Chapter 4: **Overview of solar system**

- introduction to solar system objects
- surface temperatures
- summary tables of orbital and physical properties
- sample questions

Introduction

This chapter is an introduction to the objects in the solar system; subsequent chapters will consider in greater depth the physical processes that modify the interiors, surfaces, and atmospheres of the objects in our solar system. Then we will briefly consider planetary systems around other stars. These chapters are written assuming that you are already somewhat familiar with the basic physics of light and orbits presented in the introductory chapter (Ch. 1).

The following figure shows most of the significant components of our solar system; it's probably obvious, but do note that the separations between objects are not to scale!

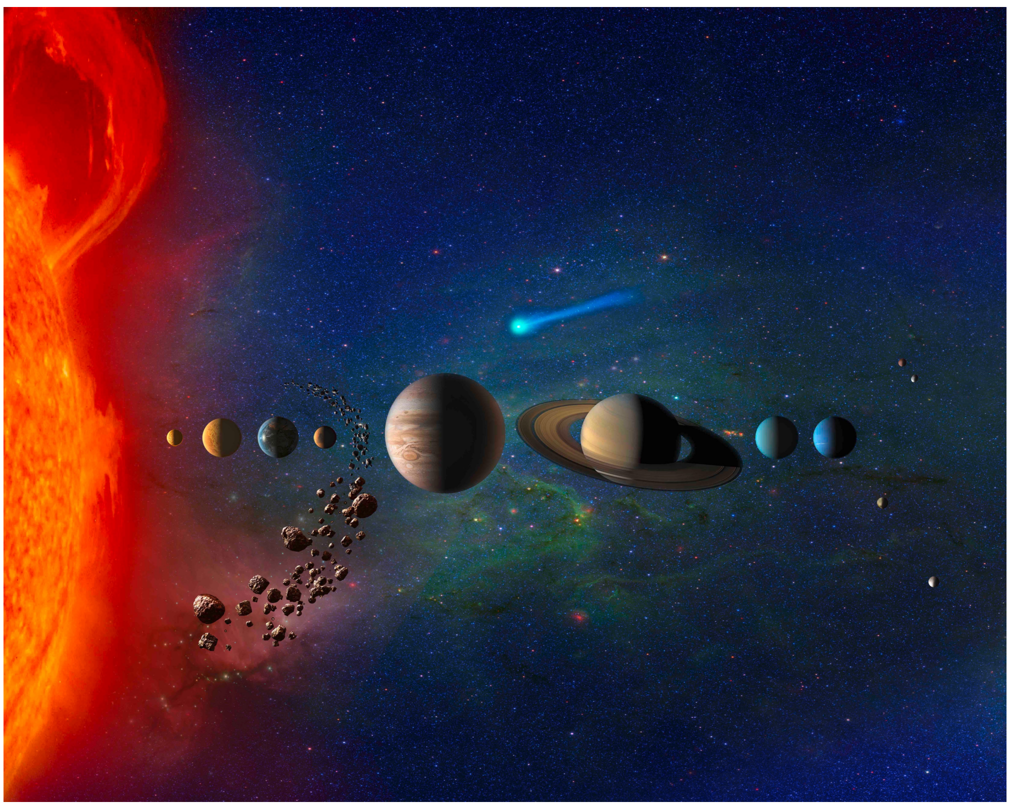


Figure 4.1: Components of the solar system; credit: NASA
http://solarsystem.nasa.gov/multimedia/gallery/solar_system_Cover_rev_40-3.jpg

The Sun, at roughly a million times the size of the Earth, is the dominant player in the solar system. The orbits of the eight major planets all lie moderately close to the plane of the Sun's equator and to the ecliptic, the plane of the Earth orbit (i.e., their orbits have low *inclinations*). The inner planets – Mercury, Venus, Earth, and Mars – are rocky objects without extensive atmospheres, sometimes called terrestrial planets because their general properties are similar to Earth, at least in comparison to the outer planets. Those outer planets – Jupiter and Saturn, Uranus and Neptune – are significantly larger and less dense (recall that density = mass / volume) than the inner rocky planets. Jupiter and Saturn are often called gas giants because of their extended atmospheres; Uranus and Neptune, intermediate in size and residing in the colder outer reaches of the solar system, are more properly called ice or slush giants. Most of the planets (except for Mercury and Venus) have satellites, several of which are in the same size range as Mercury or our Moon. A substantial band of small rocky objects, the asteroid belt, lies between the orbits of Mars and Jupiter. A broader band of small icy objects, the Kuiper Belt, lies beyond the orbit of Neptune. A few objects, called Centaurs, have orbits crossing those of the outer planets; there are also Trans-Neptunian scattered disk objects (SDOs) with eccentric and large orbits. Throughout the inner solar system there's a noticeable layer of dust that can sometimes be seen at twilight as a band of reflected sunlight called the zodiacal light. Objects that are massive enough to be round but not massive enough to be the dominant gravitational player in their region of the solar system are called dwarf planets; Pluto is a dwarf planet, as is Ceres, the largest object in the asteroid belt. Comets are small, often icy, objects, often having orbits that are substantially more eccentric than other solar system bodies. When closest to the Sun, and warmest, comets outgas and develop the characteristic coma, or "long hair", that is the root of their name. Farthest out in the solar system is the Oort cloud, a region of icy planetesimals that may extend out as far as 10^5 AU and provide a source for at least some comets.

The spacing of the planets' orbits almost follow an interesting pattern called the Titius-Bode "law" (or "rule"), named for two of the men who noticed in the 1700s that the planet spacing could be approximated by the following mathematical relationship:

$$a = (4 + n) / 10, \text{ with } n = 0, 3, 6, 12, 24, 48, 96, 192$$

The resulting pattern, in AU (recall that one Astronomical Unit is the average Earth – Sun distance), begins 0.4, 0.7, 1, 1.6, which is quite good for the orbital semi-major axes for Mercury, Venus, Earth, and Mars (1.5 AU). The next value is 2.8 AU. . .and there is no major planet there. That gap was a contributing factor to motivating the searches that resulted in the discoveries of the first few objects in the asteroid belt. And yes, Ceres, discovered in 1801, orbits 2.8 AU from the Sun. Onward: 5.2, 10, and 19.6 are not bad either for Jupiter, Saturn (9.5 AU), and Uranus (19.2 AU). Neptune doesn't fit. The next place in the sequence would be 38.8 AU, closer to the orbit of Pluto than to Neptune's 30.1 AU. Neptune, though, wasn't discovered until 1846, long after the rule had been established. It is worth remembering that Mercury and Venus are roughly 1/3 and 2/3 the distance of Earth from the Sun, and that Jupiter, Saturn, and Uranus are about 5, 10, and 20 AU from the Sun. How far a planet is from the Sun affects how warm it is and what we expect its composition to be.

