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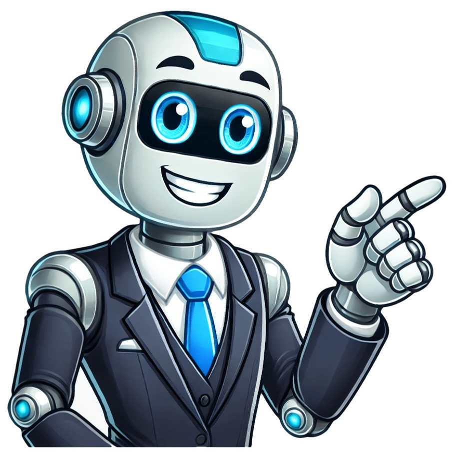

Scientists at the ORB study the state of Cassini Mercury. They have shown that the obliquity of Mercury is close to zero, i.e. that its rotation axis is almost perpendicular to the orbital plane Mercury around the Sun. This value is very important for the Peale experiment. They do this work on the long-term evolution of orbital elements of Mercury, its precession and plan Laplace. For more information: Rambaux and Bois (2004) (2004), Yseboodt and Margot (2006) (2006), and Peale, Yseboodt, and Margot (2007) (2007). Science Astronomy Mercury is an extreme planet in several respects. Because of its nearness to the Sun—its average orbital distance is 58 million km (36 million miles)—it has the shortest year (a revolution period of 88 days) and receives the most intense solar radiation of all the planets. With a radius of about 2,440 km (1,516 miles), Mercury is the smallest major planet, smaller even than Jupiter's largest moon, Ganymede, or Saturn's largest moon, Titan. In addition, Mercury is unusually dense. Although its mean density is roughly that of Earth's, it has less mass and so is less compressed by its own gravity; when corrected for self-compression, Mercury's density is the highest of any planet. Nearly two-thirds of Mercury's mass is contained in its largely iron core, which extends from the planet's centre to a radius of about 2,100 km (1,300 miles), or about 85 percent of the way to its surface. The planet's rocky outer shell—its surface crust and underlying mantle—is only some 300 km (200 miles) thick. transit of Mercury across the face of the SunTransit of Mercury across the face of the Sun, a composite of five separate images in ultraviolet light taken by the Transition Region and Coronal Explorer (TRACE) satellite in Earth orbit, November 15, 1999. The time interval between successive images is about seven minutes.As seen from Earth's surface, Mercury hides in dusk and twilight, never getting more than about 28° in angular distance from the Sun. It takes about 116 days for successive elongations—i.e., for Mercury to return to the same point relative to the Sun—in the morning or evening sky. This is called Mercury's synodic period. Its nearness to the horizon also means that Mercury is always seen through more of Earth's turbulent atmosphere, which blurs the view. Even above the atmosphere, orbiting observatories such as the Hubble Space Telescope are restricted by the high sensitivity of their instruments from pointing as close to the Sun as would be required for observing Mercury. Because Mercury's orbit lies within Earth's, it occasionally passes directly between Earth and the Sun. This event, in which the planet can be observed telescopically or by spacecraft instruments as a small black dot crossing the bright solar disk, is called a transit (see eclipse), and it occurs about a dozen times in a century. The next transit of Mercury will occur in 2019. Mercury also presents difficulties to study by space probe. Because the planet is located deep in the Sun's gravity field, a great deal of energy is needed to shape the trajectory of a spacecraft to get it from Earth's orbit to Mercury's in such a way that it can go into orbit around the planet or land on it. The first spacecraft to visit Mercury, Mariner 10, was in orbit around the Sun when it made three brief flybys of the planet in 1974–75. In developing subsequent missions to Mercury, such as the U.S. Messenger spacecraft launched in 2004, spaceflight engineers calculated complex routes, making use of gravity assists (see spaceflight: Planetary flights) from repeated flybys of Venus and Mercury over the course of several years. In the Messenger mission design, after conducting observations from moderate distances during planetary flybys in 2008 and 2009, the spacecraft entered into an elongated orbit around Mercury for close-up investigations in 2011. In addition, the extreme heat, not only from the Sun but also reradiated from Mercury itself, challenged spacecraft designers to keep instruments cool enough to operate. Mercury's orbit is the most inclined of the planets, tilting about 7° from the ecliptic, the plane defined by the orbit of Earth around the Sun; it is also the most eccentric, or elongated planetary orbit. As a result of the elongated orbit, the Sun appears more than twice as bright in Mercury's sky when the planet is closest to the Sun (at perihelion), at 46 million km (29 million miles), than when it is farthest from the Sun (at aphelion), at nearly 70 million km (43 million miles). The planet's rotation period of 58.6 Earth days with respect to the stars—i.e., the length of its sidereal day—causes the Sun to drift slowly westward in Mercury's sky. Because Mercury is also orbiting the Sun, its rotation and revolution periods combine such that the Sun takes three Mercurian sidereal days, or 176 Earth days, to make a full circuit—the length of its solar day. As described by Kepler's laws of planetary motion, Mercury travels around the Sun so swiftly near perihelion that the Sun appears to reverse course in Mercury's sky, briefly moving eastward before resuming its westerly advance. The two locations on Mercury's equator where this oscillation takes place at noon are called hot poles. As the overhead Sun lingers there, heating them preferentially, surface temperatures can exceed 700 kelvins (K; 800 °F, 430 °C). The two equatorial locations 90° from the hot poles, called warm poles, never get nearly as hot. From the perspective of the warm poles, the Sun is already low on the horizon and about to set when it grows the brightest and performs its brief course reversal. Near the north and south rotational poles of Mercury, ground temperatures are even colder, below 200 K (−100 °F, −70 °C), when lit by grazing sunlight. Surface temperatures drop to about 90 K (−300 °F, −180 °C) during Mercury's long nights before sunrise. Mercury's temperature range is the most extreme of the solar system's four inner, terrestrial planets, but the planet's nightside would be even colder if Mercury kept one face perpetually toward the Sun and the other in perpetual darkness. Until Earth-based radar observations proved otherwise in the 1960s, astronomers had long believed that to be the case, which would follow if Mercury's rotation were synchronous—that is, if its rotation period were the same as its 88-day revolution period. Telescopic observers, limited to viewing Mercury periodically under conditions dictated by Mercury's angular distance from the Sun, had been misled into concluding that their seeing the same barely distinguishable features on Mercury's surface on each viewing occasion indicated a synchronous rotation. The radar studies revealed that the planet's 58.6-day rotation period is not only different from its orbital period but also exactly two-thirds of it. Mercury's orbital eccentricity and the strong solar tides—deformations raised in the body of the planet by the Sun's gravitational attraction—apparently explain why the planet rotates three times for every two times that it orbits the Sun. Mercury presumably had spun faster when it was forming, but it was slowed by tidal forces. Instead of slowing to a state of synchronous rotation, as has happened to many planetary satellites, including Earth's Moon, Mercury became trapped at the 58.6-day rotation rate. At this rate the Sun tugs repeatedly and especially strongly on the tidally induced bulges in Mercury's crust at the hot poles. The chances of trapping the spin at the 58.6-day period were greatly enhanced by tidal friction between the solid mantle and molten core of the young planet. Mercury's orbital motion has played an important role in the development and testing of theories of the nature of gravity because it is perturbed by the gravitational pull of the Sun and the other