than it receives from the Sun. Some of the excess energy comes from the planet being compressed under its own gravity, but some may come from other sources, such as helium gas condensing in Saturn's atmosphere into droplets and raining down deeper into the planet.

### Spacecraft Missions to Saturn:

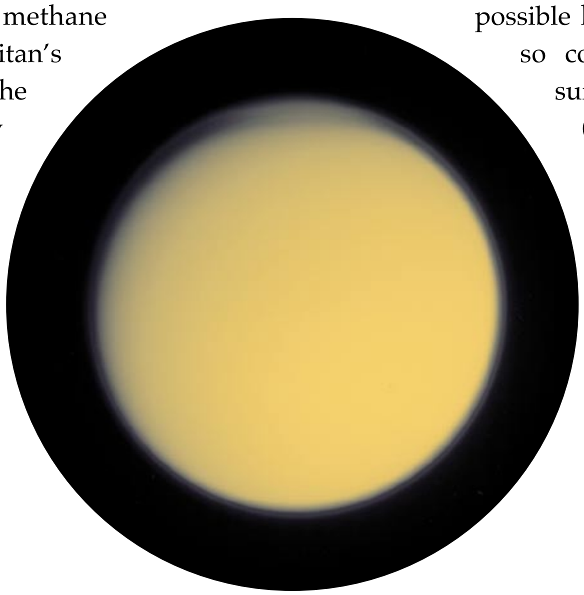
- Pioneer 11 (1979): This flyby mission provided the first close-up images of Saturn.
- Voyager 1 and 2 (1980-1981): These flyby missions provided detailed information on the planet, its atmosphere, moons and rings. For example, they discovered shepherd moons that keep the rings stable.
- Cassini-Huygens (Arrived in 2004): This orbiter mission was the first to explore the Saturn system from orbit. The mission has provided detailed information on the planet's clouds and magnetic field, as well as made close-up studies of the moons and the rings.

For a complete list of past, current, and future missions to Saturn, see http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html

*(Picture credit: NASA/JPL/Space Science Institute; http://solarsystem.nasa.gov/multimedia/gallery/Saturn_Approach.jpg)*

# Mission Log: Titan

Titan is one of the 61 known moons of Saturn. Titan's most interesting feature is that it is the only moon in to Solar System to have a significant atmosphere. At Titan's surface, the atmospheric pressure is 1.5 times that of the Earth's at sea level. The atmosphere is composed primarily of molecular nitrogen with a little argon and methane mixed in. In many ways, Titan's atmosphere is similar to the conditions on the Earth early in its history when life first emerged on our planet. But it is this thick hazy atmosphere that makes it so hard to see Titan's surface. The images taken by spacecraft exploring the moon close-up have revealed an active surface with flowing liquids (composed of methane, rather than water) and many meteorological and geologic processes in action. Titan could have been a possible host for life, if it had not been so cold—the temperature on the surface of Titan is frigid –180ºC (–290ºF)—that no living beings that we know of could survive on its surface.



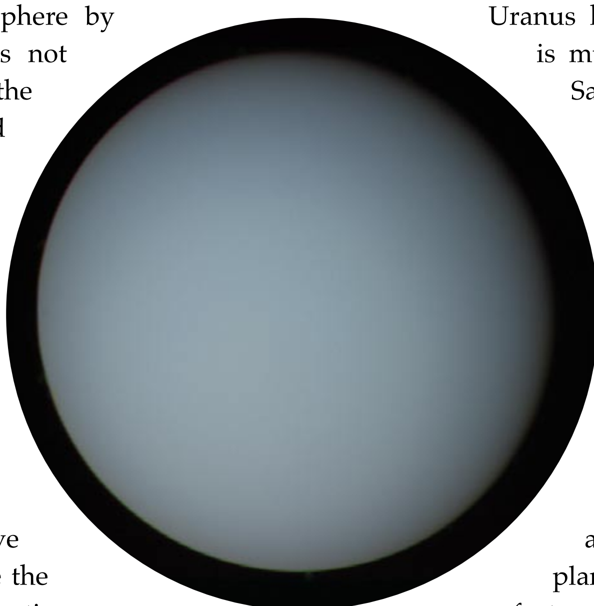
### Spacecraft Missions to Titan:

- Pioneer 11 (1979): This flyby mission provided the first close-up images of Titan as it passed through the Saturn system.
- Voyager 1 and 2 (1980-1981): These flyby missions provided more information on Titan's hazy atmosphere but were not able to see the surface.
- Cassini-Huygens (Arrived in 2004): The main spacecraft, Cassini, orbits Saturn and has flown by Titan several times, providing detailed information on the moon's atmosphere and surface features. In 2005, the Huygens probe descended through Titan's thick atmosphere and landed on the moon. The probe sent back images from the surface and provided other detailed data for about 90 minutes.

For a complete list of past, current, and future missions to the Saturn system, including Titan, see http://nssdc.gsfc.nasa.gov/planetary/planets/saturnpage.html

*(Picture credit: NASA/JPL/Space Science Institute; http://photojournal.jpl.nasa.gov/tiff/PIA06122.tif)*

# Mission Log: Uranus



Uranus is the seventh planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Neptune in size. Uranus's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of icy and rocky materials, and even though it has an extensive atmosphere by the Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Uranus (as well as Neptune) is sometimes called an "ice giant" instead of a gas giant. Uranus has no solid surface that we can see, and the apparent visible surface is just the top layers of clouds in its atmosphere. These outer layers of the atmosphere have light and dark bands where the winds blow in opposite directions, but they are very faint and not visible in images taken of the planet without extensive image enhancements. However, it may be that the visibility of the bands changes according to the planet's seasons. Underneath Uranus's atmosphere, the mixture of icy and rocky materials is probably distributed uniformly, and the planet may not have a solid core at all. Uranus's day is about 17 hours long, and its year is about 84 Earth years. Uranus has at least 27 moons (and perhaps many more yet to be discovered.) Like the other giant planets, Uranus has a ring system, though it is much fainter than the rings of Saturn. Uranus's unique feature is that it appears to have been knocked over sometime in the past. Most planets orbit around the Sun spinning upright; that is, their rotational axes are almost perpendicular with respect to their orbit (with small deviations, like the Earth's 23.5º tilt). Uranus's rotation axis, however, is almost lying within its orbital plane. The cause of this unique feature is not certain, but it may have been caused by an impact of a large object, such as an asteroid or a moon. Unlike the other giant planets in the Solar System, Uranus does not appear to have an internal heat source. Why this is the case is not certain.