The principal characteristic that distinguishes a star, such as the Sun, from planets and other solar system objects, is that stars produce their own energy by nuclear fusion. The Sun is a huge ball of plasma (an ionized fluid, or gas). The temperature at the core of the Sun, where the nuclear fusion reactions are taking place, is ~15 million K (recall that kelvins are similar to degrees Celsius, but that 0° C is +273 K). At the visible surface, the Sun is ~5,800 K. There are also some differences in the way stars and most planets form, which we will consider below, in the section on the formation of the solar system.

We will start our survey of solar system objects with the inner rocky bodies. Here, to scale for size, are Mercury, Venus, Earth & our Moon, Mars, and Ceres.

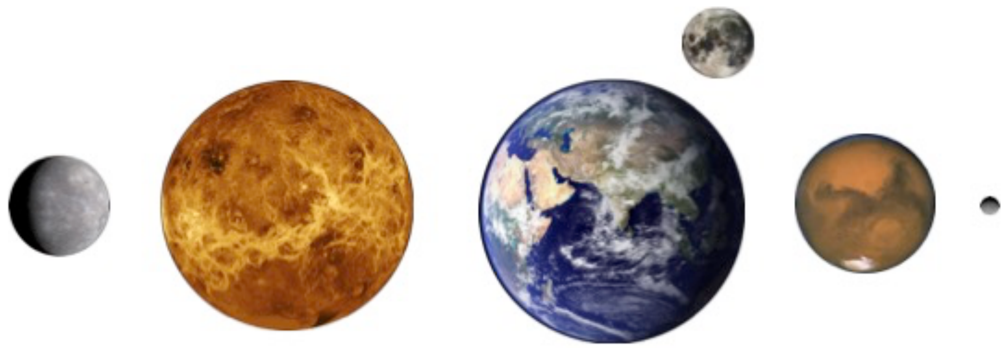


Figure 4.2: Rocky planets
Image credits: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington (https://photojournal.jpl.nasa.gov/catalog/PIA13840); NASA / JPL (https://photojournal.jpl.nasa.gov/catalog/PIA00104), NASA / Visible Earth (https://visibleearth.nasa.gov/view.php?id=57723); NASA Scientific Visualization Studio (https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4404); NASA, J. Bell (Cornell U.) and M. Wolff (SSI) (http://hubblesite.org/image/3910/printshop); NASA / JPL-Caltech/UCLA/MPS/DLR/IDA (https://photojournal.jpl.nasa.gov/catalog/PIA19544)

Mercury

Closest to the Sun is the small rocky planet Mercury. Mercury's rotation and revolution are locked in a 3:2 resonance, meaning that it rotates three times on its axis for every two orbit periods. In other words, from one perihelion to the next, i.e., over one revolution period, Mercury will have rotated 1.5 times, as shown in the figure below. With a rotation period of 58.64 days and practically no atmosphere, the daytime side of Mercury gets very hot – over 700 K – and the nighttime side gets quite cold – as low as ~80 K. It's cold enough in some of the permanently shadowed craters near the poles for water ice to collect.

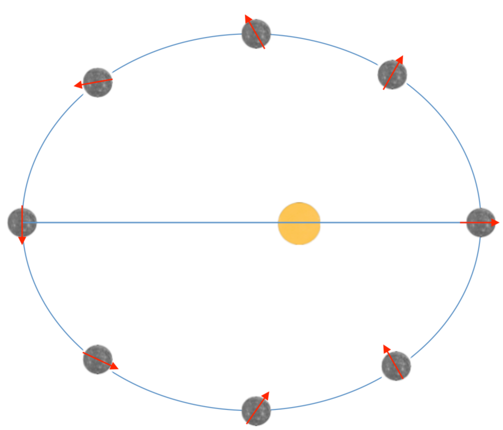


Figure 4.3:
Geometry of Mercury's orbit.
Image credit: NASA / Johns Hopkins University Applied Physics Laboratory / Carnegie Institution of Washington
https://photojournal.jpl.nasa.gov/catalog/PIA15160

Mercury's atmosphere is very tenuous, less than ~10^{-14} times the pressure of Earth's atmosphere. Atoms of hydrogen and helium can get deposited by the solar wind (the continual outflow of particles from the Sun); other atoms, such as oxygen and sodium, likely originate from the rocks in the planet's crust. The radiation pressure of the sunlight is high enough to push this tenuous atmosphere into an anti-sunward tail.

The density of a planet is determined in part by its composition and in part by whether it has enough gravity for self-compression to add to the density of its constituent parts. Mercury's density is ~5.4

g/cm^3, which is almost the same as Earth's, even though Mercury is distinctly less massive than Earth. In SI (Système International, or "metric system") units that's $5.4 \cdot 10^3$ kg/m^3; recall that liquid water at standard temperature and pressure has a density of 1 g/cm^3 or 1000 kg/m^3. Mercury must have a relatively high proportion of metal mixed in with its rock. (How do we know? For comparison, granite is ~2.7, basalt ~3.0, hematite ~5.3, iron ~7.9, gold ~19.3, and iridium is ~22, all in units of g/cm^3.)

Impact craters dominate Mercury's surface. The largest crater in the following image, obtained with the MESSENGER spacecraft, is named Duccio, and is about 130 km across. A cliff, such as the one that cuts across much of the terrain in this image, is called a *scarp*. We will look in more detail in subsequent chapters at various processes – in particular impact cratering and volcanism – that modify planetary surfaces. At this point, look at the image and think about what questions you might formulate about the features you see. For instance, are all the crater edges equally sharp or are some edges softer? Are the craters mostly round or mostly elliptical? Do all the crater interiors look the same?