planets. The effect appears as a gyration, or precession, of Mercury's orbit around the Sun. This small motion, about 9.5′ (0.16°) of arc per century, has been known for two centuries, and, in fact, all but about 7 percent of it—corresponding to 43″ (0.012°) of arc—could be explained by the theory of gravity proposed by Isaac Newton. The discrepancy was too large to ignore, however, and explanations were offered, usually invoking as-yet-undiscovered planets within Mercury's orbit. In 1915 Albert Einstein showed that the treatment of gravity in his general theory of relativity could explain the small discrepancy. Thus, the precession of Mercury's orbit became an important observational verification of Einstein's theory. Mercury was subsequently employed in additional tests of relativity, which made use of the fact that radar signals that are reflected from its surface when it is on the opposite side of the Sun from Earth (at superior conjunction) must pass close to the Sun. The general theory of relativity predicts that such electromagnetic signals, moving in the warped space caused by the Sun's immense gravity, will follow a slightly different path and take a slightly different time to traverse that space than if the Sun were absent. By comparing reflected radar signals with the specific predictions of the general theory, scientists achieved a second important confirmation of relativity. One day on Mercury equals 176 earth-days. This drawing follows the position of a single point, in yellow, as Mercury spins (day to night) and as Mercury travels around the Sun (year). The yellow point faces the Sun only once every 176 earth-days or two Mercury years. Image from: NASA Comparison of Mercury with Earth It takes Mercury about 59 Earth days to spin once on its axis (the rotation period), and about 88 Earth days to complete one orbit about the Sun. However, the length of the day on Mercury (sunrise to sunrise) is 176 Earth days. How can this happen? The figure shows the path of Mercury about the Sun with a mark indicating the same spot on the surface of the planet at different times in the orbit. A point initially pointing toward the Sun will point in the same direction after one rotation (59 days or 2/3 of the orbital period), but that point will no longer be directed toward the Sun. It takes three rotations of the planet during two orbits of the planet about the Sun, or 88 x 2=176 days, for the mark to get back to the same position. Mariner 10 The first probe sent to Mercury was a U.S. spacecraft: Mariner 10. It made three flybys of Mercury in March 1974, September 1974 and March 1975. The first flyby has allowed discovering that Mercury, contrary to what was thought, had a magnetic field and an atmosphere. The low density of the crust of the planet was also observed and the pictures revealed a surface covered with craters. The second flyby allowed mapping 45% of the planet's surface. The last flyby revealed that the magnetic field was not only due to solar winds, the mechanism that creates this field is one of the questions that the probes BepiColombo and Messenger will try to elucidate. Mariner 10 has significantly advanced our knowledge on Mercury by answering some of our questions, but also, by raising new ones. Messenger (MErcury Surface, Space ENvironment, Geochemistry, and Ranging) is the second spacecraft launched to Mercury, on the third of August 2004. This is a NASA mission. It will fly once by the Earth, twice by Venus and three times by Mercury. Then, in March 2011, it will be the first spacecraft in orbit around Mercury, after six and a half years of travel. The Messenger probe(credit: JPL/NASA) This mission aims to answer the following questions: What is the geological history of Mercury ? Why is Mercury so dense ? What is the structure of Mercury's core ? What is the nature of the magnetic field of Mercury ? What do the poles of Mercury consist of ? Why volatiles, which constitute the thin layer of gas surrounding the planet, are so important on Mercury ? To answer these questions, the spacecraft carries eight instruments: Mercury Dual Imaging System MDIS: two cameras, wide angle and small-angle, whose role will be to map the topography and terrain of the surface of Mercury. Gamma-Ray and Neutron Spectrometer GRNS : this spectrometer will detect gamma rays and neutrons. It will be used to map the relative abundance of certain elements on Mercury and determine whether the poles, which are never directly exposed to the Sun, do or do not contain ice. X-ray Spectrometer XRS: this spectrometer will detect X-rays from the Sun, and analyze how they interact with the surface of Mercury, completing the analysis by the GRNS. Magnetometer MAG: this magnetometer will map Mercury's magnetic field and look for magnetic rocks on the crust. Mercury Laser Altimeter MLA: a laser altimeter that will send a ray to Mercury and measure the time it takes for this ray to reach the ground and return to the instrument. Recording of the variations in these measurements will allow to know the precise topography of Mercury. Mercury Atmospheric and Surface Composition Spectrometer MASCS: this spectrometer is sensitive to light ranging from infrared to ultraviolet; it will measure the abundance of atmospheric gases and detect minerals on the surface of Mercury. EEnergetic Particle and Plasma Spectrometer EPPS: this spectrometer will measure the composition, distribution and energy of charged particles in the magnetosphere of Mercury. Radio Science RS: this instrument uses the Doppler effect on the radio signal to measure very small changes in the speed of the probe in orbit around Mercury. These data will allow to study the mass distribution of Mercury and the variations in the thickness of the crust. In order to view the official website of the NASA MESSENGER : click here. BepiColombo BepiColombo is a mission of ESA (European Space Agency) to Mercury in collaboration with ISAS (Japan). Its departure is scheduled for 2014. Six years later, in 2020, BepiColombo will split into two probes: the Japanese one (Mercury Magnetospheric Orbiter MMO) and the European one (Mercury Planetary Orbiter MPO). Both will be in orbit around Mercury and withstand temperatures up to 350 Ã‚Â°C. BepiColombo is named after Professor Giuseppe Colombo (1920-1984), nicknamed Bepi, an Italian mathematician and engineer who was the first to suggest that Mercury had a resonance 3/2. The mission objective is to answer the following questions: What can we learn from Mercury on the composition of the solar nebula and on the formation of the solar system ? Why is the density of Mercury so high ? How is the "unknown face" of Mercury ? Is the core of Mercury liquid or solid ? Does Mercury have a tectonic activity today ? The BepiColombo probe(credit:ESA) Why does such a small planet have an intrinsic magnetic field, while Venus, Mars and the Moon have not ? What is the origin of this magnetic field ? Why do spectroscopic observations not reveal the presence of iron when this element is assumed to be the major constituent of Mercury ? How did Mercury evolve geologically ? Do the craters of the polar regions, constantly in the shadow, contain sulfur or water ice ? What are the mechanisms of formation of the exosphere ? In the absence of ionosphere, how does the magnetic field interact with the solar wind ? The progress of the perihelion of Mercury is explained by the curvature of space-time. The proximity of the Sun can thus be used to test general relativity with greater precision. To obtain the answers to these questions, the following instruments will be aboard Mercury Planetary Orbiter : Bepi Laser Altimeter BELA: BELA will measure the time the signal will take to make a round trip between the probe and the surface of Mercury. A transmitter will issue light pulses and a collector (telescope and receiver) receives the signal reflected from the surface of Mercury. An electronic system will provide the emission and the detection of pulses, measure the time of flight and control everything. The instrument will always point to the center of mass of the planet. Thanks to BELA, the topography of Mercury's surface will be known with an accuracy of 1 meter. Italian Spring Accelerometer ISA: the accelerometer will measure the non-gravitational accelerations of the probe. By analyzing the trajectory of the probe, it will allow to obtain the gravitational acceleration (to separate the parties and non-gravitational gravitational acceleration felt by the probe). Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System SYS-SIMBIO: these infra-red spectrometers and stereo high-resolution cameras will map the global mineralogy. Mercury Orbiter Radio science Experiment MORE: The objective of MORE is de determination of the gravity field of the planet, its rotation, its dimension, the physical state of its core, and to provide information on the internal structure of Mercury. A radio signal is sent from Earth, will be received by the probe and returned to Earth where we measure the time taken to complete the round-trip and the effect on the frequency due to the velocity of the probe relative to the Earth (Doppler effect). As the solar wind distorts the signals, two waves of different frequencies are sent in order to calculate and remove the effect of solar wind on the signal. Through these measures, we can first reconstruct the trajectory of the probe and thanks to ISA, which measures non-gravitational accelerations of the probe, we refine our knowledge of Mercury's gravitational field. Measurements of deviations of the trajectory of the probe on top of geological formations or craters will allow, in combination with data from the altimeter BELA, to reconstruct the mass anomalies on the surface and below the surface of Mercury. Moreover, using SIMBIO-SYS, we can observe the movements of Mercury in space and reconstruct its libration. Indeed, for the first time the camera will move compared to the surrounding stars. Then, when the probe will pass over a particularly area (a target), it will take a photo. Measurements made by MORE from Earth will then be used to locate the spacecraft in space. These steps will be repeated over time, what allows comparing the photos and getting with great accuracy the positions of targets in space and at different times. Deviations from the position of the observed area when considering uniform rotation of Mercury will provide its libration. One will then be able to obtain information on the interior of Mercury through the formula of Peale. The deviations of the signal path caused by the Sun will be analyzed for more information on the parameters of general relativity. Click here to visualise the MORE experiment. Mercury Magnetometer MERMAG: this magnetometer will measure the magnetic field of Mercury and will deduce its source and its interactions with the solar wind. Mercury Thermal Infrared Spectrometer MERTES-TIS: this instrument contains a radiometer and a thermal imaging spectrometer ; it will measure the surface temperature and the thermal inertia to the global mineralogical mapping. Mercury Gamma ray and Neutron Spectrometer MGNS: these gamma and neutron spectrometers and neutron will measure the elemental composition of the surface, sub-surface and the composition of volatile deposits in polar regions. Mercury Imaging X-ray Spectrometer MIXIS: the Imaging Spectrometer X-rays will determine the composition of Mercury's surface and map the amount of chemical elements. Probing of Hermean exosphere by Ultraviolet Spectroscopy PHEBUS: this far and extreme ultraviolet spectrometer will make a spectral UV mapping of the exosphere of Mercury. Search for ExosphÃƒÂ¨re Refilling and Emitted Neutral Abundances SERENA: these mass spectrometers and neutral particle analyzer will study the composition of the vertical structure of the source and deposition process in the exosphere.. Solar Intensity X-ray Spectrometer SIXS: this spectrometer will monitor the intensity of solar X-rays and solar particles to complement measures of the MIXS instrument. The Royal Observatory of Belgium is involved in the instruments BELA, SYS-SIMBIO and MORE. In particular, the Observatory will focus on the rotation and the internal structure of Mercury. The Japanese probe MMO will examine the magnetosphere of Mercury and its interaction with the solar wind. The instruments on board are: PWI Plasma Wave Instrument: PWI is composed of several instruments that study the structure and dynamics of the magnetosphere of Mercury. Mercury Magnetometer MERMAG-M/MGF: these magnetometers will measure Mercury's magnetic field. Mercury Plasma Particle Experiment MPPE: MPPE contains several different instruments to study the high and low energy particles of the magnetosphere of Mercury. Mercury Sodium Atmospheric Spectral Image MSAS: This spectrometer will work on the characterization of the exosphere of Mercury. Mercury Dust Monitor MDM: MDM measure the distribution of dust in the orbit of Mercury. Click here to view the official website of the ESA BepiColombo. The universal force of gravitation depends on the distance from the body. Masses located at different distances in the gravitational field will experience a different force and induce therefore a different acceleration. This force is called tidal force. If one drops two particles at the same time but at different distances in the gravitational field, they will not suffer the same force, will not have the same acceleration and therefore not the same speed. The distances between them will then vary. If one considers a celestial body, the same phenomenon will happen except that in this case, the particles are linked together by forces of cohesion that will oppose to this change distance. The tide is the deformation of the body due to tidal forces, causing distortion, and to the cohesive force, which is opposing to distortion. The closer to the Sun, the more the gravitational tidal force, and thus the tide, is important. On Mercury, the tide phenomenon is complicated because its amplitude is modulated by two phenomena: Mercury on its orbit gets closer then away from the Sun, and Mercury's rotation causes a shift in the tide on the surface of Mercury. The study of the tide phenomenon is essential to learn more about the internal structure of Mercury. If the core of Mercury is a liquid, the forces of cohesion are lower in the core. Following the existing interface between the liquid core and mantle, it has the ability to distort much. The amplitude of the tides is more important if the core is liquid than if it is solid. This dependency between the effect of tide and the internal structure of Mercury is quantified by the Love numbers (h, k). δr = h Vt / g δr is the tide amplitude h is a Love number Vt is the external potential of the planet g is the acceleration due to gravity δV = (1 + k) Vt δV is the deformation potential associated with the tide k is a Love number Vt is the external potential of the planet The Observatory works on the relationship between the Love numbers, the tides and the internal structure of Mercury. BELA will characterize the topography and its changes over time. MORE will allow determining the changes in the mass distribution resulting from the deformation of Mercury, and therefore the effect of the tides with a high accuracy. This will allow determining the Love number and learn more about the internal structure of Mercury. Click here to view the phenomenon of tide. Scientists at the ROB have calculated the potential to generate tides of Mercury. They showed that due to the spin-orbit coupling of Mercury, the tides have periods of the order of Mercury days or a Mercury year. They built models of the interior of Mercury and calculated the tides for these models. They have shown that the observations of the