



## SCIENCE OVERVIEW

There are many different ways to cope with being in the presence of a hot object. A familiar one is to move away from it so that you do not feel its heat as strongly. Another is to change your position so that you do not face the hot object directly. It is also possible to use other cooling methods—such as air conditioning—but they can be more complicated and more expensive (though often also more efficient) than these simple methods.

Just as we prefer to work in a comfortable environment, it is important to make sure spacecraft components are kept at temperatures where they can operate normally during the mission. Using simple cooling or heating methods can greatly improve the cost-effectiveness of missions heading to very hot or very cold environments. In this lesson, we discuss how the amount of heat felt by an object can be altered by changing its distance or the angle at which the source of heat is faced.

The idea of using passive heating and cooling methods in the presence of a heat source can be demonstrated with the example of a campfire. If you hold your hands near a fire, they will warm up. The closer your hands are to the heat, the warmer they feel. If your hands are turned at an angle, only partially toward the fire, the heat received by your palms is less than if you were to hold your hands directly facing the fire. Therefore, you are able to conclude that the amount of heat felt depends on both the distance from

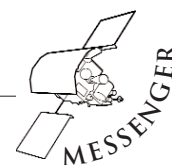
the heat source and the angle at which your hands are inclined toward that source. If your hands become too warm, there are effective ways to cool them passively. For example, they can be moved farther from the heat, or the angle at which the hands are held can be increased.

### How Heat Travels

Heat passes from one substance or object to another by three methods—conduction, convection, and radiation. Although conduction and convection need media through which to travel, heat transmitted via radiation does not need any intervening material, though it also works through some material. The Sun sends its energy through the vacuum of space via radiation, but sunlight also travels through material—the atmosphere—before reaching the surface of Earth.

### Sunlight

Sunlight is the source of almost all energy on Earth. It affects many aspects of life on Earth, from allowing temperatures on our planet to remain hospitable for life to providing energy for photosynthesis. When sunlight interacts with matter, its energy is felt in various ways. For example, we can feel the warmth generated by sunlight on our skin when we stand outside on a sunny day. At the speed of light (300,000 km/s or 186,000 miles/s in a vacuum such as space), it takes about eight minutes for sunlight emitted from the Sun to reach Earth.





Sunlight is not always beneficial, however. If we stay in sunlight too long, the Sun's ultraviolet radiation may cause sunburn, which over time and with repeated exposure can develop into skin cancer. The Sun can also heat and damage items left in the sunlight. We can protect these items by placing them in shade or turning them so that they are not exposed to sunlight face-on. One thing we cannot do is change the distance of the items from the Sun since any change we could make on Earth is minimal compared with the distance from the Earth to the Sun.

### The Effect of Distance on Heat

The idea of cooling by increasing the distance to a heat source radiating energy is based on the "inverse square law." This law states that the intensity of radiation to which an object is exposed depends on its distance from the source,  $R$ , as  $1/R^2$  (see Figure 2). For example, Earth is one AU away from the Sun (Astronomical Unit = average Sun-Earth distance: about 150 million kilometers, or 93 million miles).

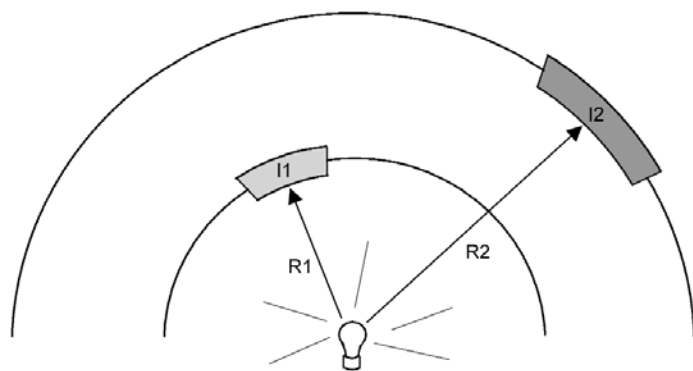
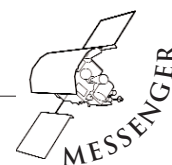


Figure 2. Intensity ( $I$ ) of radiation falls off as a square of the distance from the source of radiation:  $I_2/I_1 = (R_1/R_2)^2$ .