### Spacecraft Missions to Uranus:

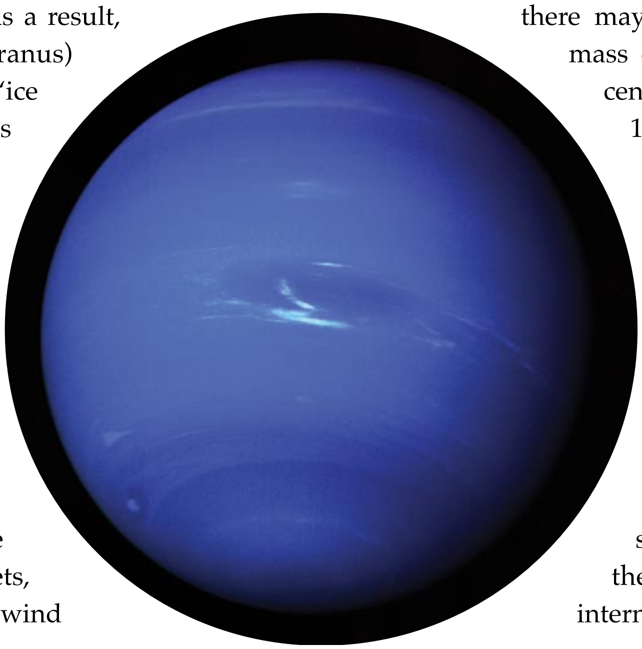
- Voyager 2 (1986): This flyby mission provided the first close-up images of Uranus. Its observations have provided much of our current knowledge of the planet, its rings and moons. It also discovered that the magnetic field is peculiar in its properties (origin, orientation, etc.)

For a complete list of past, current, and future missions to Uranus, see http://nssdc.gsfc.nasa.gov/planetary/planets/uranuspage.html

*(Picture credit: NASA/JPL; http://photojournal.jpl.nasa.gov/tiff/PIA00032.tif)*

# Mission Log: Neptune

Neptune is the eighth planet from the Sun. It is smaller than Jupiter and Saturn, but similar to Uranus in size. Neptune's composition is a little different from Jupiter and Saturn in the sense that it seems to be made of mostly of a mixture of icy and rocky materials, and even though it has an extensive atmosphere by Earth's standards, it is not as large a component of the planet as it is on Jupiter and Saturn. As a result, Neptune (as well as Uranus) is sometimes called an "ice giant" as opposed to a gas giant. We cannot see Neptune's solid surface, and the apparent visible surface is just the top layers of clouds in its atmosphere. Giant storm centers can be seen on its visible surface, similar to those on the other giant planets. Also, like on the other giant planets, the atmosphere has great wind patterns creating bands on the atmosphere where winds blow in different directions. In fact, the winds on Neptune are the fastest in the Solar System, reaching speeds of 2,000 km/hour (or 1,200 miles/hour) relative to the planet's interior rotation rate. Underneath the atmosphere, the mixture of icy and rocky materials making up the bulk of the planet is probably uniformly mixed, though there may be a solid core about the mass of the Earth at the planet's center. Neptune's day is about 17 hours long, and its year is about 165 Earth years. It has at least 13 moons; probably many more are yet to be discovered. Like the other giant planets, Neptune has a ring system, though it is much fainter than the rings of Saturn. Neptune radiates more energy into space than it receives from the Sun; the source of this internal energy is uncertain.



### Spacecraft Missions to Neptune:

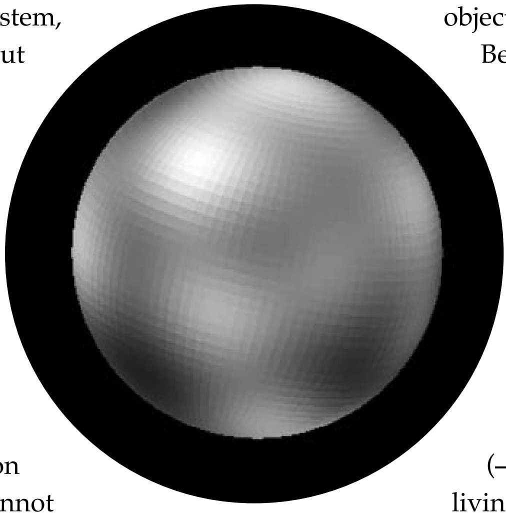
- Voyager 2 (1986): This flyby mission provided the first close-up images of Neptune. Its observations have provided much of our current knowledge of the planet, its rings and moons. It detected auroras on Neptune, and showed the atmosphere to be very active with high winds and large storms.

For a complete list of past, current, and future missions to Neptune, see http://nssdc.gsfc.nasa.gov/planetary/planets/neptunepage.html

*(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/Neptune_Full.jpg)*

# Mission Log: Pluto

Pluto used to be known as the ninth planet, but it always seemed a bit odd when compared with the other eight planets. Like the terrestrial planets (Mercury, Venus, the Earth, and Mars), it is small, but, because it is a mixture of rock and ice, its density is low, and it is not located in the same part of the Solar System as the terrestrial planets. Instead, it is located in the outer part of the planetary realm of the Solar System, where the giant planets reside, but it certainly is not a gas or an ice giant, either. Instead, Pluto appears to be more closely related to the hundreds of objects astronomers have discovered beyond Neptune's orbit in recent years. When one of these so-called Kuiper Belt Objects was discovered to be larger than Pluto, the International Astronomical Union decided in 2006 that Pluto cannot be considered a major planet any more, and belongs to a new class of objects called dwarf planets, instead. As a result, there are now only eight major planets in the Solar System, and Pluto is just an example of the new group of objects called dwarf planets. There are probably many more dwarf planets in the outer regions of the Solar System yet to be discovered. Pluto has three moons, but this is not unusual for small Solar System objects: many dwarf planets, Kuiper Belt Objects, and even asteroids have moons. Not much is known about the properties of the dwarf planet or of its thin atmosphere. Pluto's day is about 6.4 Earth days long, and its year is about 248 Earth years. The frigidly cold temperatures—the temperature on the surface of Pluto is thought to reach –230ºC (–450ºF)—make it unlikely for any living beings to live on the dwarf planet.