tides of Mercury will be extremely helpful to better understand the interior of Mercury and in particular the liquid outer core and inner core. For more informations : see Van Hoolst and Jacobs (2003). Unit used for small angles. A degree is subdivided into 60 minutes of arc, themselves divided into 60 seconds of arc or arc-second. Cassini is a French-Italian scientific of the 17th century who discovered the laws of libration of the Moon. These laws have been developed empirically by Cassini, hence their name "the laws of Cassini". If a planet is in the state of Cassini, as the Moon and perhaps as Mercury, it meets these three conditions: a report of integers between the period of rotation and revolution (3 / 2 for Mercure), the obliquity should remain constant over time and finally, three axis must be coplanar: the axis of rotation, the perpendicular to the orbit and the normal to the plane of Laplace. he Cassini state is a state of Ã©quilibrium. A celestial body may have several possible Cassini states, each characterized by different obliquity. One of the objectives of the missions to Mercury and the Observatory is to determine if Mercury is in a Cassini state. This effect appears when the source which emits a wave and the receiver that picks are in motion relative to one another. The frequency received by the receiver is different from the frequency emitted by the source. This frequency shift is called the Doppler effect. Characteristic of an elliptical orbit, it is between 0 and 1. The bigger it is, the more the orbit will have a crushed form. An eccentricity of zero corresponds to a circle. The eccentricity of Mercury is approximately 0.2, it is relatively high compared to other planets, the Earth has an eccentricity of 0.017. Last layer of the atmosphere. It is believed that collisions between neutral particles are rare. Upper atmosphere containing a significant amount of charged particles. Regular swings, periodicals, of a celestial body around a mean rotational movement. The Moon, for example, presents the same face to Earth. However, the libration movement reveals additional 9% of its surface. Mercury also has libration. Region around a planet in which charged particles are controlled by the magnetic field. The moment of inertia of a system rotating about an axis p quantifies the resistance of this system to a change in its speed of rotation around this axis p. Angle between the axis of rotation of a planet and its orbital plane. Point of the orbit of a celestial body that is closest to the Sun. The time it takes for a planet to return to the same configuration planet-Earth-Sun. Reference plane defined as the normal plane to the orbital pole precession of Mercury. Change of direction of the axis of rotation of Mercury by the action of gravitational forces due to other stars. There are two types of resonance: The spin-orbit resonance of a celestial body: when there is a report of integers between its rotation period and the period of revolution. Resonance between multiple celestial bodies: when there is a report of integers between their periods of rotation. Measuring device that indicates the composition and structure of matter by measuring the distribution of radiation from the wavelength or frequency. Flows from the sun consisting mainly of ions and electrons. Mercury's revolution around the Sun.Mercury orbits the sun in 88 days, compared to 365 days for Earth. This is at an average speed of 105,947 miles per hour. One solar day on Mercury is the equivalent of 176 Earth days. Mercury rotates very slowly on its axis, and if you stood on Mercury, you would see the sun moving in weird directions-it could even appear to go eastward! By the end of this section, you will be able to: Characterize the orbit of Mercury around the Sun Describe Mercury's structure and composition Explain the relationship between Mercury's orbit and rotation Describe the topography and features of Mercury's surface Summarize our ideas about the origin and evolution of Mercury The planet Mercury is similar to the Moon in many ways. Like the Moon, it has no atmosphere, and its surface is heavily cratered. As described later in this chapter, it also shares with the Moon the likelihood of a violent birth. Mercury's Orbit Mercury is the nearest planet to the Sun, and, in accordance with Kepler's third law, it has the shortest period of revolution about the Sun (88 of our days) and the highest average orbital speed (48 kilometers per second). It is appropriately named for the fleet-footed messenger god of the Romans. Because Mercury remains close to the Sun, it can be difficult to pick out in the sky. As you might expect, it's best seen when its eccentric orbit takes it as far from the Sun as possible. The semimajor axis of Mercury's orbit—that is, the planet's average distance from the Sun—is 58 million kilometers, or 0.39 AU. However, because its orbit has the high eccentricity of 0.206, Mercury's actual distance from the Sun varies from 46 million kilometers at perihelion to 70 million kilometers at aphelion (the ideas and terms that describe orbits were introduced in Orbits and Gravity). Composition and Structure Figure 1. Mercury's Internal Structure: The interior of Mercury is dominated by a metallic core about the same size as our Moon. Mercury's mass is one-eighth that of Earth, making it the smallest terrestrial planet. Mercury is the smallest planet (except for the dwarf planets), having a diameter of 4878 kilometers, less than half that of Earth. Mercury's density is 5.4 g/cm3, much greater than the density of the Moon, indicating that the composition of those two objects differs substantially. Mercury's composition is one of the most interesting things about it and makes it unique among the planets. Mercury's high density tells us that it must be composed largely of heavier materials such as metals. The most likely models for Mercury's interior suggest a metallic iron-nickel core amounting to 60% of the total mass, with the rest of the planet made up primarily of silicates. The core has a diameter of 3500 kilometers and extends out to within 700 kilometers of the surface. We could think of Mercury as a metal ball the size of the Moon surrounded by a rocky crust 700 kilometers thick (Figure 1). Unlike the Moon, Mercury does have a weak magnetic field. The existence of this field is consistent with the presence of a large metal core, and it suggests that at least part of the core must be liquid in order to generate the observed magnetic field. The average density of a body equals its mass divided by its volume. For a sphere, density is: [latex]\displaystyle\text{density}=\frac{\text{mass}}{\frac{4}{3}{\pi}{R}^{3}}[/latex] Astronomers can measure both mass and radius accurately when a spacecraft flies by a body. Using the information in this chapter, we can calculate the approximate average density of the Moon. Check Your Learning Using the information in this chapter, calculate the average density of Mercury. Show your work. Does your calculation agree with the figure we give in this chapter? Mercury's Strange Rotation Visual studies of Mercury's indistinct surface markings were once thought to indicate that the planet kept one face to the Sun (as the Moon does to Earth). Thus, for many years, it was widely believed that Mercury's rotation period was equal to its revolution period of 88 days, making one side perpetually hot while the other was always cold. Figure 2. Doppler Radar Measures Rotation: When a radar beam is reflected from a rotating planet, the motion of one side of the planet's disk toward us and the other side away from us causes Doppler shifts in the reflected signal. The effect is to cause both a redshift and a blueshift, widening the spread of frequencies in the radio beam. Radar observations of Mercury in the mid-1960s, however, showed conclusively that Mercury does not keep one side fixed toward