Mercury's orbit gets to within 0.3 AU from the Sun. This means that a spacecraft studying the planet Mercury (such as MESSENGER) is exposed to as much as 11 times the sunlight that it would normally experience in space near Earth ( $1/0.3^2 = 11$ ). Note that the inverse square law applies to light and heat transmitted by radiation, but not to heat traveling by other means (such as hot air currents moving from one place to another or heat conducted through material). The inverse square law is based on the fact that radiation spreads out in all directions in space from its source. By the time it has traveled a distance  $R$ , the radiation has spread over an area  $4\pi R^2$ , (the surface area of a sphere with radius  $R$ ), and the intensity has therefore fallen as  $1/R^2$  from its original value.

### The Effect of Viewing Angle on Heat

The angle at which a radiant heat source is viewed also changes the amount of heat experienced by the object. This is because the amount of radiation received by the object decreases when it is tilted away from the source (see Figure 3). Because the same amount of radiation is now spread over a larger area, the intensity (the amount of radiation per unit area) received by the object is smaller than if it were viewing the source face-on. You can calculate the intensity of radiation experienced by the object based on the viewing angle, but the mathematical treatment of the problem is not necessary for this lesson.



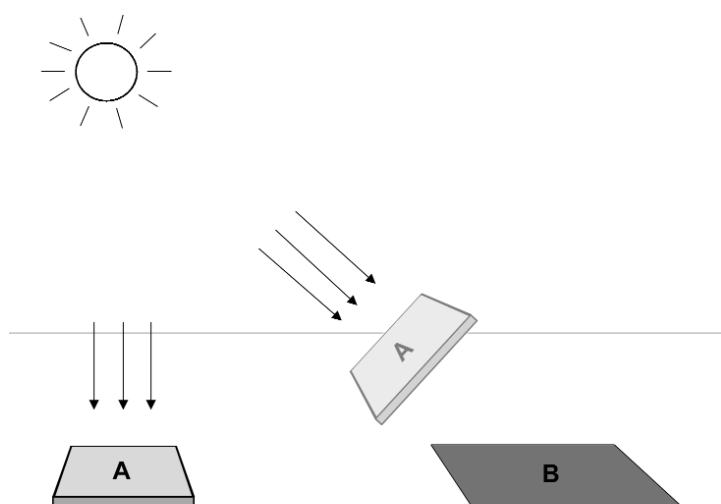


Figure 3. Effect of the viewing angle on the amount of radiation received from the Sun. Sunlight is spread over a larger area (B on right) when it strikes the ground at an angle than when it strikes the ground face-on (area A on left). If the surface were tilted toward the incoming sunlight face-on (dotted area A on right), the intensity of sunlight would be the same as the intensity on area A. (Note: the distance to the Sun appears different in the picture in the two cases, but it is just to make both images fit in the same picture; in reality the distance from the Sun for objects on the surface of Earth is basically the same wherever they are.)

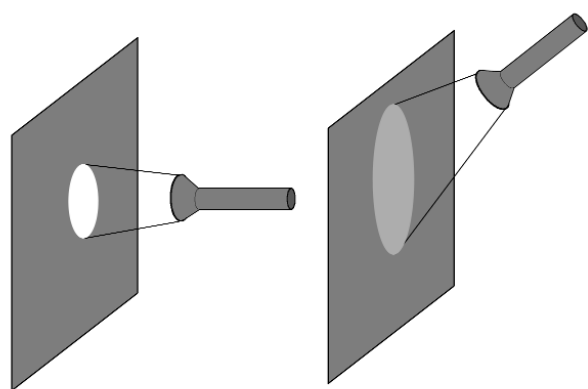


Figure 4. Shining a flashlight on a wall to demonstrate the effect of the viewing angle. When the flashlight is tilted (right-hand case), the light is spread over a larger area, and the amount of light received by unit area is reduced.