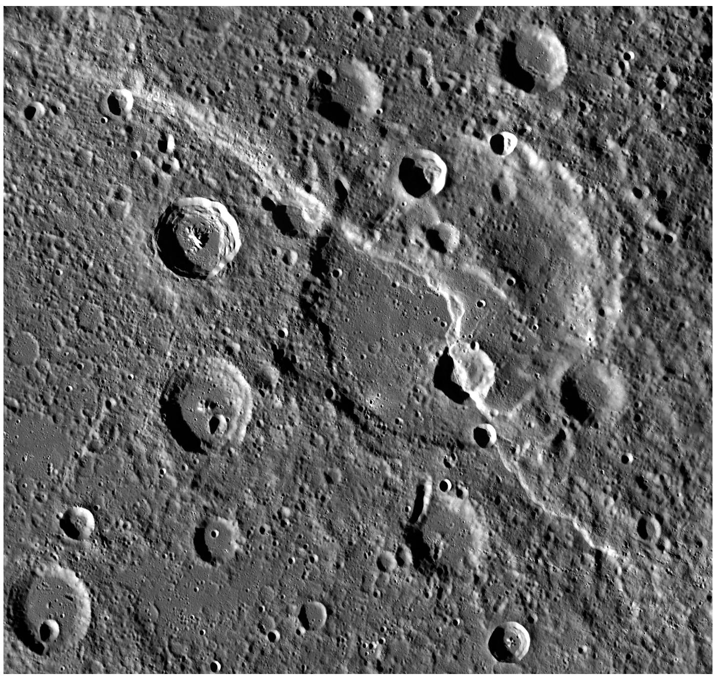


Figure 4.4: Mercury; NASA / Johns Hopkins University Applied Physics Laboratory / Carnegie Institution of Washington

http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/Carnegie%20Rupes.jpg

Venus

Venus is sometimes called Earth's "twin" because it is similar in size, mass, and density. It is not, however, a place you'd be comfortable visiting. The thick CO_2 atmosphere of Venus contributes to a classic example of the greenhouse effect run wild: the surface temperature on Venus is a toasty 737 K and the atmospheric pressure at the surface is 92 bars (the pascal is the SI unit for pressure; 1 bar is 10^5 Pa and is approximately the sea level pressure on Earth). From the early 1960s, i.e., nearly as soon as space missions were possible, until the early 1980s the Soviet Union conducted a series of reasonably successful missions to Venus. Several of the Venera landers successfully sent back images of the surface before succumbing to the harsh conditions. The image below is from the 1982 Venera 13 mission.

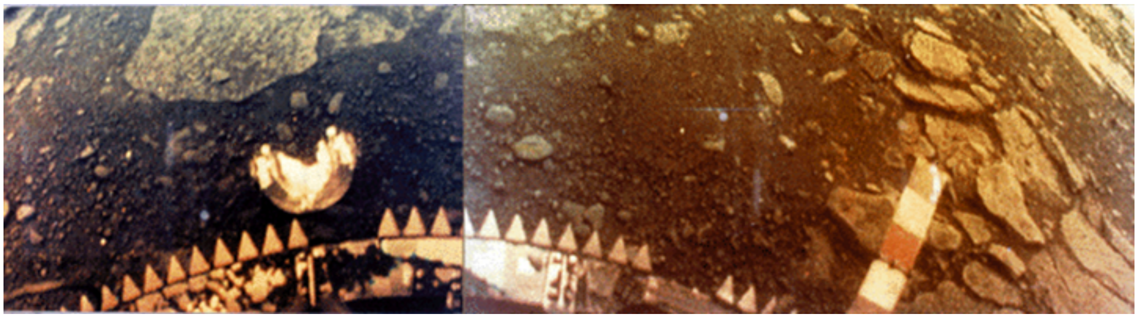


Figure 4.5: Venus, Venera 13
https://solarsystem.nasa.gov/planets/profile.cfm?Object=Venus&Display=OverviewLong

Venus is totally shrouded in clouds, which makes it very reflective (it has a high *albedo*) and, after the Sun and Moon, the brightest object in our sky. The U.S. Pioneer Venus Orbiter mission took pictures in the ultraviolet, which increases the contrast in the clouds a bit. On the left is an image of Venus from February 1979, on the right a false-color surface map:

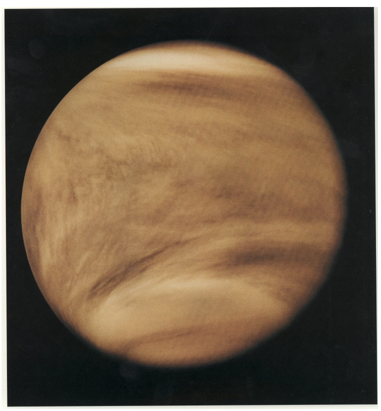


Figure 4.6a: Pioneer Venus
http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-venus.html

http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=6183
Figure 4.6b: Magellan Venus radar. Credit: NASA / JPL

The clouds make it tough to get a good idea of what the surface of Venus looks like. The best data have come from the NASA Magellan spacecraft's radar mapping. Radar bouncing straight down to the surface and back, gives us elevations, based on the light travel time; radar aimed a bit to the side tells us whether the surface is rough or smooth. If it's rough, a significant portion of the signal bounces back toward the spacecraft. If it's smooth, much of the signal reflects off into space and not back to the spacecraft. Magellan revealed a surface with several large impact craters and a wide range of volcanic features, some of which don't seem to have terrestrial counterparts. The image above, on the right hand side, shows, in false color, one hemisphere of Venus based on the Magellan radar mapping.

One additional feature of Venus is a bit odd: it rotates backwards. More properly, we could say that the *obliquity* (i.e., the tilt) of Venus' axis is 177°, or basically upside down when compared with the directions for the axes of the Sun, Earth, and most other solar system objects. Venus' day is long: 243 days long! From Earth outwards the planets all rotate in about a day, meaning that the long days of Mercury and Venus are distinctive characteristics that require explanation.

Earth & Moon

Earth is the only planet in our solar system where we find liquid water at the surface. With the development of spacecraft in the 1960s it became possible for the first time to see the Earth from space. One of the most stunning early views was taken by the Apollo 8 astronauts on 24 December 1968. The gibbous Earth is rising over the lunar landscape, in what became one of the most celebrated images from the Apollo program:

Figure 4.7: Earth and Moon.

Credit: NASA / Apollo 8. http://www.nasa.gov/centers/johnson/home/earthrise.html

As we consider other solar system objects and the processes that have shaped them, we will often use terrestrial examples for comparison. We have earthquakes and plate tectonics, as well as seismometers, and can thus know something about the interior of our planet. We have volcanic features of various sorts and can study the composition of gases, lava flows, and other volcanic ejecta. We can understand our atmosphere fairly well (even if we can't necessarily predict the weather for a month from now). We have impact craters, albeit not as well preserved as on the Moon. Use a compass, or see the Northern Lights, and you are reminded that Earth has a magnetic field. All these things make possible comparative planetology.