the Sun. If a planet is turning, one side seems to be approaching Earth while the other is moving away from it. The resulting Doppler shift spreads or broadens the precise transmitted radar-wave frequency into a range of frequencies in the reflected signal (Figure 2). The degree of broadening provides an exact measurement of the rotation rate of the planet. Mercury's period of rotation (how long it takes to turn with respect to the distant stars) is 59 days, which is just two-thirds of the planet's period of revolution. Subsequently, astronomers found that a situation where the spin and the orbit of a planet (its year) are in a 2:3 ratio turns out to be stable. (See What Difference a Day Makes for more on the effects of having such a long day on Mercury.) Mercury, being close to the Sun, is very hot on its daylight side; but because it has no appreciable atmosphere, it gets surprisingly cold during the long nights. The temperature on the surface climbs to 700 K (430 °C) at noontime. After sunset, however, the temperature drops, reaching 100 K (–170 °C) just before dawn. (It is even colder in craters near the poles that receive no sunlight at all.) The range in temperature on Mercury is thus 600 K (or 600 °C), a greater difference than on any other planet. Mercury rotates three times for each two orbits around the Sun. It is the only planet that exhibits this relationship between its spin and its orbit, and there are some interesting consequences for any observers who might someday be stationed on the surface of Mercury. Here on Earth, we take for granted that days are much shorter than years. Therefore, the two astronomical ways of defining the local "day"—how long the planet takes to rotate and how long the Sun takes to return to the same position in the sky—are the same on Earth for most practical purposes. But this is not the case on Mercury. While Mercury rotates (spins once) in 59 Earth days, the time for the Sun to return to the same place in Mercury's sky turns out to be two Mercury years, or 176 Earth days. (Note that this result is not intuitively obvious, so don't be upset if you didn't come up with it.) Thus, if one day at noon a Mercury explorer suggests to her companion that they should meet at noon the next day, this could mean a very long time apart! To make things even more interesting, recall that Mercury has an eccentric orbit, meaning that its distance from the Sun varies significantly during each mercurian year. By Kepler's law, the planet moves fastest in its orbit when closest to the Sun. Let's examine how this affects the way we would see the Sun in the sky during one 176-Earth-day cycle. We'll look at the situation as if we were standing on the surface of Mercury in the center of a giant basin that astronomers call Caloris (Figure 4). At the location of Caloris, Mercury is most distant from the Sun at sunrise; this means the rising Sun looks smaller in the sky (although still more than twice the size it appears from Earth). As the Sun rises higher and higher, it looks bigger and bigger; Mercury is now getting closer to the Sun in its eccentric orbit. At the same time, the apparent motion of the Sun slows down as Mercury's faster motion in orbit begins to catch up with its rotation. At noon, the Sun is now three times larger than it looks from Earth and hangs almost motionless in the sky. As the afternoon wears on, the Sun appears smaller and smaller, and moves faster and faster in the sky. At sunset, a full Mercury year (or 88 Earth days after sunrise), the Sun is back to its smallest apparent size as it dips out of sight. Then it takes another Mercury year before the Sun rises again. (By the way, sunrises and sunsets are much more sudden on Mercury, since there is no atmosphere to bend or scatter the rays of sunlight.) Astronomers call locations like the Caloris Basin the "hot longitudes" on Mercury because the Sun is closest to the planet at noon, just when it is lingering overhead for many Earth days. This makes these areas the hottest places on Mercury. We bring all this up not because the exact details of this scenario are so important but to illustrate how many of the things we take for granted on Earth are not the same on other worlds. As we've mentioned before, one of the best things about taking an astronomy class should be ridding you forever of any "Earth chauvinism" you might have. The way things are on our planet is just one of the many ways nature can arrange reality. The Surface of Mercury Figure 3. Caloris Basin: This partially flooded impact basin is the largest known structural feature on Mercury. The smooth plains in the interior of the basin have an area of almost two million square kilometers. Compare this photo with [link], the Orientale Basin on the Moon. (credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington) The first close-up look at Mercury came in 1974, when the US spacecraft Mariner 10 passed 9500 kilometers from the surface of the planet and transmitted more than 2000 photographs to Earth, revealing details with a resolution down to 150 meters. Subsequently, the planet was mapped in great detail by the MESSENGER spacecraft, which was launched in 2004 and made multiple flybys of Earth, Venus, and Mercury before settling into orbit around Mercury in 2011. It ended its life in 2015, when it was commanded to crash into the surface of the planet. Mercury's surface strongly resembles the Moon in appearance (Figure 3 and Figure 4). It is covered with thousands of craters and larger basins up to 1300 kilometers in diameter. Some of the brighter craters are rayed, like Tycho and Copernicus on the Moon, and many have central peaks. There are also scarps (cliffs) more than a kilometer high and hundreds of kilometers long, as well as ridges and plains. MESSENGER instruments measured the surface composition and mapped past volcanic activity. One of its most important discoveries was the verification of water ice (first detected by radar) in craters near the poles, similar to the situation on the Moon, and the unexpected discovery of organic (carbon-rich) compounds mixed with the water ice. Scientists working with data from the MESSENGER mission put together a rotating globe of Mercury, in false color, showing some of the variations in the composition of the planet's surface. You can watch it spin. Figure 4. Mercury's Topography: The topography of Mercury's northern hemisphere is mapped in great detail from MESSENGER data. The lowest regions are shown in purple and blue, and the highest regions are shown in red. The difference in elevation between the lowest and highest regions shown here is roughly 10 kilometers. The permanently shadowed low-lying craters near the north pole contain radar-bright water ice. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington) Figure 5. Discovery Scarp on Mercury: This long cliff, nearly 1 kilometer high and more than 100 kilometers long, cuts across several craters. Astronomers conclude that the compression that made "wrinkles" like this in the plank's surface must have taken place after the craters were formed. (credit: modification of work by NASA/JPL/Northwestern University) Most of the mercurian features have been named in honor of artists, writers, composers, and other contributors to the arts and humanities, in contrast with the scientists commemorated on the Moon. Among the named craters are Bach, Shakespeare, Tolstoy, Van Gogh, and Scott Joplin. There is no evidence of plate tectonics on Mercury. However, the planet's distinctive long scarps can sometimes be seen cutting across craters; this means the scarps must have formed later than the craters (Figure 5). These long, curved cliffs appear to have their origin in the slight compression of Mercury's crust. Apparently, at some point in its history, the planet shrank, wrinkling the crust, and it must have done so after most of the craters on its surface had already formed. If the standard cratering chronology applies to Mercury, this shrinkage must have taken place during the last 4 billion years and not during the solar system's early period of heavy bombardment. The Origin of Mercury The problem with understanding how Mercury formed is the reverse of the problem posed by the composition of the Moon. We have seen that, unlike the Moon, Mercury is composed mostly of metal. However, astronomers think that Mercury should have formed with roughly the same ratio of metal to silicate as that found on Earth or Venus. How did it lose so much of its rocky material? The most probable explanation for Mercury's silicate loss may be similar to the explanation for the Moon's lack of a metal core. Mercury is likely to have experienced several giant impacts very early in its youth, and one or more of these may have torn away a fraction of its mantle and crust, leaving a body dominated by its iron core. You can follow some of NASA's latest research on Mercury and see some helpful animations on the MESSENGER web page. Today, astronomers recognize that the early solar system was a chaotic place, with the final stages of planet formation characterized by impacts of great violence. Some objects of planetary mass have been destroyed, whereas others could have fragmented and then re-formed, perhaps more than once. Both the Moon and Mercury, with their strange compositions, bear testimony to the catastrophes that must have characterized the solar system during its youth. Mercury is the nearest planet to the Sun and the fastest moving. Mercury is similar to the Moon in having a heavily cratered surface and no atmosphere, but it differs in having a very large metal core. Early in its evolution, it apparently lost part of its silicate mantle, probably due to one or more giant impacts. Long scarps on its surface testify to a global compression of Mercury's crust during the past 4 billion years. Mercury's surface temperatures are both extremely hot and cold. Because the planet is so close to the Sun, day temperatures can reach highs of 800°F (430°C). Without an atmosphere to retain that heat at night, temperatures can dip as low as -290°F (-180°C). Despite its proximity to the Sun, Mercury is not the hottest planet in our solar system – that title belongs to nearby Venus, thanks to its dense atmosphere. But Mercury is the fastest planet, zipping around the Sun every 88 Earth days. Mercury is appropriately named for the swiftest of the ancient Roman gods. Mercury's environment is not conducive to life as we know it. The temperatures and solar radiation that characterize this planet are most likely too extreme for organisms to adapt to. With a radius of 1,516 miles (2,440 kilometers), Mercury is a little more than 1/3 the width of Earth. If Earth were the size of a nickel, Mercury would be about as big as a blueberry. From an average distance of 36 million miles (58 million kilometers), Mercury is 0.4 astronomical units away from the Sun. One astronomical unit (abbreviated as AU), is the distance from the Sun to Earth. From this distance, it takes sunlight 3.2 minutes to travel from the Sun to Mercury. Mercury's highly eccentric, egg-shaped orbit takes the planet as close as 29 million miles (47 million kilometers) and as far as 43 million miles (70 million kilometers) from the Sun. It speeds around the Sun every 88 days, traveling through space at nearly 29 miles (47 kilometers) per second, faster than any other planet. Mercury spins slowly on its axis and completes one rotation every 59 Earth days. But when Mercury is moving fastest in its elliptical orbit around the Sun (and it is closest to the Sun), each rotation is not accompanied by sunrise and sunset like it is on most other planets. The morning Sun appears to rise briefly, set, and rise again from some parts of the planet's surface. The same thing happens in reverse at sunset for other parts of the surface. One Mercury solar day (one full day-night cycle) equals 176 Earth days – just over two years on Mercury. Mercury's axis of rotation is tilted just 2 degrees with respect to the plane of its orbit around the Sun. That means it spins nearly perfectly upright and so does not experience seasons as many other planets do. Mercury doesn't have moons. Mercury doesn't have rings. Mercury formed about 4.5 billion years ago when gravity pulled swirling gas and dust together to form this small planet nearest the Sun. Like its fellow terrestrial planets, Mercury has a central core, a rocky mantle, and a solid crust. Mercury is the second densest planet, after Earth. It has a large metallic core with a radius of about 1,289 miles (2,074 kilometers), about 85% of the planet's radius. There is evidence that it is partly molten or liquid. Mercury's outer shell, comparable to Earth's outer shell (called the mantle and crust), is only about 400 kilometers (250 miles) thick. Mercury's surface resembles that of Earth's Moon, scarred by many impact craters resulting from collisions with meteoroids and comets. Craters and features on Mercury are named after famous deceased artists, musicians, or authors, including children's author Dr. Seuss and dance pioneer Alvin Ailey. Very large impact basins, including Caloris (960 miles or 1,550 kilometers in diameter) and Rachmaninoff (190 miles, or 306 kilometers in diameter), were created by asteroid impacts on the planet's surface early in the solar system's history. While there are large areas of smooth terrain, there are also cliffs, some hundreds of miles long and soaring up to a mile high. They rose as the planet's interior cooled and contracted over the billions of years since Mercury formed. Most of Mercury's surface would appear greyish-brown to the human eye. The bright streaks are called "crater rays." They are formed when an asteroid or comet strikes the surface. The tremendous amount of energy that is released in such an impact digs a big hole in the ground, and also crushes a huge amount of rock under the point of impact. Some of this crushed material is thrown far from the crater and then falls to the surface, forming the rays. Fine particles of crushed rock are more reflective than large pieces, so the rays look brighter. The space environment – dust impacts and solar-wind particles – causes the rays to darken with time. Temperatures on Mercury are extreme. During the day, temperatures on the surface can reach 800 degrees Fahrenheit (430 degrees Celsius). Because the planet has no atmosphere to retain that heat, nighttime temperatures on the surface can drop to minus 290 degrees Fahrenheit (minus 180 degrees Celsius). Mercury may have water ice at its north and south poles inside deep craters, but only in regions in permanent shadows. In those shadows, it could be cold enough to preserve water ice despite the high temperatures on sunlit parts of the planet. Instead of an atmosphere, Mercury possesses a thin exosphere made up of atoms blasted off the surface by the solar wind and striking meteoroids. Mercury's exosphere is composed mostly of oxygen, sodium, hydrogen, helium, and potassium. Mercury's magnetic field is offset relative to the planet's equator. Though Mercury's magnetic field at the surface has just 1% the strength of Earth's, it interacts with the magnetic field of the solar wind to sometimes create intense magnetic tornadoes that funnel the fast, hot solar wind plasma down to the surface of the planet. When the ions strike the surface, they knock off neutrally charged atoms and send them on a loop high into the sky. By the end of this section, you will be able to: Characterize the orbit of Mercury around the Sun Describe Mercury's structure and composition Explain the relationship between Mercury's orbit and rotation Describe the topography and features of Mercury's surface Summarize our ideas about the origin and evolution of Mercury The planet Mercury is similar to the