### Spacecraft Missions to Pluto:

- New Horizons (will arrive in 2015): This flyby mission will be the first to make close-up observations of Pluto and its moons.

For a complete list of past, current, and future missions to Pluto, see http://nssdc.gsfc.nasa.gov/planetary/planets/plutopage.html

*(Picture credit: NASA; http://solarsystem.nasa.gov/multimedia/gallery/nssdc_hst_pr96_09a.jpg)*

# Mission Log: Asteroids

Asteroids are small rocky objects that can be found in different regions of the Solar System. They orbit the Sun like planets, but they are a lot smaller. Ceres used to be known as the largest asteroid; it is about 950 km (590 miles) in diameter. However, Ceres is now classified as a "dwarf planet", a new category of objects in the Solar System defined by the International Astronomical Union in 2006 to include objects like Ceres and Pluto, which are too small to be considered major planets, but resemble them in many other ways. Ceres is still associated with asteroids, since it is located in the same part of the Solar System as the vast majority of asteroids—the Asteroid Belt, a region between the orbits of Mars and Jupiter. The largest asteroids are Pallas, Vesta and Hygiea, which are between 400 km (249 miles) and 525 km (326 miles) in diameter. There are hundreds of thousands of known asteroids. Astronomers probably have seen almost all of the asteroids larger than 100 km, and about half of those with diameters in the 10-100 km range. But there are probably millions of asteroids with sizes in the 1 km range that have never been seen. Some of the moons of planets, such as the two moons of Mars and the outer moons of Jupiter and Saturn, are similar to asteroids, and they may be captured asteroids rather than having formed in the same way around the planet as other moons. Asteroids are thought to be remnants of the formation of the Solar System that did not accrete onto planets. Because asteroids are small, they are unlikely to host living beings.

### Some of the Most Successful Spacecraft Missions to asteroids:

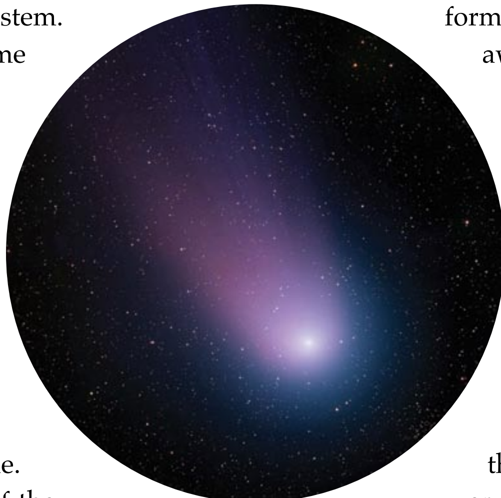
- Galileo (1991, 1993): On its way to Jupiter, the spacecraft flew by Gaspra and Ida, providing the first close-up images of asteroids, and also discovering the first moon (Dactyl) of an asteroid (Ida).
- NEAR Shoemaker (2000-2001): After flying by Mathilde, the spacecraft orbited Eros before landing on it. This marked the first time a spacecraft made a soft landing on a small Solar System object.
- Dawn (Launched in 2007): The spacecraft will fly by Ceres and Vesta in 2011-2015.

For a complete list of past, current, and future missions to asteroids, see http://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html

*(Pictured above: Asteroid Gaspra; picture credit: NASA/JPL; http://photojournal.jpl.nasa.gov/tiff/PIA00118.tif)*

# Mission Log: Comets

Comets reside in the outer regions of the Solar System. They are basically dirty ice balls composed of ices (water ice, as well as other kinds, such as carbon dioxide, ammonia, and methane ices), rock, and dust. They are thought to be remnants of or the actual building blocks of (at least the outer) planets, and, therefore, are a subject of great interest for researchers interested in understanding the early history of the Solar System. Comets spend most of their time in the outer reaches of the Solar System and are not visible to observers on the Earth. There, the comet consists of only its solid body, the nucleus, which is only a few kilometers across and darker than charcoal. It is only when a comet's orbit takes it to the inner parts of the Solar System that a comet becomes observable. The Sun heats the frozen body of the comet, and causes ices on the comet's surface to sublimate—change directly from solid to gas. The gases blown off the nucleus, as well as specks of dust caught in the outflow, form a large cloud of gas and dust particles around the nucleus, called the coma, which can be over 1.6 million km (1 million miles) in size. Sunlight pushes against the dust particles in the coma, while the solar wind—fast outflow of electrically charged particles from the Sun—interacts with the gas. As a result, material in the coma is pushed away from the nucleus, forming a very long tail stretching away from the comet pointed away from Sun. It is not unusual for the tails of comets to extend tens of millions of kilometers. If comets venture close to the Earth, they can be some of the most striking objects in the sky. Because comets are small, because they are located in the far reaches of the Solar System during much of their orbit, and because they have very unstable surfaces when they get close to the Sun, they are unlikely to host living beings.



### Some of the Most Successful Spacecraft Missions to comets:

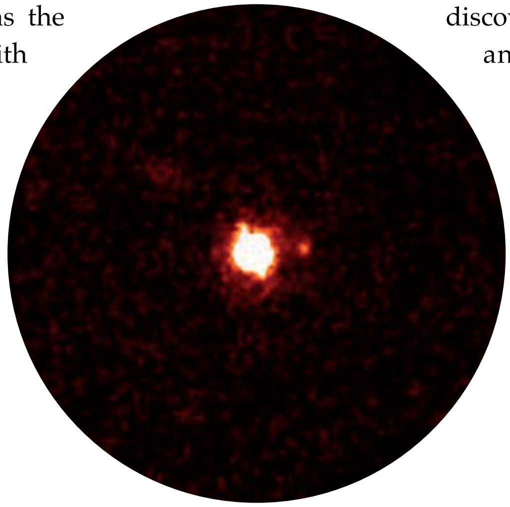
- International Cometary Explorer (1985): This flyby mission was the first to observe a comet close-up.
- Stardust (2004): This flyby mission collected samples from the coma of comet Wild 2 and returned them to the Earth for analysis.
- Deep Impact (2005): The flyby spacecraft included a lander/impactor that smashed into comet Tempel 1.
- Rosetta (Launched in 2004): Arriving at the comet 67P/Churyumov-Gerasimenko in 2014, the main spacecraft will orbit the comet while a probe will land on the nucleus.