Earth is unique in having stable liquid water on the surface now. Why we have so much water is a not-quite-settled research question. Did our planet's water come from comets or asteroids or the primordial material from which the planet formed, or, perhaps more likely, some combination of the above? How can we tell? The relative abundances of isotopes of hydrogen and oxygen differed slightly at different locations in the solar nebula from which the planets, comets, asteroids, etc., formed. In particular, the ratio of deuterium to normal hydrogen (i.e., ^{2}H / ^{1}H or D/H) for terrestrial surface water is close to the D/H ratio for asteroids, better than the match with comets. But in addition to ocean water we can also measure the D/H ratio for volcanic rocks whose eruptions sampled different mantle depths. The D/H ratio for the deepest, most pristine lavas is sufficiently different from the oceanic D/H ratio to suggest that both impacts and the original solar nebula contributed to Earth's water. Elsewhere in the solar system liquid water is buried, either under layers of rock or ice or both. Water is quite abundant, though, and most objects will have some amount of water ice or water vapor.

Our Moon is also both an object worthy of study in its own right and useful by way of comparison with other solar system objects. The Moon is enough smaller than Earth that its interior is distinctly cooler, it has very little atmosphere, and its surface has well-preserved impact craters. We have lunar rock samples and good spectra of the lunar surface, both of which help us understand the composition and history of the Moon.

One characteristic of the Moon that was not apparent until the space age is the fact that the near and far sides are distinctly different. The near side is dominated by *maria*, the large dark basalt flows that some say look like a face or a rabbit (or perhaps a poodle); the far side is much more heavily cratered. Here are two composite images of the near and far sides of the Moon to illustrate that difference:

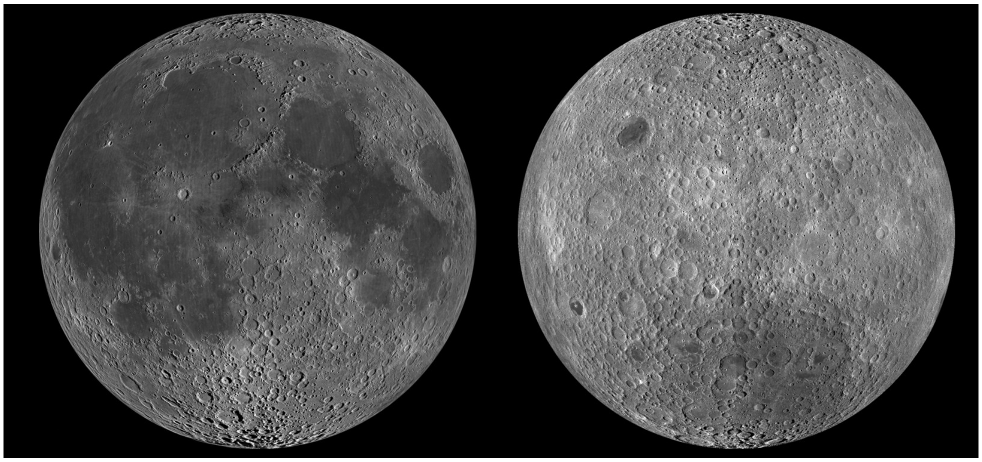


Figure 4.8: lunar near and far (right) sides. Credit: NASA / GSFC / Arizona State University. http://lroc.sese.asu.edu/posts/298

Earth and Moon are almost similar enough to be considered a double planet. The center of mass between the two does lie inside the Earth, though, indicative of our larger mass.

Example: Calculate the location of the Earth – Moon center of mass. The center of mass is the balance point between two objects. The relevant equations are

$m_1 r_1 = m_2 r_2$ and

$r_1 + r_2 = a$,

where a is the semi-major axis of the Moon's orbit, i.e., the total separation between the two bodies. We'll need to masses and the total separation to figure this out:

$\text{mass}_{\text{Earth}} = 5.97 \cdot 10^{24}$ kg

$\text{mass}_{\text{Moon}} = 7.35 \cdot 10^{22}$ kg

$a_{\text{Moon orbit}} = 384 \cdot 10^3$ km

The algebra: $r_2 = a - r_1$

$m_1 r_1 = m_2 (a - r_1) \rightarrow r_1 = m_2 a / (m_1 + m_2)$

$= (7.35 \cdot 10^{22} \text{ kg} \cdot 384 \cdot 10^3 \text{ km}) / (5.97 \cdot 10^{24} \text{ kg} + 7.35 \cdot 10^{22} \text{ kg})$

$= 4670$ km.

That means that the center of mass of the Earth – Moon system lies 4670 km from the center of the Earth. That's less than the 6371 km radius of the Earth, although still substantial enough that the Earth wobbles noticeably as it orbits that center of mass.

Mars

While Venus is a runaway greenhouse, Mars is a freeze-dried desert. Mars' average distance from the Sun is 1.52 AU (plus or minus ~10%), half again as far from the Sun as Earth is. Light falls off as the square of the distance, meaning that the flux of sunlight Mars receives is ~0.43 x as much light as Earth receives.

Example: Verify that factor of 0.43. Flux here means energy received per second per square meter. We could calculate it from the total solar luminosity this way:

$$F = L_{\text{solar}} / (4\pi\, r^2),$$

where r is the distance from the Sun and we are assuming that light spreads out evenly in all directions from the Sun. Here we want a ratio rather than the actual number of watts of energy received per square meter:

$$F_{\text{Mars}} / F_{\text{Earth}} = r_{\text{Earth}}^2 / r_{\text{Mars}}^2 = (1 / 1.52)^2 = 0.43$$

(Note that the factors of 4π cancel.)

Mars' mass is about 1/10$^{\text{th}}$ Earth's mass, meaning that Mars has both cooled off more inside and that it is less able to hold onto a blanket of atmosphere. On the other hand, Mars is larger and more massive than our Moon, so it makes sense that we see features at Mars that are intermediate between terrestrial and lunar features. For instance, Mars has an atmosphere, but it's rather tenuous, only ~6 mbar at the average surface level. It has craters, but also has had volcanic activity, which, along with wind and water, means that many of the expected original craters have been resurfaced. Mars has polar ice caps, seasons, and a day that is very similar to ours, at 24.62 hours.

The following is a classic mosaic of Mars images, created from images taken by Viking orbiters in the 1970s. The Valles Marineris, named for the Mariner Mars missions, cuts ~4,000 km across Mars' surface, near the equator. At its deepest points this rift valley is ~7 km deep. Near the limb on the left are the three volcanoes of the Tharsis rise. Olympus Mons, the largest volcano in the solar system, is out of the picture, farther around the left-hand limb.