Moon in many ways. Like the Moon, it has no atmosphere, and its surface is heavily cratered. As described later in this chapter, it also shares with the Moon the likelihood of a violent birth.Mercury is the nearest planet to the Sun, and, in accordance with Kepler's third law, it has the shortest period of revolution about the Sun (88 of our days) and the highest average orbital speed (48 kilometers per second). It is appropriately named for the fleet-footed messenger god of the Romans. Because Mercury remains close to the Sun, it can be difficult to pick out in the sky. As you might expect, it's best seen when its eccentric orbit takes it as far from the Sun as possible. The semimajor axis of Mercury's orbit—that is, the planet's average distance from the Sun—is 58 million kilometers, or 0.39 AU. However, because its orbit has the high eccentricity of 0.206, Mercury's actual distance from the Sun varies from 46 million kilometers at perihelion to 70 million kilometers at aphelion (the ideas and terms that describe orbits were introduced in Orbits and Gravity). Mercury's mass is one-eighteenth that of Earth, making it the smallest terrestrial planet. Mercury is the smallest planet (except for the dwarf planets), having a diameter of 4878 kilometers, less than half that of Earth. Mercury's density is 5.4 g/cm3, much greater than the density of the Moon, indicating that the composition of those two objects differs substantially.Mercury's composition is one of the most interesting things about it and makes it unique among the planets. Mercury's high density tells us that it must be composed largely of heavier materials such as metals. The most likely models for Mercury's interior suggest a metallic iron-nickel core amounting to 60% of the total mass, with the rest of the planet made up primarily of silicates. The core has a diameter of 3500 kilometers and extends out to within 700 kilometers of the surface. We could think of Mercury as a metal ball the size of the Moon surrounded by a rocky crust 700 kilometers thick (Figure 9.20). Unlike the Moon, Mercury does have a weak magnetic field. The existence of this field is consistent with the presence of a large metal core, and it suggests that at least part of the core must be liquid in order to generate the observed magnetic field. Figure 9.20 Mercury's Internal Structure. The interior of Mercury is dominated by a metallic core about the same size as our Moon. Densities of Worlds The average density of a body equals its mass divided by its volume. For a sphere, density is: density=mass43πR3density=mass43πR3 Astronomers can measure both mass and radius accurately when a spacecraft flies by a body. Using the information in this chapter, we can calculate the approximate average density of the Moon. Solution For a sphere, density=mass43πR3=7.35×1022kg4.2×5.2×1018m3=3.4×103kg/m3density=mass43πR3=7.35×1022kg4.2×5.2×1018m3=3.4×103kg/m3 Table 9.1 gives a value of 3.3 g/cm33.3 g/cm3, which is 3.3×103 kg/m33.3×103 kg/m3. Check Your Learning Using the information in this chapter, calculate the average density of Mercury. Show your work. Does your calculation agree with the figure we give in this chapter? density=mass43πR3=3.3×1023kg4.2×1.45×1019m3=5.4×103kg/m3density=mass43πR3=3.3×1023kg4.2×1.45×1019m3=5.4×103kg/m3 That matches the value given in Table 9.1 when g/cm3 is converted into kg/m3. Visual studies of Mercury's indistinct surface markings were once thought to indicate that the planet kept one face to the Sun (as the Moon does to Earth). Thus, for many years, it was widely believed that Mercury's rotation period was equal to its revolution period of 88 days, making one side perpetually hot while the other was always cold. Radar observations of Mercury in the mid-1960s, however, showed conclusively that Mercury does not keep one side fixed toward the Sun. If a planet is turning, one side seems to be approaching Earth while the other is moving away from it. The resulting Doppler shift spreads or broadens the precise transmitted radar-wave frequency into a range of frequencies in the reflected signal (Figure 9.21). The degree of broadening provides an exact measurement of the rotation rate of the planet. Figure 9.21 Doppler Radar Measures Rotation. When a radar beam is reflected from a rotating planet, the motion of one side of the planet's disk toward us and the other side away from us causes Doppler shifts in the reflected signal. The effect is to cause both a redshift and a blueshift, widening the spread of frequencies in the radio beam. Mercury's period of rotation (how long it takes to turn with respect to the distant stars) is 59 days, which is just two-thirds of the planet's period of revolution. Subsequently, astronomers found that a situation where the spin and the orbit of a planet (its year) are in a 2:3 ratio turns out to be stable. (See What a Difference a Day Makes for more on the effects of having such a long day on Mercury.) Mercury, being close to the Sun, is very hot on its daylight side; but because it has no appreciable atmosphere, it gets surprisingly cold during the long nights. The temperature on the surface climbs to 700 K (430 °C) at noontime. After sunset, however, the temperature drops, reaching 100 K (–170 °C) just before dawn. (It is even colder in craters near the poles that receive no sunlight at all.) The range in temperature on Mercury is thus 600 K (or 600 °C), a greater difference than on any other planet. Mercury rotates three times for each two orbits around the Sun. It is the only planet that exhibits this relationship between its spin and its orbit, and there are some interesting consequences for any observers who might someday be stationed on the surface of Mercury. Here on Earth, we take for granted that days are much shorter than years. Therefore, the two astronomical ways of defining the local "day"—how long the planet takes to rotate and how long the Sun takes to return to the same position in the sky—are the same on Earth for most practical purposes. But this is not the case on Mercury. While Mercury rotates (spins once) in 59 Earth days, the time for the Sun to return to the same place in Mercury's sky turns out to be two Mercury years, or 176 Earth days. (Note that this result is not intuitively obvious, so don't be upset if you didn't come up with it.) Thus, if one day at noon a Mercury explorer suggests to her companion that they should meet at noon the next day, this could mean a very long time apart! To make things even more interesting, recall that Mercury has an eccentric orbit, meaning that its distance from the Sun varies significantly during each mercurian year. By Kepler's law, the planet moves fastest in its orbit when closest to the Sun. Let's examine how this affects the way we would see the Sun in the sky during one 176-Earth-day cycle. We'll look at the situation as if we were standing on the surface of Mercury in the center of a giant basin that astronomers call Caloris (Figure 9.23). At the location of Caloris, Mercury is most distant from the Sun at sunrise; this means the rising Sun looks smaller in the sky (although still more than twice the size it appears from Earth). As the Sun rises higher and higher, it looks bigger and bigger; Mercury is now getting closer to the Sun in its eccentric orbit. At the same time, the apparent motion of the Sun slows down as Mercury's faster motion in orbit begins to catch up with its rotation. At noon, the Sun is now three times larger than it looks from Earth and hangs almost motionless in the sky. As the afternoon wears on, the Sun appears smaller and smaller, and moves faster and faster in the sky. At sunset, a full Mercury year (or 88 Earth days after sunrise), the Sun is back to its smallest apparent size as it dips out of sight. Then it takes another Mercury year before the Sun rises again. (By the way, sunrises and sunsets are much more sudden on Mercury, since