For a complete list of past, current, and future missions to comets, see http://nssdc.gsfc.nasa.gov/planetary/planets/cometpage.html

*(Pictured above: Comet C/2001 Q4 – NEAT; picture credit: T. Rector (University of Alaska Anchorage), Z. Levay and L. Frattare (Space Telescope Science Institute) and National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation; http://solarsystem.nasa.gov/multimedia/gallery/Comet_NEAT.jpg)*

# Mission Log: Kuiper Belt Objects

Since 1992, astronomers have found hundreds of objects similar to Pluto beyond Neptune's orbit. These objects are all small icy worlds most commonly called Kuiper Belt Objects (KBO), after the astronomer Gerard Kuiper, though they are sometimes also called trans-Neptunian objects, because they reside in space beyond the orbit of Neptune. The Kuiper Belt region, located at a distance of 30 to 50 times as far from the Sun as the Earth, may have 35,000 objects with diameters larger than 100 km (60 miles). These objects are similar to Pluto: they are small bodies made of a mixture of rock and ice. Most of the Kuiper Belt Objects discovered to date are smaller than Pluto, but detailed observations of an object named Eris, first discovered in 2003, revealed that it is larger than Pluto. This led the International Astronomical Union to decide in 2006 that Pluto (as well as Eris) belongs to a new class of objects called dwarf planets. There probably are more dwarf planets, in addition to smaller KBOs, yet to be discovered in the Kuiper Belt. Because the objects there are so far away from the Sun and are so small, they are hard to discover without powerful telescopes and advanced observation techniques. The frigidly cold temperatures in the Kuiper Belt—the temperatures on the surfaces of KBOs are not thought to reach much above –230ºC (–450ºF)—make them unlikely hosts for any living beings.



### Spacecraft Missions to Kuiper Belt Objects:

- New Horizons: After flying by Pluto in 2015, the spacecraft probably will be directed to fly by one or more Kuiper Belt Objects, providing the first close-up observations of these objects.

*(Pictured above: Dwarf planet Eris; picture credit: Courtesy W. M. Keck Observatory; http://www.keckobservatory.org/images/gallery/solar_system/4_73.jpg)*

# Strange New Planet

**Materials**

- Plastic ball, Styrofoam© ball, or round fruit
- Modeling clay, Playdoh©
- Vinegar, perfume, or other scents
- Small stickers, sequins, candy, marbles, etc.
- A few cotton balls
- A few toothpicks
- Glue
- Towel or a large sheet of opaque paper
- Push-pin
- Pen, pencil, or marker
- Index card
- Sheet of clear or colored cellophane
- Knife (optional)
- Paper towel rolls or a few sheets of letter-size paper rolled up
- 5”x5” square of clear cellophane (optional)
- 6” piece of tape or a rubber band (optional)

Your name: ______________________________

Other members of your team: ______________________________

______________________________

______________________________

The name of your team: ______________________________

Date: ______________________________

**Introduction**

In this activity, your team will make a model planet for your partner team to explore. You will then explore the model planet created by your partner team through different methods of exploration.

**A. Create a Model Planet**

Use a plastic ball, a Styrofoam© ball, or round fruit as your model planet. Use the materials available to your class to decorate the planet with features modeling landforms, moons, atmosphere, etc. For example, you can:

- Carve channels with a toothpick or a knife;
- Attach small stickers or embed other objects onto the ball or fruit (to represent different kinds of landforms);
- Apply scents (vinegar, perfume, etc.) sparingly to a small area;
- Use a sheet of clear or colored cellophane to wrap up the model planet (to represent an atmosphere);
- Create clouds by using cotton and glue;
- Attach a toothpick with a piece of modeling clay at the end (to represent a moon).

Record each feature in the table below (example: 1 – toothpick with clay – moon.) Use your imagination to create a unique planet! Make sure to place some features so that they are not obvious when seen from a distance. Write down on an index card the name of your team and the name of your planet to identify it when all planets are gathered together.

**The name of your planet**: ______________________________________________

| Feature Number | Item Used | Feature Modeled |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**B. Mission 1: Earth-Based Observations**

1) Estimate your distance from your target world (meters or feet):

2) A paper towel tube or a rolled-up sheet of paper will act as the Viewer with which you will make your observations. If your teacher wants you to simulate the effect of the Earth's atmosphere, crumple up and then straighten out a piece of clear cellophane. Attach the piece to the end of your Viewer. If you don't use the cellophane, your observations would be similar to using a space telescope located near the Earth. What types of things do you observe? Use your Viewer to observe the world. Remove the cellophane from your viewer (if you used it) and record your observations (color, size, features seen, etc.):

3) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

4) As a team, write questions to be explored in future missions to the world. What else do you wish to know and how could you find out that information?

a.

b.

c.

d.

**C. Mission 2: Flyby**

Each person on your team will have a turn walking quickly past the model planet and observing it using the Viewers. Make sure you keep farther from the planet than the distance marked on the floor. Answer the questions below when you have returned from your flyby.

1) Record your observations of the planet. What did you see that was the same as your Earth-based observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

2) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

4) As a team, write observations you would like to make on an orbiter mission:

a.

b.

c.

d.

**D. Mission 3: Orbiter**

Each team member gets two minutes to orbit (circle) the planet and observe it using the Viewers. Make sure you keep farther from the planet than the distance marked on the floor. You must circle the planet the whole time; do not stop to look more carefully at any part of the planet. After your observations, return to the Mission Control and answer the questions below.

1) Record your observations of the planet. What did you see that was the same as your Earth-based or flyby observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

2) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

3) As a team, develop a plan for a lander expedition onto the planet's surface.

a. Where will you go and why? How did your team decide where to land?

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

______________________________________________________________________________

b. What are the risks and benefits of landing there?

c. What specifically do you want to explore at this site?

d. What type of special equipment or instruments would you need to accomplish your exploration goals? (Remember, anything you bring has to be small and light enough to fit aboard a spacecraft.)