You can try a simple demonstration of this effect by shining a flashlight at a wall (see Figure 4). If you point the flashlight so that it is perpendicular to the wall, you can see a bright circle of light created on the wall. If you tilt the flashlight, the circle on the wall changes to an oval, and the lighted area becomes dimmer. The more you tilt the flashlight, the larger the lighted area becomes. The light received per unit area decreases, and therefore the light appears dimmer.

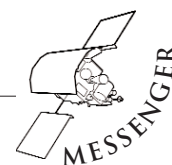
### Seasons on Earth

An important example of the effect of the viewing angle is the seasons on Earth.

The angle between the equatorial plane and the orbital plane of the Earth is  $23.5^\circ$  (see Figures 5 and 6). The corresponding tilt of the rotational axis is called the obliquity of the Earth. The orientation of the Earth's rotational axis does not change as our planet orbits the Sun—the northern end of the axis points toward a star called Polaris, also called the North Star, in the constellation Ursa Minor, throughout the year.

The tilt of the rotational axis—and the resulting change in the direction of the arriving sunlight during the year—has the following effects on the amount of sunlight received by different regions on the surface of the Earth:

- ▲ The angle at which the sunlight strikes the Earth changes throughout the year: during the summer, the angle between the surface and the arriving





sunlight is greater than during the winter. For an observer standing on the surface of the Earth, this effect can be seen as the Sun's position in the sky at local noon being higher during summer than during winter.

- ▲ There are more hours of daylight during summer than during winter.

The first effect is connected with the viewing angle toward a light or radiant heat source. If the sunlight arrives on the surface of Earth from directly overhead, sunlight heats a given place at maximum intensity. If the sunlight arrives at an angle, the same amount of

sunlight is spread over a larger area, and the amount of radiation received by the same place is smaller (just as in the flashlight demonstration). Sunlight arriving at an angle also has to travel through more of the Earth's atmosphere, and more of the energy of the sunlight is lost before it arrives at the surface.

The magnitude of the second effect depends on the part of the Earth. At the equator, the number of daylight hours does not change during the year, while at the poles the days change from 24 hours of daylight in the summer to 24 hours of night in the winter. Although the length of daylight has an effect on temperature (and climate), it is not nearly as noticeable as

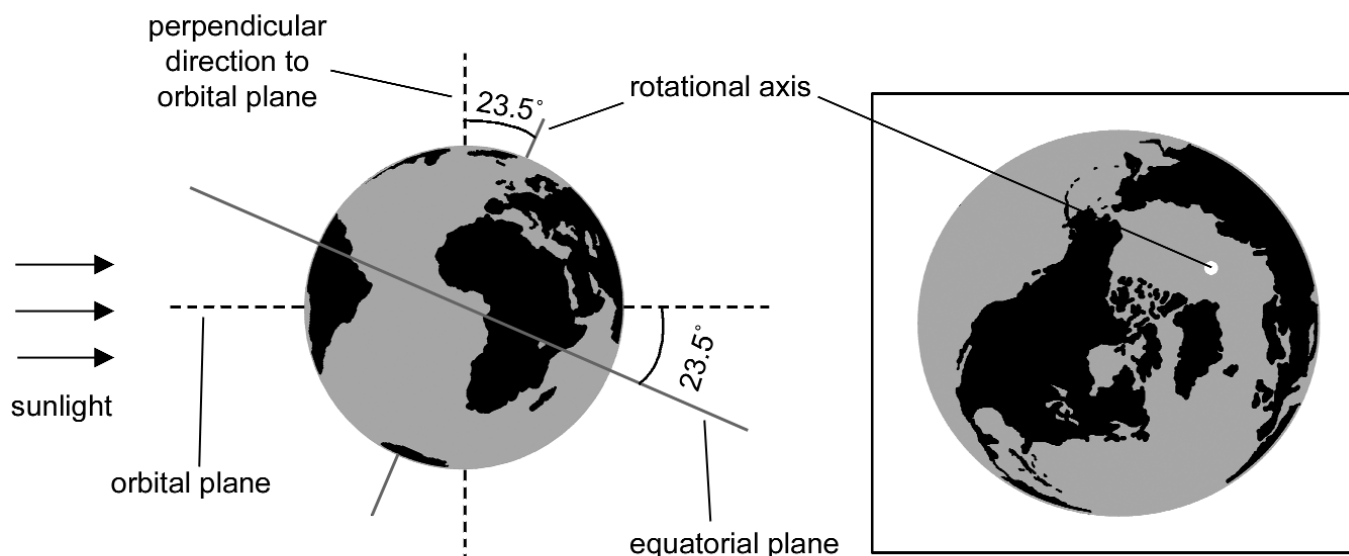
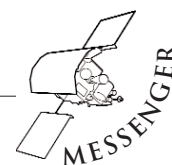