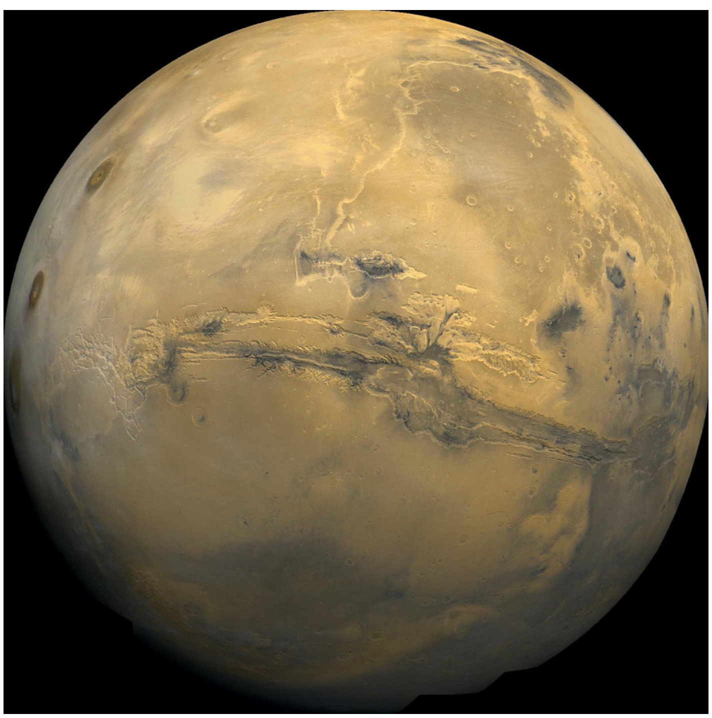


Figure 4.9: Mars. Credit: NASA / Viking Project; USGS
http://nssdc.gsfc.nasa.gov/image/planetary/mars/marsglobe1.jpg

Olympus Mons rises approximately 25 km above the surrounding plains. The caldera at the top is about 60 km wide; the volcano as a whole is about 600 km wide. It is a shield volcano, similar to Hawaii's Mauna

Kea and Mauna Loa, but many times larger. It is tough to get a good impression of just how massive this volcano is, in part because shield volcanoes are so gently sloped. This one is so large that if you were standing on it, say, near the summit (but not down in the caldera!), you would have a hard time telling that you were on an immense mountain. Your horizon would be only a few kilometers away, not nearly far enough to reach the distant plains beyond the volcano's edge. There are some cliffs around the flanks, several km high; falling off one of those might tell you that you were on a mountain! Below is an oblique view of Olympus Mons, taken by the Mars Global Surveyor and a sketch showing the relative sizes of Olympus Mons and the island of Hawaii (from the seafloor, not just above water).

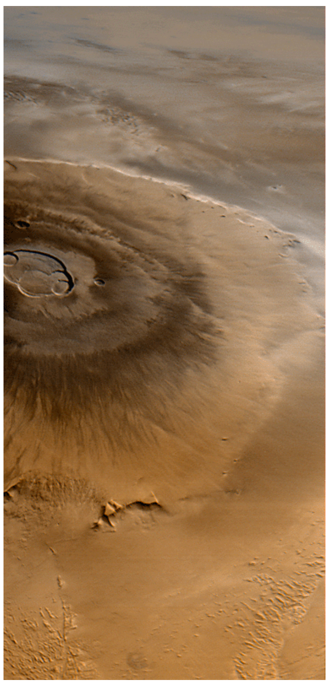


Figure 4.10 a: Olympus Mons.
Credit: NASA / JPL / Malin Space Science Systems; Mars Global Surveyor https://photojournal.jpl.nasa.gov/catalog/PIA01476

Figure 4.10 b: Below, relative sizes of Olympus Mons and Hawaii

There are features on Mars that resemble arroyos or dry riverbeds. These features were one of the first indications that Mars might have had, at least sporadically, running water on the surface. Kasei Valles, north of Valles Marineris, is a huge channel system; the image below is 1550 km east-to-west and 987 km north-to-south and still fails to capture the entire system from source to flood plain. Elevations on the lower left are several kilometers higher than at the upper right. The lower image shows the topography. Notice the lenticular (streamlined, or lens-shaped) islands carved by fluid flow; e.g., there is one at ~305° E / 26.5° N, headed by an impact crater on the left end. Understanding when and why Mars had floods and what has happened to Mars' water over the history of the planet is a challenge.

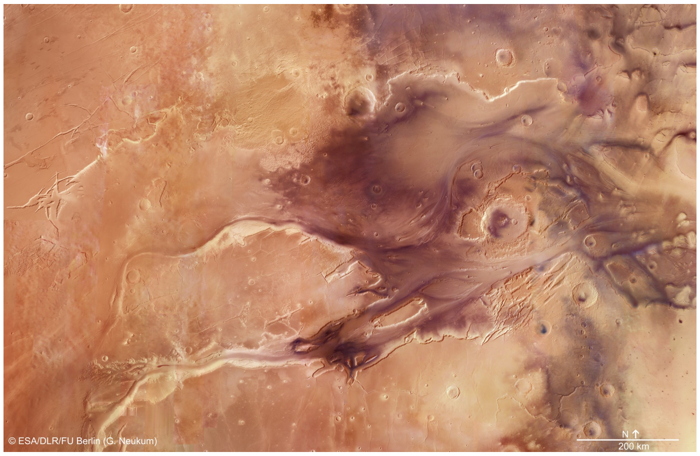


Figure 4.11 a: Kasei Valles Image credit: ESA/DLR/FU Berlin (CC BY-SA); Mars Express http://sci.esa.int/mars-express/55576-kasei-valles-mosaic/

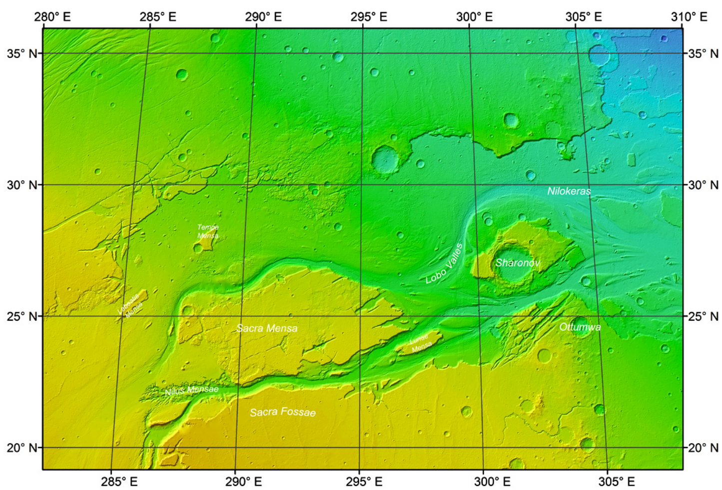


Figure 4.11 b: Topographic map http://solarsystem.nasa.gov/news/display.cfm?News_ID=43890