**E. Mission 4: Lander**

If your partner team used colored cellophane on their model planet to represent an atmosphere, have your teacher remove it carefully. Removing the model atmosphere simulates the effect of making observations on the ground, and not having to look through the atmosphere. Mark your landing site on your target planet with a push-pin or a small piece of masking tape. Place the Viewer around the push-pin, and draw a circle on the model planet's surface around the Viewer. Set the Viewer aside and remove the push-pin. The circle marks the maximum area around the landing site that you can explore. Do not make any observations of features beyond the circle! You have a total of five minutes to explore the landing site. After your observation, return to the Mission Control and answer the questions below.

1) Record your observations of the planet. What did you see that was the same as your Earth-based, flyby, or orbital observations? What did you see that was different? Can you hypothesize (make a science guess) as to why there were any differences?

______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

2) Discuss your observations with the rest of your team. Record any team observations that are different from yours:

______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

3) Was your mission successful? Why or why not?

______________________________________________

______________________________________________

______________________________________________

______________________________________________

______________________________________________

4) Now that you have landed once on the planet, are there any additional questions you would like to answer during follow-up missions?

5) What were the greatest challenges of this mission (personally and as a team)? What would you change for the next mission?

**F. Compare Different Mission Types**

Write down the pros and cons of the different mission types. For example, what kind of science can you do with each? What may be the difficulties or the hazards? Think of both your own experiences in this activity and those of professional scientists designing different types of missions.

1) Earth-Based Observations:

Pros:

Cons:

2) Flyby Mission:

Pros:

Cons:

3) Orbiter Mission

Pros:

Cons:

4) Lander Mission

Pros:

Cons:

# Mission Design

Members of your team: ______________________________

______________________________

______________________________

______________________________

______________________________

Date: ______________________________

**Introduction**

Your team will design a spacecraft mission to explore another world in the Solar System. You must decide which world you want to explore, what you want to learn about your target world, and how you want to accomplish your mission. It can be tricky because space exploration is expensive and hazardous. Along the way, you may need to re-examine your mission goals based on available funding and other constraints. At the end, you must prepare a comprehensive proposal that you could submit to NASA. In your proposal, you must make a convincing argument why your mission should be selected for funding. Good luck!

**1. Choose a World to Explore**

As a team, choose a world you would like to explore. You can use the *Mission Log* given by your teacher to find an interesting world to investigate. If you are operating with a limited budget, you may also want to look at Table S1 in the Mission Cost List (at the end of this Worksheet) to help decide which world to investigate, since some worlds are more expensive to explore than others.

Your target world: ______________________________

A) The basic cost to explore this world (table S1, Mission Cost List): ______________________________

This includes the approximate costs associated with building the spacecraft, sending it on the journey to explore your target world, communicating with the spacecraft, as well as the labor costs of the scientists and engineers designing and testing the spacecraft and the instruments, monitoring the spacecraft during its entire mission, and analyzing and interpreting the gathered data.

**2. Mission Goals**

Examine the *Mission Log* to see what is known about your target world. Come up with three questions that the previous missions have not answered. These are your mission goals:

Mission Goal 1:

______________________________________________________________________________

______________________________________________________________________________

Mission Goal 2:

______________________________________________________________________________

______________________________________________________________________________

Mission Goal 3:

______________________________________________________________________________

______________________________________________________________________________

**3. Type of Mission**

Now that you understand what your mission needs to accomplish, you can decide what type of mission (flyby, orbiter or lander) will best help you meet your goals. Remember the pros and cons of each type of mission, and what you can learn through the different methods. You may also want to check the costs in Table S2 in the Mission Cost List, since some types of missions cost more than others. Also, the more complicated the mission you want to perform, the more chances there are for something to go wrong. The possibility of failure can be estimated by using a risk factor: the higher the factor, the riskier the mission.

Your mission will be (circle one): Flyby Orbiter Lander

Why?

______________________________________________________________________________

______________________________________________________________________________

B) Additional cost for this mission (Table S2, Mission Cost List): ____________________

B1) Risk Factor (Table S2, Mission Cost List): ____________________________________

**4. Length of Mission**

Once you have selected the type of mission, you need to consider the length of the mission. The longer the mission, the greater the cost due to:

- Communications with ground control on the Earth to operate the spacecraft and transmit data for analysis;
- Spacecraft operations to make course corrections that may be necessary, to maintain the well-being of the spacecraft, and to respond to any emergencies that may arise;
- Data analysis by scientists on the Earth; the more data that is gathered, the more time (and/or more scientists) are needed for analysis; even after the spacecraft has ceased functioning, there usually is additional time scheduled for data analysis;
- Extra propellant that may be necessary to make course corrections, etc.

The length of the mission depends on the time it takes to travel to the target world, as well as the time spent observing the world. The cost of traveling to the world was considered in cost item A. You must now decide how long your spacecraft will operate once it arrives to your target world. See Table S3 in the Mission Cost List to determine how much the length of your mission affects your plan. While a longer mission means that you have more time to meet your science goals, the additional length also means that there are more chances for something to go wrong before the end of the mission. Mark the appropriate risk factor below, as well.

Time spent to explore the world: ______________________________ years

C) Additional cost for the length of the mission (Table S3, Mission Cost List): ____________

C1) Risk Factor (Table S3, Mission Cost List): ________________________________

**5. Payload**

Now you have to decide which instruments to include in your spacecraft to help you accomplish your mission goals. These instruments together are called the spacecraft's payload or instrument suite. See Table S4 in the Mission Cost List for the different kinds of instruments available for your spacecraft. You can pick up to five instruments. Explain why each instrument is necessary to meet your mission goals.

Instrument 1: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

______________________________________________________________

______________________________________________________________

Instrument 2: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

______________________________________________________________

______________________________________________________________

Instrument 3: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

______________________________________________________________

______________________________________________________________

Instrument 4: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

______________________________________________________________

______________________________________________________________

Instrument 5: ______________________________

Cost (Table S4, Mission Cost List): ______________________________

Reason for choosing the instrument:

______________________________________________________________

______________________________________________________________

D) The total cost of your instrument suite (add up the cost of individual instruments):

______________________________________________________________

**6. Spacecraft Construction**

The cost of building the spacecraft depends on how complicated the spacecraft is due to the kind of exploration it will conduct and the environment in which it will operate. Spacecraft and its instruments are often developed together so that each component can fit in their allotted space aboard the spacecraft. As a result, the size of the spacecraft and the size and types instruments must be considered in building a spacecraft. There are also additional costs involved in testing the instruments and the spacecraft. The base price for building your spacecraft has been included in cost item A. However, it is possible to find savings if you can use some components that are similar to those used by earlier spacecraft. In this case, you don't have to engineer new spacecraft components from scratch; you can use the same design used before. Review the Mission Log to see if a similar mission has been performed in the past to your target or another but similar world. If it has, you can deduct some construction costs.