Figure 5. Definitions of terms used to describe Earth's orientation in space. Rotational axis is the geometric axis around which the Earth rotates once a day. The equatorial plane is the geometric plane going through the Earth at the equator. It is perpendicular (at  $90^\circ$  angle) to the rotational axis. The orbital plane of the Earth (also called the ecliptic), is the geometric plane in which the orbit of Earth around the Sun is located. The angle between Earth's equatorial and orbital planes is  $23.5^\circ$ ; or, the rotational axis is tilted  $23.5^\circ$  from the perpendicular direction of the orbital plane. (Note that the sunlight arriving on Earth is always parallel to the orbital plane but does not always come from the same direction with respect to the orientation of the Earth. By the way the sunlight is falling on Earth in this figure, it would be winter in the northern hemisphere and summer in the southern hemisphere.)





the effect of the angle of sunlight—remember that the arctic summer is still cool when compared with the tropics, even when the poles get 24-hour sunlight.

Let us consider how the Earth is affected as it goes through one revolution around the Sun (one year). You can use Figure 6 as a guide; we will start at the top of the figure and proceed counter-clockwise. The situation is described from the perspective of the northern hemisphere.

On the spring equinox (on or about March 20), the Earth’s rotational axis is perpendicular to the direction of the arriving sunlight. (Remember that the rotational axis is always pointing toward the North Star, but during the equinox the angle between the Sun, the Earth, and the North Star is 90°.) At this time, both northern and southern hemispheres are half in sunlight, half in darkness, and the length of daylight is more or less equal (about 12 hours) in all parts of the world.