Mars has two small, irregularly shaped moons. Phobos and Deimos were discovered in 1877 by Asaph Hall, at the Naval Observatory in Washington, D.C.. The larger of the two, Phobos, is only ~6000 km from the surface of Mars (the semi-major axis of its orbit is ~9400 km), so close that it isn't even visible from Mars' polar regions. Its orbit period is only 7.66 hours, which is shorter than one Mars day. Phobos orbits Mars prograde; assuming that you were at a low enough latitude to see Phobos, you'd see it rise in the west every 11.12 hours.

Example: Why 11 hours? That's a *synodic* (or phase) period question. We get it by beating together the frequency of Mars' rotation on its axis with the frequency of Phobos' orbit around Mars to get the frequency with which Phobos would be seen to rise from a given location on Mars' surface. Here's the relevant equation:

$$\left|\frac{1}{P_1} - \frac{1}{P_2}\right| = \frac{1}{S}.$$

P_1 and P_2 are the two *sidereal* periods (periods with respect to the stars) and S is the resulting synodic period. Here, the periods are 7.66 hours for Phobos' revolution and 24.62 hours for Mars' rotation:

$$\left|\frac{1}{7.66^{\mathrm{h}}} - \frac{1}{24.62^{\mathrm{h}}}\right| = \frac{1}{S}, \text{ or } S = 11.12 \text{ hours.}$$

Yes, Phobos rises in the west; Deimos, farther away, has a longer orbit period and rises in the east, like our Moon.

Neither Phobos or Deimos is exactly round, but more properly called triaxial ellipsoids. Phobos is 27 x 21.6 x 18.8 km, Deimos 10 x 12 x 16 km. Phobos has an impressive crater on one end, so large that the impact that created it might have come close to shattering Phobos entirely. Phobos is on the left, in the images below, and Deimos is on the right.

Figure 4.12 a: Phobos; NASA / JPL-Caltech / University of Arizona
http://photojournal.jpl.nasa.gov/catalog/PIA10368

Figure 4.12 b: Deimos; NASA / JPL-Caltech / University of Arizona
https://photojournal.jpl.nasa.gov/catalog/PIA11826

Phobos and Deimos both have fairly low densities, ~2 g/cm^3. Their densities, small irregular sizes, colors, and surface compositions indicative of carbonaceous rock have a lot in common with certain types of asteroids, suggesting that Phobos and Deimos might have originated in the asteroid belt, had their orbits gravitationally perturbed, and later been captured by Mars.

The asteroid belt

The asteroid belt is a band of mostly small rocky objects with orbits lying between ~2 and ~3.5 AU. Several additional groups of asteroids, collectively called Trojans, have been gravitationally caught by planets, particularly Jupiter, and orbit around the Sun at the same distance as their capturing planet (specifically, near the L4 and L5 Lagrange points). Near-Earth asteroids are objects whose orbits are smaller and bring them, as the name suggests, in near the orbit of the Earth. The several thousand (we have catalogued ~ 2,000 and estimate that there are many more) whose orbits are likely to intersect Earth's, and whose diameters are more than about 140 m, are often referred to as potentially hazardous objects (usually asteroids, but sometimes comets). Several small objects are likely to pass closer to the Earth than the distance to the Moon each year. On Friday April 13th, 2029, the 300-ish meter diameter asteroid Apophis should pass within ~38,000 km of Earth (that's within the orbits of geosynchronous satellites) at which point it should be visible with binoculars, most likely from Africa and eastern Europe.

Technical terminology note, for those who are interested, on subtypes of near-Earth asteroids, named for the first, or one of the first, asteroids of each type to have been discovered:

Atiras or Apoheles: lie entirely within Earth's orbit, i.e., Q < Earth's perihelion distance (we don't know, yet, of any asteroids whose orbits lie entirely within the orbit of Venus);

Atens: $a < 1$ AU, Q > Earth's perihelion distance;

Apollos: $a > 1$ AU, q < Earth's aphelion distance;

Amors: q > Earth's aphelion distance but crossing the orbit of Mars.

Back to the majority of asteroids, those living in the asteroid belt. There are some orbital sizes that are missing. These gaps, called Kirkwood gaps, are locations where an object would have an orbital period around the Sun that is a simple fraction of Jupiter's orbit. Being in such an orbital *resonance* results in being tugged on by Jupiter at the same location, time after time. This regular tugging eventually nudges objects out of these orbits, leading to gaps. See chapter 2, on celestial mechanics, for a bit more detail; there are also orbits, such as those the Trojans occupy, where gravity encourages objects to pile up rather than disperse.

Reflection spectra show that there are several relatively distinct composition classes of asteroids. The major divisions are C-type, S-type, and M-type, standing for carbonaceous, silicate or stony, and metal-rich, respectively.

C-type asteroids, as their name indicates, contain a relatively higher proportion of carbon-containing minerals than other asteroids. They tend to be dark, with albedos under ~0.1 (translation: their surfaces reflect less than 10% of the sunlight that falls on them) and to have orbits lying in the more distant half of the asteroid belt. The left-hand image, below, is of the 50-ish km C-type asteroid 253 Matilde (the "253" means it was the 253rd asteroid to be discovered), taken by the spacecraft NEAR Shoemaker as it traveled to an encounter with 433 Eros.