Is there a similar previous mission (circle one): Yes No

If you answered "Yes", then:

Provide the name of the similar previous mission: ______________________________

E) You receive a price reduction for using similar components from previous spacecraft: – $10 million

E1) Using similar components and design from a previous mission reduces the risk, so the risk factor is: 0.5

**7. Spacecraft Launch**

Launching the spacecraft is a significant cost item, since you have to lift a massive spacecraft from the surface of the Earth to space, and then give the spacecraft a boost toward its target. As a result, the cost of the launch depends on both the target world and the mass of the spacecraft, which in turn can depend on many factors, such as the number of instruments, the environment in which the spacecraft has to operate, as well as the type and length of the mission. You can reduce the mass of the spacecraft by building your components smaller; for example, by creating miniature versions of your instruments. The basic cost of launching spacecraft to different worlds on missions of different lengths and types are included in the previous cost items, but in this step you must determine whether your spacecraft has so many instruments that the launch costs have to be increased. You can also decide if you want to spend additional engineering time to reduce the size of the spacecraft; however, engineering new, miniaturized components may also increase the risks.

Does your spacecraft have more than three instruments (circle one)? Yes No

If you answered "Yes":

F) Add \$50 million for extra launch costs.

Do you want to spend additional engineering funds to create a smaller version of your spacecraft (circle one)? Yes No

If you answered "Yes":

G) Cross out cost item E and risk factor E1). Instead, you gain – \$50 million for launch cost savings. Miniaturized instruments may require additional engineering, which increases your risk factor:

G1) Risk factor for miniaturized components: 2

**8. Total Cost and Risk**

Write down the cost items for your mission:

A) ______________________________

B) ______________________________

C) ______________________________

D) ______________________________

E) ______________________________ (if not crossed out)

F) ______________________________ (if it applies to your mission)

G) ______________________________ (if it applies to your mission)

Add A) through G) together to calculate the total cost of your mission:

________________________________________________________________

Write down the risk factors for your mission:

B1) ______________________________

C1) ______________________________

E1) ______________________________ (if not crossed out)

G1) ______________________________ (if it applies to your mission)

Multiply B1) through G1) with each other to calculate the total risk factor for your mission:

________________________________________________________________

**9. Human Spaceflight versus Robotic Spacecraft Mission**

The costs discussed in the previous pages apply to both humans and robotic spacecraft exploring your target world. However, there are additional costs associated with keeping the astronauts alive and healthy, such as making sure there are enough supplies (food, water, and air) for the entire expedition. The astronauts must be protected from the harsh space environment, especially from the vacuum, damaging radiation, and freezing cold or scorching hot temperatures (depending on how far from the Sun the expedition goes.) The mission will also take longer to complete, because you not only need to take the astronauts to your target world and give them time to perform their exploration, but you also must return the crew safely back to the Earth. Estimating the additional costs involved with a human spaceflight mission instead of a robotic spacecraft is difficult. For the present purposes, just multiply both the total cost and the risk factor from Step 8 by 1,000.

Total cost of a human spaceflight mission: ______________________________

Risk factor for a human spaceflight mission: ______________________________

**10. Final Cost**

Make the final choice between a human spaceflight or a robotic spacecraft mission, and write your decision here:

Your mission will be done with (mark one):

☐ Robotic spacecraft; use numbers from Step 8

☐ Human spaceflight; use numbers from Step 9

Final cost of your mission: ______________________________

Final risk factor for your mission: ______________________________

**11. Reconsider Mission Details**

Look back at your mission goals and other details and decide if you want to change them. For example, if you think your mission costs too much, you might want to change your mission goals so that you can meet them with a smaller payload, and so reduce the cost of the mission.

Do you want to change the details of your mission? (Circle one)

Yes No

If "Yes," explain how your mission will change. If "No," explain why you want to keep the mission the way it is.

**12. NASA Proposal**

Prepare a proposal of your mission to NASA using the tools provided by your teacher. Be sure your proposal includes:

- ▼ Where your spacecraft is going and why;
- ▼ The goals of your mission; why are these goals important?
- ▼ What type of mission (flyby, orbiter, lander) will you use and why?
- ▼ Payload selection and why you chose these instruments;
- ▼ Total cost and justification for the costs.

Remember, you are competing with other mission proposals, and not all can be selected for funding. You must be convincing in your argument that your mission offers the best bang for the buck. Good luck!

**MISSION COST LIST**

Table S1. The basic cost to explore different worlds.

| Destination | Cost |
|---|---|
| The Moon | $50 million |
| Mercury | $200 million |
| Venus | $100 million |
| Mars and/or its moons | $100 million |
| Asteroids and comets in the inner Solar System | $100 million |
| Jupiter and/or its moons | $300 million |
| Saturn and/or its moons | $350 million |
| Uranus and/or its moons | $400 million |
| Neptune and/or its moons | $450 million |
| Pluto and/or other dwarf planets | $500 million |
| Kuiper Belt Objects | $500 million |
| Comets far from the Sun | $500 million |

Table S2. Considerations associated with different types of missions.

| Type of Mission | Additional Cost | Risk Factor |
|---|---|---|
| Flyby | (none) | 1 |
| Orbiter | $100 million | 2 |
| Lander | $200 million | 5 |

Table S3: Considerations associated with missions of different length.

| Time Spent Exploring the World (in addition to the travel time to get to the world) | Additional Cost | Risk Factor |
|---|---|---|
| 1 year | (none) | 1 |
| 2 years | $1 million | 1 |
| 5 years | $5 million | 2 |
| 10 years | $10 million | 3 |

*Note: for a flyby mission, the longer time includes several flybys of the target world.*

Table S4: Payload cost: the cost and purpose of instruments for various types of missions.