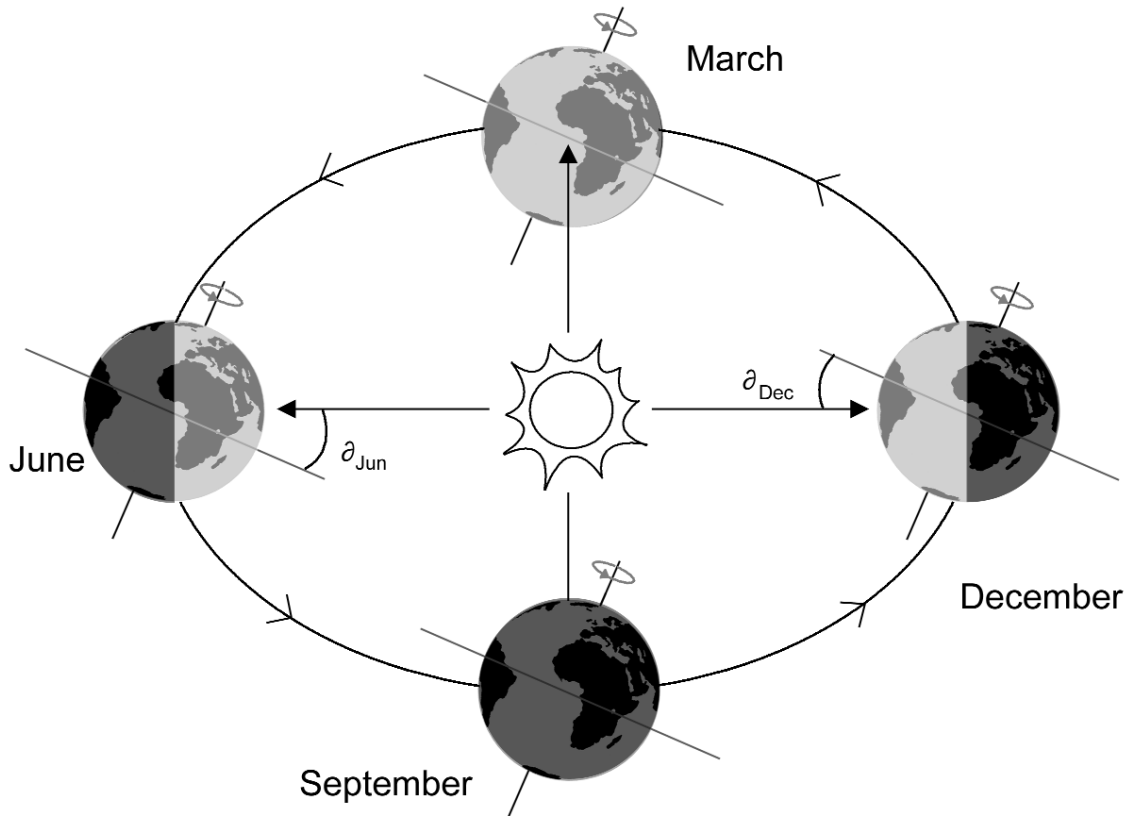


Figure 6. The inclination of Earth’s rotational axis (“tilt”) explains why the summer starts in June in the northern hemisphere. At this time, the Sun’s rays strike the northern hemisphere most directly: the angle between arriving sunlight and Earth’s equator is  $\theta_{Jun} = 23.5^\circ$ . The tilt does not change, so in the winter the Sun’s rays strike the surface at a low angle:  $\theta_{Dec}$  is  $-23.5^\circ$  (minus sign since the northern end of the rotational axis is pointed away). On the equinoxes (March and September), the sunlight arrives at the equator exactly perpendicular to it,  $\theta_{Mar} = \theta_{Sep} = 0^\circ$  (these angles are not drawn in the picture). The seasons occur in the opposite times of the calendar year in the southern hemisphere.

NOTE: Figure not drawn to scale.





During spring and summer months, more than half of the northern hemisphere is in sunlight at any given time, and the days are longer than the nights. The North Pole is in sunlight all the time, and as the spring progresses, regions in lower (but still arctic) latitudes experience 24-hour sunlight, as well. On the summer solstice (on or about June 21), the angle between the rotational axis and the direction of the arriving sunlight is smallest (see Figure 6). Regions above the Arctic Circle (at  $66.5^\circ$  latitude and above) have 24-hour sunlight during this time. After the summer solstice, the number of daylight hours dwindles toward the winter, and the limiting line of regions with 24-hour sunlight moves back toward the pole.

On the autumnal equinox (on or about September 23), the Earth's rotational axis is perpendicular to the arriving sunlight again, and the northern and southern hemispheres both are half in sunlight, half in darkness.

As the autumn progresses, less than half of the northern hemisphere receives sunlight, as the North Pole is directed away from the Sun. In fact, no sunlight reaches the North Pole from this point until the spring, and a six-month long night begins. The limiting line of regions receiving no sunlight moves down from the pole as the autumn progresses, until the winter solstice (on or about December 21), when regions above the Arctic Circle receive no sunlight. From the

solstice on toward the summer, the number of daylight hours increases, and the limiting line of no sunlight during the day moves back toward the pole. On the spring equinox, the cycle begins again.