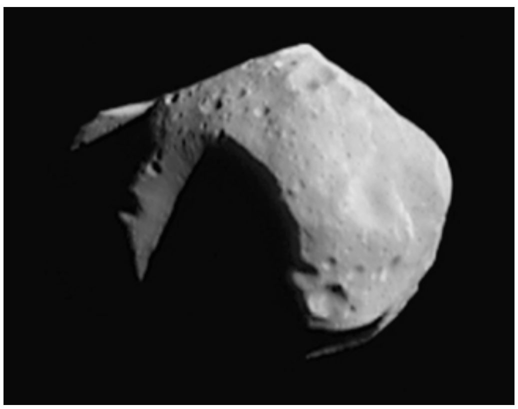


Figure 4.13: 253 Mathilde. Credit: NASA / JPL / JHUAPL; NEAR Shoemaker
https://photojournal.jpl.nasa.gov/catalog/PIA02477

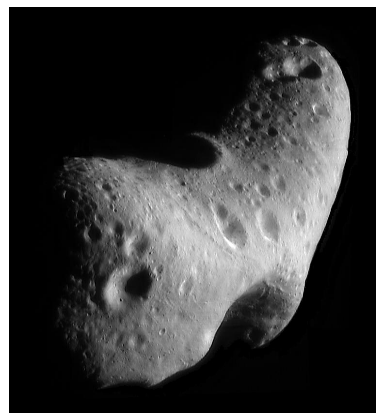


Figure 4.14: 433 Eros. Credit: NASA / JPL / JHUAPL; NEAR Shoemaker
http://photojournal.jpl.nasa.gov/catalog/PIA02923

About 75% of main-belt asteroids are C-type. S-type, composed mostly of magnesium- and iron-rich silicates, makes up another 17% of main belt objects. Their albedos are higher, ~0.1 – 0.2, and they dominate the inner part of the asteroid belt. The right-hand image, above, is of the S-type asteroid 433 Eros, and was constructed from six images taken while NEAR Shoemaker was in orbit around 433 Eros. It's about 34 x 11 x 11 km in size. Its orbit crosses inside the orbit of Mars, bringing it relatively close to Earth. The spacecraft name, NEAR Shoemaker, stands for Near-Earth Asteroid Rendezvous and for Eugene Shoemaker, a planetary scientist known for his pioneering work on impact cratering. Shoemaker died in 1997, while the spacecraft that bears his name was en route to 433 Eros. The spacecraft orbited 433 Eros for a year before landing, relatively gently, on the surface, in February 2001. It survived the landing, and sent back data from the surface for about two more weeks.

M-type asteroids are the third most common class. They also have albedos in the ~0.1 – ~0.2 range, but spectra that, at least for some, indicate a relatively high percentage of metal. Not all asteroids originally classified as M-type turn out actually to be metallic, which is a bit confusing! It's possible that the ones that are metallic are the cores of differentiated asteroids subsequently broken apart by impacts.

Let's unpack that last sentence a bit: Early in the history of the solar system, tiny bits of dust and ice occupied the region where now there are planets. These tiny bits bumped into each other, accreting into larger rock or rock and ice clumps. Large-ish clumps, on the order of a kilometer or so, had enough mass to attract other clumps gravitationally. If those *planetesimals* struck each other gently enough they built up into even larger *protoplanets*. Even in a gentle impact a lot of energy is released, warming the interior of the protoplanet. There is also likely heat released from any radioactive elements that are incorporated into our protoplanet. If it warms enough to be somewhat mushy inside, then the denser, mostly metallic, minerals will sink to the center in a process called *differentiation*. This results in an object with a relatively dense core, a less dense mantle, and, at the surface, a crust. In the asteroid belt, the gravitational influence of Jupiter kept those protoplanets from accreting into a full-sized planet. A differentiated asteroid could suffer an impact sufficient to shatter it; the fragments, rather than being homogeneous in their composition, would now show evidence of having been part of a once-larger, differentiated object. The dwarf planet Ceres (diameter ~950 km) and its relatively large neighbors 2 Pallas and 4 Vesta (~530-540 km across) are likely protoplanets. Vesta shows basalt on its surface. Pallas is an S-type asteroid with a highly inclined orbit (~35°). Along with 10 Hygiea, the largest C-type asteroid, these four objects contain nearly half of the mass in the asteroid belt. The Dawn spacecraft has orbited both Vesta and Ceres and we'll look at some of its findings later on.

Next in our survey of solar system residents we'll look at the giant planets. Here, to scale for size, are Jupiter and Ganymede (its largest satellite), Saturn, Uranus, and Neptune; Earth, for comparison, is under Saturn.

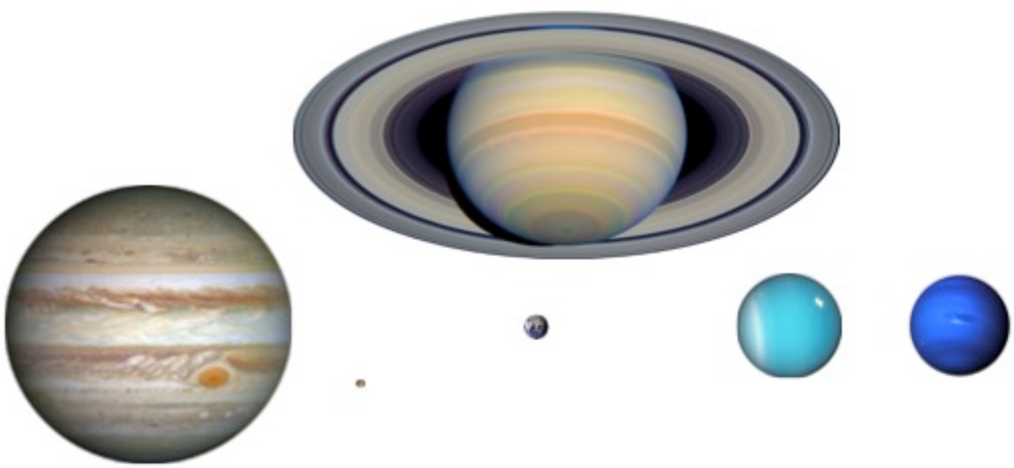
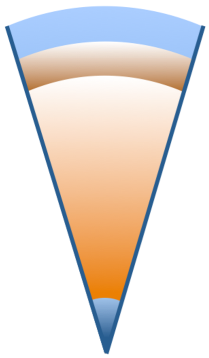


Figure 4.15: Giant planets (and friends)
Image credits: NASA, ESA, and A. Simon (GSFC) (http://hubblesite.org/image/3372/news_release/2014-24); NASA / JPL (https://photojournal.jpl.nasa.gov/catalog/PIA01972); NASA, ESA, and E. Karkoschka (University of Arizona) (http://hubblesite.org/image/1545/news_release/2004-18); NASA / Visible Earth (https://visibleearth.nasa.gov/view.php?id=57723); NASA, ESA, and M. Showalter (SETI Institute) (http://hubblesite.org/image/1799/news/86-uranus); NASA / JPL (https://photojournal.jpl.nasa.gov/catalog/PIA01492)