| Instrument | Explanation and Purpose | Suitable Missions | Cost |
|---|---|---|---|
| Long-distance camera | Digital camera with a telescope; takes images of the target from a distance | Flyby<br>Orbiter<br>Lander | $3 million |
| Stereo Camera | Digital camera that can take 3D images of the target | Flyby<br>Orbiter<br>Lander | $3 million |
| Panoramic Camera | Digital camera with a wide field of view; provides panoramic images of the target | Lander | $3 million |
| Microscopic camera | Combination of a microscope and a digital camera; provides detailed images of the target's rocks and soils | Lander | $3 million |
| Spectrometer 1 (using visible or infrared light) | Measures the properties of different colors and types of light; determines the composition of the target (rocks, atmosphere) | Flyby<br>Orbiter<br>Lander | $1 million |
| Spectrometer 2 (using either visible and infrared *or* visible and ultraviolet light) | Combination spectrometer that measures the properties of different colors and types of light; determines the composition of the target (rocks, atmosphere) | Flyby<br>Orbiter<br>Lander | $3 million |

*(continued on the next page)*

Table S4 (continued): Payload cost: the cost and purpose of instruments for various types of missions.

| Instrument | Explanation and Purpose | Suitable Missions | Cost |
|---|---|---|---|
| Spectrometer 3 (high-energy and particle radiation) | Measures the properties of magnetic fields, the space environment, and the solar wind in detail | Flyby<br>Orbiter<br>Lander | $2 million |
| Magnetometer | Measures basic properties of magnetic fields, the space environment, and the solar wind | Flyby<br>Orbiter<br>Lander | $0.5 million |
| Basic Radar | Takes radar images of the target using microwaves bounced off the surface | Flyby<br>Orbiter | $1 million |
| Advanced Radar | Measures the properties of the target's atmosphere and features below the surface | Flyby<br>Orbiter | $2.5 million |
| Laser Altimeter | Determines the heights of planetary features using a laser beam bounced off the surface of the target | Orbiter | $1.5 million |
| Seismometer | Monitors quakes on the target world (e.g., marsquakes) | Lander | $0.5 million |
| Meteorology Instrument Suite | Monitors weather by measuring temperature, pressure, winds, etc. | Lander | $1 million |
| Geologic Exploration Tool: Rock Abrasion Tool | Powerful grinder that can drill into rocks on the target's surface to provide close-up observations and analysis | Lander | $2 million |
| Geologic Exploration Tool: Digger Arm | Can dig below the surface to take samples for detailed analysis | Lander | $2 million |
| Life Experiment Suite | Laboratory experiments designed to look for signs of life (e.g., organic molecules, chemical markers of feeding or respiration) | Lander | $2 million |

# Answer Key

## Student Worksheet 1

B) – E) Answers will vary. The main goal of the activity is to have the students understand the differences in what kind of information can be gathered with the different mission types, and appreciate the amount of planning that is required for the different missions.

F) Answers will vary. Some possibilities are included below:

**Mission 1: Earth-based observations**

*Pros:*

- The lowest cost (unless the telescope is large or space-based, but even then the cost per observation is probably lower than for a spacecraft mission traveling to the target.)
- Can easily change instruments that are mounted on the telescope.
- Can easily point the telescope to observe many interesting targets.
- Can collect large amounts of data over long periods of time.
- Can be operated easier than the other mission types.

*Cons:*

- Observations limited: cannot provide detailed information on small-scale features.
- Observational problems due to the Earth's atmosphere (not for space telescopes.)
- Observational problems due to light pollution from cities (not for space telescopes.)
- If only one side of the target can be seen from the Earth, only that side can be observed (for example, the Moon.)
- Can only observe the target at night (unless observing the Sun or using radio waves.)
- Cannot observe in bad weather.

**Mission 2: Flyby**

*Pros:*

- Can observe more details of the world than Earth-based observations.
- Can observe the target all the time during approach and departure.

- Can observe the target with several instruments simultaneously.
- Can observe several targets (for example, a planet and its moons; or fly by several planets), if mission is so designed.

*Cons:*

- Costs more than most Earth-based observations.
- Cannot repair or replace instruments.
- Observation time and area observed is limited by the amount of time that the spacecraft spends near the target.
- Spacecraft and its instruments must be controlled at least part of the time through computer programs stored onboard the spacecraft.
- Since data must be stored onboard the spacecraft, and sent to the Earth at a specified time, there are limitations to the amount of data that can be returned.
- Communications become more difficult the farther the spacecraft is from the Earth.

**Mission 3: Orbiter**

*Pros:*

- Can observe more details of a target for a longer period of time than a flyby mission.
- Can observe more of the (if not the entire) target
- Can observe global and regional changes on the target's surface and atmosphere over time.
- Can observe the target with several instruments simultaneously.

*Cons:*

- Costs more than a flyby mission or observations from the Earth.
- Cannot repair or replace instruments.
- Needs more propellant than a flyby mission.
- More hazardous than a flyby mission.
- Communications with the Earth may be more difficult if the spacecraft is behind the target during part of its orbit.

- May need to perform orbit correction maneuvers to remain in orbit around the target.
- Spacecraft and its instruments must be controlled at least part of the time through computer programs stored onboard the spacecraft.
- Needs more complicated computer programs than a flyby mission.

**Mission 4: Lander**

*Pros:*

- Can observe more details of a portion of the target than the other mission types.
- Can observe changes on the surface of the world or its atmosphere in more detail (but only around the landing area.)
- Can observe the area around the landing site with several instruments simultaneously.
- If the lander is movable (e.g., it includes a rover), it can provide detailed observations on several interesting surface features that are within driving distance.
- Can investigate the rocks, and the soil in detail, for example through sample analysis.
- Can perform experiments to see if there are living beings present.
- Can record seismic events (e.g., moonquakes or marsquakes.)

*Cons:*

- Costs more than the other mission types.
- Cannot repair or replace instruments.
- Needs more propellant than a flyby mission (but maybe not more than an orbiter mission.)
- More hazardous than the other mission types.
- Communications are more difficult because data must be sent from the lander to the Earth (often via an orbiting spacecraft.)
- Communications with the Earth may be more difficult when the lander or the orbiter that acts as a communications relay is behind the target.
- Since data must be stored onboard the spacecraft, and sent to the Earth at specific times, there are limitations to the amount of data that can be returned.

- Spacecraft and its instruments must be controlled through computer programs stored onboard the spacecraft for at least part of the time.
- Needs more complicated computer programs than the other mission types.