The seasons follow the same pattern in the southern hemisphere, but there they are reversed. During the summer in the northern hemisphere, it is winter in the southern hemisphere, and vice versa. This is because when the angle between the North Pole and the Sun is the smallest, the angle between the South Pole and the Sun is the largest, and vice versa (see Figure 6).

The apparent position of the Sun at a given time of day changes during the course of the year. (Remember that the Sun does not actually move—it appears to move in the sky during the day because of the Earth's rotation.) The highest position of the Sun in the sky during a day occurs at local noon, but the position of the Sun at noon varies during the year. It is highest on the summer solstice in June and lowest on the winter solstice in December in the northern hemisphere, and exactly opposite in the southern hemisphere. The highest position that the Sun can reach depends on the observer's latitude. If you live between  $23.5^\circ$  latitude and the North (or South) Pole, subtract your latitude from  $90.0^\circ$  and add  $23.5^\circ$  in order to determine the Sun's highest position in the sky viewed from your hometown. For example, if your hometown is Orlando, Florida, which has a latitude





of  $28.5^\circ$ , the Sun will be at an angle of  $85.0^\circ$  from the horizon at local noon on the summer solstice. Alternatively, if your hometown is Seattle, Washington, at a latitude of  $47.5^\circ$ , the Sun's angle will be  $66.0^\circ$  at local noon on the summer solstice. Note that the names for the solstices and equinoxes are based on northern hemisphere seasons and it can become a little confusing when talking about the seasons in the southern hemisphere at the same time.

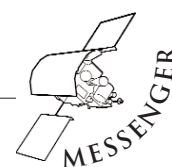
It is a common misconception that the seasons on Earth are caused by the Earth being closer to the Sun in the summer than in the winter. **THIS IS WRONG!** The Earth orbits the Sun in a nearly circular orbit: the average distance from the Earth to the Sun is 1.00 AU (about 150 million kilometers, or 93 million miles). The closest distance that the Earth gets to the Sun (perihelion) is 0.98 AU, and the farthest (aphelion) is 1.02 AU. The change is small and, in fact, the Earth is actually farther away from the Sun during the summer in the northern hemisphere than it is during the winter. This clearly demonstrates how important the  $23.5^\circ$  tilt of the rotational axis is to the existence of seasons here on Earth. There are planets for which the changes in the distance around the Sun are larger and therefore a more important factor in determining their seasons. For example, the tilt of the rotational axis of Mars ( $25^\circ$ ) is approximately the same as Earth's, but the distance from the Sun changes from 1.41 AU to 1.64 AU (with an average distance of 1.52 AU). The change in the distance is much larger than

for Earth, and the resulting influence on the seasons much greater. *IF* Earth's rotational axis were not tilted, the seasons on Earth would be caused by the varying distance, but in this case, the seasonal changes would be nowhere near as significant as they are now. Since the Earth's rotational axis is tilted, contemplating about this is just a fun "What if...?" exercise. It is important to stress that on the Earth, the seasons are caused by the tilt of the Earth's rotational axis, not the changing distance from the Sun.

### Orbits, Planets, and Satellites

There are two angles that are important for the current discussion with regards to planets: obliquity and inclination angle. The planet's obliquity describes the angle between the equatorial plane and the orbital plane (or the "tilt" of the planet). The Earth's obliquity, as discussed earlier, is  $23.5^\circ$ . If a planet's obliquity is  $0^\circ$ , the planet "spins upright" on its orbit around the Sun, and the Sun appears to be at the same height in the sky at noon each day during the year. Note that this height depends on the latitude of where you are—at the equator, the Sun would appear to be directly overhead at noon every day during the year, while at the latitude of  $30^\circ$ , it would get to be  $60^\circ$  above the horizon. Mercury's obliquity, for example, is very close to  $0^\circ$ .