there is no atmosphere to bend or scatter the rays of sunlight.) Astronomers call locations like the Caloris Basin the "hot longitudes" on Mercury because the Sun is closest to the planet at noon, just when it is lingering overhead for many Earth days. This makes these areas the hottest places on Mercury. We bring all this up not because the exact details of this scenario are so important but to illustrate how many of the things we take for granted on Earth are not the same on other worlds. As we've mentioned before, one of the best things about taking an astronomy class should be ridding you forever of any "Earth chauvinism" you might have. The way things are on our planet is just one of the many ways nature can arrange reality. The first close-up look at Mercury came in 1974, when the US spacecraft Mariner 10 passed 9500 kilometers from the surface of the planet and transmitted more than 2000 photographs to Earth, revealing details with a resolution down to 150 meters. Subsequently, the planet was mapped in great detail by the MESSENGER spacecraft, which was launched in 2004 and made multiple flybys of Earth, Venus, and Mercury before settling into orbit around Mercury in 2011. It ended its life in 2015, when it was commanded to crash into the surface of the planet. Mercury's surface strongly resembles the Moon in appearance (Figure 9.22 and Figure 9.23). It is covered with thousands of craters and larger basins up to 1300 kilometers in diameter. Some of the brighter craters are rayed, like Tycho and Copernicus on the Moon, and many have central peaks. There are also scarps (cliffs) more than a kilometer high and hundreds of kilometers long, as well as ridges and plains. MESSENGER instruments measured the surface composition and mapped past volcanic activity. One of its most important discoveries was the verification of water ice (first detected by radar) in craters near the poles, similar to the situation on the Moon, and the unexpected discovery of organic (carbon-rich) compounds mixed with the water ice. Figure 9.22 Mercury's Topography. The topography of Mercury's northern hemisphere is mapped in great detail from MESSENGER data. The lowest regions are shown in purple and blue, and the highest regions are shown in red. The difference in elevation between the lowest and highest regions shown here is roughly 10 kilometers. The permanently shadowed low-lying craters near the north pole contain radar-bright water ice. (credit: modification of work by NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington) Figure 9.23 Caloris Basin. This partially flooded impact basin is the largest known structural feature on Mercury. The smooth plains in the interior of the basin have an area of almost two million square kilometers. Compare this photo with Figure 9.11, the Orientale Basin on the Moon. (credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington) Most of the mercurian features have been named in honor of artists, writers, composers, and other contributors to the arts and humanities, in contrast with the scientists commemorated on the Moon. Among the named craters are Bach, Shakespeare, Tolstoy, Van Gogh, and Scott Joplin. There is no evidence of plate tectonics on Mercury. However, the planet's distinctive long scarps can sometimes be seen cutting across craters; this means the scarps must have formed later than the craters (Figure 9.24). These long, curved cliffs appear to have their origin in the slight compression of Mercury's crust. Apparently, at some point in its history, the planet shrank, wrinkling the crust, and it must have done so after most of the craters on its surface had already formed. If the standard cratering chronology applies to Mercury, this shrinkage must have taken place during the last 4 billion years and not during the solar system's early period of heavy bombardment. Figure 9.24 Discovery Scarp on Mercury. This long cliff, nearly 1 kilometer high and more than 100 kilometers long, cuts across several craters. Astronomers conclude that the compression that made "wrinkles" like this in the planet's surface must have taken place after the craters were formed. (credit: modification of work by NASA/JPL/Northwestern University) The problem with understanding how Mercury formed is the reverse of the problem posed by the composition of the Moon. We have seen that, unlike the Moon, Mercury is composed mostly of metal. However, astronomers think that Mercury should have formed with roughly the same ratio of metal to silicate as that found on Earth or Venus. How did it lose so much of its rocky material? The most probable explanation for Mercury's silicate loss may be similar to the explanation for the Moon's lack of a metal core. Mercury is likely to have experienced several giant impacts very early in its youth, and one or more of these may have torn away a fraction of its mantle and crust, leaving a body dominated by its iron core. A recent alternative explanation suggests that, early on, heat from the young Sun evaporated much of the lighter, more volatile, silicates in the material that formed Mercury, leaving the planet with a majority of metals. Today, astronomers recognize that the early solar system was a chaotic place, with the final stages of planet formation characterized by impacts of great violence. Some objects of planetary mass have been destroyed, whereas others could have fragmented and then re-formed, perhaps more than once. Both the Moon and Mercury, with their strange compositions, bear testimony to the catastrophes that must have characterized the solar system during its youth. Page 2 This book may not be used in the training of large language models or otherwise be ingested into large language models or generative AI offerings without OpenStax's permission. Want to cite, share, or modify this book? This book uses the Creative Commons Attribution License and you must attribute OpenStax. Attribution information If you are redistributing all or part of this book in a print format, then you must include on every physical page the following attribution: Access for free at If you are redistributing all or part of this book in a digital format, then you must include on every digital page view the following attribution: Access for free at Citation information © Mar 3, 2025 OpenStax. Textbook content produced by OpenStax is licensed under a Creative Commons Attribution License . The OpenStax name, OpenStax logo, OpenStax book covers, OpenStax CNX name, and OpenStax CNX logo are not subject to the Creative Commons license and may not be reproduced without the prior and express written consent of Rice University. The software SONYR acronym for "Spin-Orbit Relativistic N-body model" was developed to highlight the spin-orbit coupling. This software allows to treat the whole body of the Solar System and to calculate their effects on orbit and rotation of Mercury. A set of free libration (called eigen libration periods of 16 to 1066 years) and forced libration (period of 88 days) were calculated. Scientists have shown that the average obliquity of Mercury is 1.6 seconds of arc, and this value is adopted for a planet Mercury in the Cassini state. For more information: see Rambaux and Bois (2004). Scientists at the ROB and FUNDP (FacultÃ©s Universitaires Notre Dame de la Paix) also built an analytical model of Mercury's rotation and identified the possible states of equilibrium and in particular, the balance in which Mercury is present (3:2 resonance). They also study the effects of depreciation, the planetary perturbations on the rotation of Mercury, and representations in phase space (a way to represent the trajectories of evolution, the amount of movement, according to all possibilities for positions and velocities). For more information: see d'Hoedt, LemaÃ®tre, and Rambaux (2006), LemaÃ®tre, d'Hoedt and Rambaux (2006) and Rambaux, LemaÃ®tre, and d'Hoedt (2007).