## Student Worksheet 2

2. Mission Goals

Answers will vary. Listed below are a few examples of currently open questions about the worlds described in the *Mission Log*. The students are encouraged to come up with their own questions, and the resulting mission goals may be quite different from the questions below.

Mercury

- Is there water ice in the permanently shadowed craters near Mercury's poles?
- Need to study surface features in detail to understand the history of Mercury's surface.
- Why is Mercury's core so large?
- Need to perform a geologic analysis of rocks and soil.
- What are the properties of Mercury's magnetic field?

Venus

- Need to study the atmosphere and its changes in greater detail.
- Need to study surface features, rocks and soil in greater detail.
- Why did Venus become so different from the Earth?
- Could there be life on Venus?
- Monitor weather on the planet.

The Moon

- How does the amount of undeground water vary on different parts of the Moon?
- Need to study rocks in greater detail.
- Are there any resources on the Moon that could be used by human colonists in the future?

Mars

- Why did the water on Mars disappear from the surface? Where did it go?
- Is there any life on Mars today (such as bacteria in ice), or is there any proof of past life?
- Need to study soil and rocks in greater detail.
- Monitor the weather on the planet.

Jupiter

- How can the Great Red Spot have lasted 300 years? What drives the storm?
- Why does Jupiter have an internal energy source?
- Does Jupiter have a solid core?
- Need to understand Jupiter's internal structure better.
- Why are Jupiter's rings so much smaller and fainter than Saturn's?
- Are there more moons yet to be discovered?

Galilean Moons

- Need to understand the interaction between Io and Jupiter better.
- Do Ganymede and Callisto have undersurface oceans?
- Could there be life in the ocean under Europa's icy surface?
- Need to map the surfaces of the moons in greater detail.

Saturn

- Need to understand the phenomena in Saturn's atmosphere better.
- Why does Saturn have such magnificent rings? What is their origin?
- Need to understand the behavior of Saturn's rings better.
- Why does Saturn have an internal energy source?

- Need to understand Saturn's internal structure better.
- Are there more moons yet to be discovered?

Titan

- Why is Titan the only moon in the Solar System with a substantial atmosphere?
- The Huygens probe returned photos of only a small part of Titan's surface. What does the rest of the surface look like close-up?
- If Titan's atmosphere is so similar to Earth's early atmosphere, what can we learn about the early Earth by studying Titan?
- Could there be life on Titan even though it is so cold there?

Uranus

- Why does Uranus appear to have fewer features on its atmosphere than the other giant planets? Do more features appear as the seasons change?
- Why are Uranus's rings so much smaller and fainter than Saturn's?
- Need to understand Uranus's internal structure better.
- Why does Uranus not have an internal energy source like the other giant planets?
- What happened when the planet was "knocked over"? Exactly what caused it?
- Are there more moons yet to be discovered?

Neptune

- What drives the strong storms and fast winds on Neptune?
- Why are Neptune's rings so much smaller and fainter than Saturn's?
- Need to understand Neptune's internal structure better.
- Why does Neptune have an internal energy source?
- Are there more moons yet to be discovered?

Pluto

- What does the surface of Pluto look like?
- What is Pluto's composition?
- How does it compare with other dwarf planets?
- What is the composition of Pluto's atmosphere?

Asteroids

- Need to explore more asteroids to see how they compare with each other.
- Need to study the composition of different asteroids in greater detail.
- Do asteroids have resources that could be used by humans in the future?

Comets

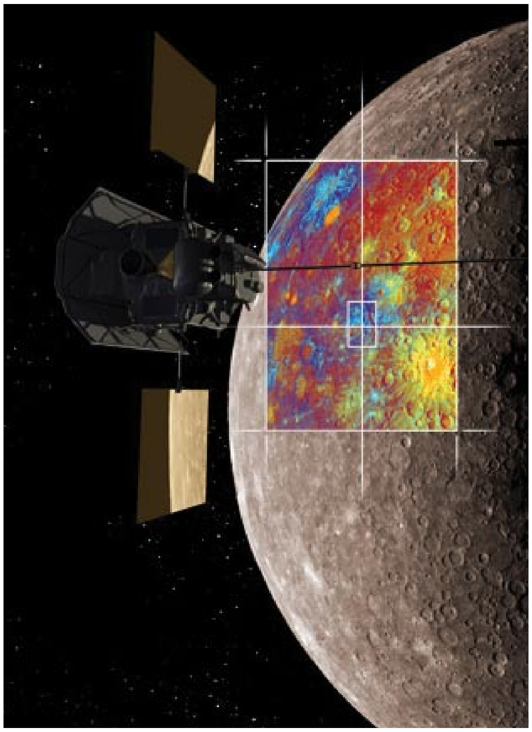
- Need to understand the structure of the comets better, especially the nucleus.
- Need to explore more comets to see how they compare with each other and what they can tell us about the formation of the Solar System.
- Do comets have resources that could be used by humans in the future?

Kuiper Belt Objects

- What do these objects look like close-up?
- Are there many Kuiper Belt Objects that could be classified as dwarf planets?
- How do these objects compare with Pluto?
- Are there many different kinds of Kuiper Belt Objects; how are they similar to or different from each other?

The answers to the rest of the Worksheet will vary. The main goal of this activity is to have the students understand that detailed planning is needed to send a spacecraft to explore another world and that there are significant costs and risks associated with these missions.

# MESSENGER Mission Information Sheet



MESSENGER is an unmanned NASA spacecraft that was launched in 2004 to study the planet Mercury. After three flybys of its target planet in 2008 and 2009, the spacecraft will go into orbit around Mercury in 2011. It will not land but will make detailed observations from orbit. MESSENGER will never return to the Earth, but will stay in orbit around Mercury to gather data until at least 2012.

MESSENGER is an acronym that stands for "MErcury Surface Space ENvironment, GEochemistry and Ranging," but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be the second spacecraft ever to study Mercury; in 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for about one Earth year, during which time it will make close-up and long-term observations, allowing us to see the whole planet in detail for the first time.

During its mission, MESSENGER will attempt to answer several questions about Mercury. How was the planet formed and how has it changed? Mercury is the only rocky planet besides the Earth to have a global magnetic field; what are its properties and origin? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist in the permanently shadowed craters near the planet's poles? Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.