Inclination is a way to describe how an object deviates from a horizontal position or how two geometric lines or planes differ in their direction. Inclination angle is





one of the basic parameters describing the orbit of an object around another object—it describes the angle between the orbit of the object and some reference plane. For Earth-orbiting satellites, the reference plane is the Earth’s equatorial plane. For a planet orbiting the Sun, the reference plane is the ecliptic (the plane of the Earth’s orbit). Since the ecliptic is defined as the Earth’s orbital plane, the inclination of Earth’s orbit is  $0^\circ$ .

The inclination of the orbit of artificial satellites (remember that moons are natural satellites) determines how they can view the Earth (see Figure 7). A satellite in a geostationary orbit is always in the same position in the sky as seen from the surface of the rotating Earth. That is, the orbital period of the satellite is the same as the rotational period of the Earth.

Geostationary orbits are in the equatorial plane of the Earth. Polar-orbiting satellites fly over the Earth close to the north-south direction, passing over or near the poles. Satellites in polar orbits can see the entire surface of the Earth, not just the areas near the equator. Inclined orbits fall between these two extremes: they have an inclination angle between  $0^\circ$  (equatorial orbit) and  $90^\circ$  (polar orbit). The orbit of the satellite is determined based on its intended use.

### MESSENGER, Distance, and Inclination

The MESSENGER mission to Mercury poses a great engineering challenge because of the close distance of the planet to the Sun. During the mission, the spacecraft will be exposed to 5-11 times the amount of sunlight that it would near Earth, depending on where Mercury is in its orbit around the Sun. Since the

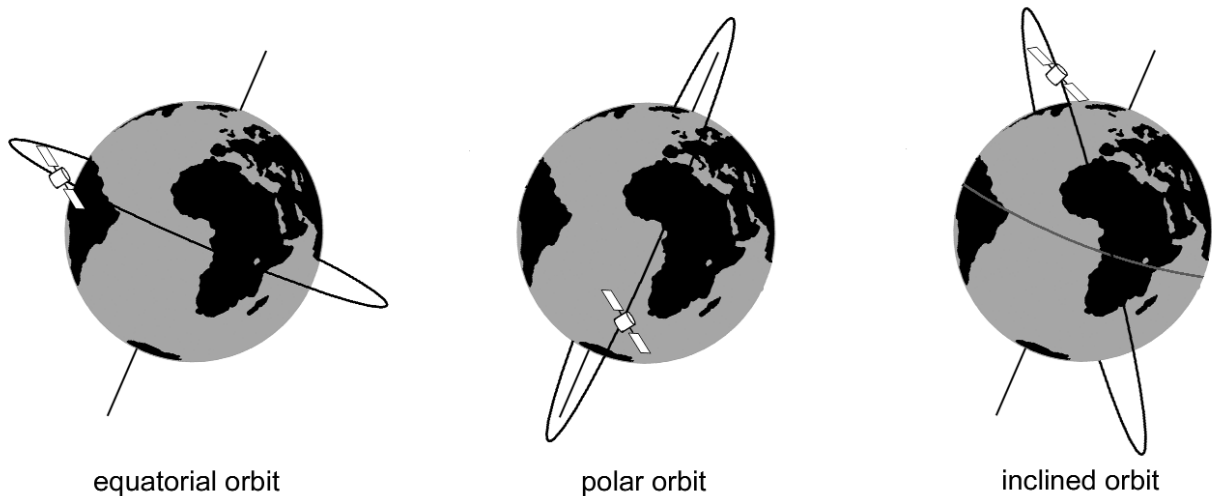


Figure 7. Satellite orbits. Equatorial orbit is in the equatorial plane of the Earth. Geostationary orbit is a version of an equatorial orbit where the satellite stays over one specific place on Earth. A satellite on a polar orbit flies over the poles and sees the whole Earth. Inclined orbit is between these two extremes; the inclination of the orbit in the figure is about  $60^\circ$ . [Note: satellite and its orbit not drawn to scale.]





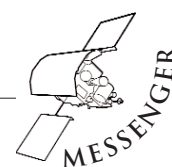
Earth's atmosphere allows only about half of solar radiation to pass through, the MESSENGER spacecraft will be exposed to as much as 22 times the amount of solar radiation as it would on the surface of Earth. (Note that spacecraft operating in orbit around Earth but above the atmosphere also need to worry about heat and radiation—for MESSENGER, this will be a much greater problem.) This exposure to extreme heat and radiation could seriously damage components of the spacecraft. In order to limit the amount of sunlight falling on the spacecraft, it will use several cooling methods, such as a sunshade that is pointed toward the Sun at all times. As a result, the sensitive instruments aboard the spacecraft can operate in a safe temperature range, from a few degrees below 0°C (32°F) to 33°C (91°F).

The consideration of distance from a hot source also affects the choice of MESSENGER's orbit around Mercury. The sunlit side of Mercury heats up in the baking sunlight and emits infrared radiation into space as a result. The surface also reflects some solar radiation back into space. The spacecraft's orbit around Mercury has been designed so that its closest approach to the planet is away from the most sun-baked region of the surface and so that it flies quickly over the sunlit areas. This is achieved by an orbit where the periapsis (the closest point to the surface of Mercury, and also the part of the orbit where the spacecraft's speed is at its highest) is at a high latitude

and the apoapsis (the farthest point of the orbit, and also the part of the orbit where the spacecraft's speed is at its lowest) is far away from the surface of Mercury. In this manner, infrared radiation received by the spacecraft can be kept at safe levels.

Inclination is important for MESSENGER in several ways. First, the orbit of the spacecraft will be highly inclined, a near polar orbit; the inclination angle is about 80°. As the spacecraft orbits the planet once every 12 hours, it can view a swath of the planet's surface in the north-south direction. As the planet rotates, the spacecraft can view the whole planet's surface during successive orbits. If the orbit were not highly inclined, the spacecraft would not be able to observe the polar regions at high resolution. The near polar orbit also makes it possible for the closest approach to the planet's surface to be at a high latitude, away from the most sun-baked regions, as described above.

Another consideration of inclination is in the design of the solar panels that provide power to the spacecraft. At Mercury's distance from the Sun, the solar panels can receive more sunlight than they can handle. One way to deal with the problem is to spread out the cells enough so that they can radiate their heat into space as infrared light. In MESSENGER's two solar panels, 70% of the area is covered with mirrors, while only 30% has actual solar cells generating energy.





Another approach, this one using inclination to stay cool, is to keep the solar panels from facing the Sun directly. Using this method, the temperature of the solar panels can be reduced by about  $100^{\circ}\text{C}$ , in addition to the  $125^{\circ}\text{C}$  cooling effect given by the spread-out design. Combined, these passive cooling methods will keep the solar panel temperatures at around  $150^{\circ}\text{C}$  ( $300^{\circ}\text{F}$ ) instead of the more than  $400^{\circ}\text{C}$  ( $750^{\circ}\text{F}$ ) they could experience otherwise.

The third important aspect of the inclination for the mission is the fact that Mercury's rotation axis is not tilted. This means that as Mercury moves around its orbit during its year, the Sun appears to reach the same height in the sky at noon each day—for exam-

ple, directly overhead at the equator. At Mercury's poles, this means that the Sun appears very low in the horizon every day, all year round, apparently just crawling around the horizon as the planet rotates. This is not an important effect for the MESSENGER spacecraft itself, but it is the basis for one of the central science questions the mission is trying to answer. The low angle at which sunlight arrives at Mercury's poles makes it possible for ice to exist in permanently shaded craters that never see sunlight. Confirming or rejecting the idea of the existence of ice, suggested by Earth-based radar observations of Mercury, is one of the principal scientific goals of the MESSENGER mission.