Jupiter and Saturn

Jupiter and Saturn are gas giants, composed mostly of hydrogen and helium. In that respect, their composition resembles that of the Sun more closely than does the makeup of other planets. At the surface layers that we can see, ~90% of the atoms in Jupiter's atmosphere are hydrogen, ~10% are helium, and only a tiny fraction are any heavier atoms. Jupiter is the more massive of the two gas giants, about 318 times more massive than Earth. Saturn is about 95 times Earth's mass. These two are not like Earth, where we have a solid body with a thin atmosphere; most of the volume of Jupiter and Saturn is "atmosphere" of liquid and, farther out, gas. Because they are mostly atmosphere, they are also quite low density: 1.33 g/cm^3 for Jupiter and a whopping 0.7 g/cm^3 for Saturn, less than the density of water. That atmosphere may dominate, but the cores of the gas giants are exceedingly hot and dense, conditions so extreme that they are hard to replicate in the lab on Earth. The following sketch shows the various regions in Jupiter's interior; note that there may not be any distinct boundaries between layers.



The conditions vary from ~125 K at the cloud tops to ~10,000 K / 200 GPa at the point at which hydrogen becomes metallic. The nature of the core, and even its existence, is not well constrained. We expect temperatures in excess of 30,000 K and pressures in excess of 4,500 GPa in a core of 12 – 45-ish Earth masses.

Figure 4.16: Jupiter interior model

The interior of Saturn seems to be similar to that of Jupiter, just a bit less massive, a bit less dense, a bit less hot. The existence of a liquid conducting layer seems to be necessary for the maintenance of Jupiter's immense magnetic field. Jupiter's magnetic field is an order of magnitude stronger than Earth's and its magnetosphere is the largest structure inside the solar system. A planet's magnetosphere is the region within which the magnetic field of the planet dominates over the interplanetary magnetic field and solar wind particles. The Sun has a larger magnetosphere, and in that case we would compare the region dominated by the Sun's magnetic field to the strength of the local interstellar magnetic field. Magnetospheres are compressed on the sunward side and tail off "downwind". In Jupiter's case, the tail of its magnetosphere extends beyond the orbit of Saturn. Here is a rough sketch, not to scale!, of a planet and its magnetosphere, showing the magnetic field lines and the impinging solar wind particles from the Sun:

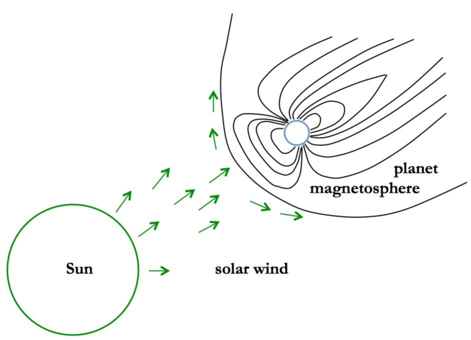


Figure 4.17: Planetary magnetosphere

Saturn's magnetic field is more similar to Earth's, and not early as strong as Jupiter's.

Both Jupiter and Saturn radiate more heat than they receive from the Sun. Jupiter is probably still contracting and radiating away released gravitational potential energy. If you have not yet met the *virial theorem*, or need a refresher on this concept, now would be a good time: As the material that forms a planet (or a star or a galaxy or a cluster of galaxies. . .) falls together under the influence of its mutual gravity, the gravitational potential energy that existed when the bits and pieces were far apart from each other will be converted to kinetic energy and radiation. We can show (with a bit of calculus) that half the gravitational potential energy will go into the kinetic energy of the particles that make up the resulting planet (or whatever we have formed) and the other half of the released gravitational potential energy will be radiated away. In the context of the gas giants, and particularly Jupiter, continued slow contraction results in released gravitational potential energy. What we observe is Jupiter emitting more light than it receives from the Sun. Saturn, being less massive, gets less energy out of contracting slightly. In Saturn's case, some of the excess energy may be coming from helium "raining" out of the upper layers, sinking down and swapping places with lighter-weight hydrogen atoms. When we look at the composition of Saturn's outermost layers, the ratio of helium to hydrogen is lower than it is for Jupiter, suggesting that Saturn's outer layers are depleted in helium.

Jupiter and Saturn both rotate in about 10 hours, a bit longer for Saturn, a bit faster for Jupiter. Because they are so massive and have a lot of inertia, compared to any nearby objects, it's not likely that there have been any significant influences acting to slow them down over their lifetimes. This means that 10 hours is probably a good indicator of how rapidly planets in general rotated early on.

Both Jupiter and Saturn have lots of natural satellites, Jupiter at least 79 and Saturn several hundred, if you count moonlets; if not, there are 62 known moons otherwise, 53 of which are named. Most are small, less than a few kilometers across, and at some point it becomes tough to say what counts as a small moonlet as opposed to a large ring particle. We'll look at the larger moons in some detail, because they are interesting objects in their own right. As for the smaller bits, note that all the giant planets have rings. Saturn's rings are extensive and include particles that are not just dark rocky chunks but are coated with water ice. That's what makes them so reflective and obvious even in small telescopes from Earth. Saturn's main belt of rings lies in the planet's equator; Saturn's axis is tilted at 27° (similar to Earth's 23.5°), so it has seasons (likewise, similar to Earth). The tilt also means that over the course of its 29-year orbit we observe the rings go from fairly wide open (Saturn having a solstice), where from our perspective we see them from the north or south, to edge-on (Saturn's equinox), and back to open again. The following montage of images from the Hubble Space Telescope illustrates this.

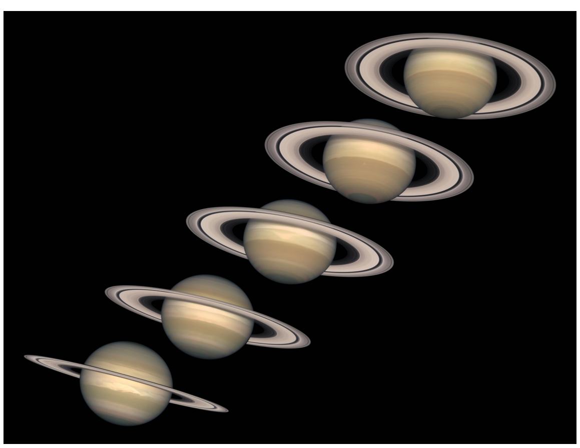


Figure 4.18: Saturn's seasons; images from 1996 to 2000

Credit: NASA and the Hubble Heritage Team (STScI/AURA)
http://photojournal.jpl.nasa.gov/catalog/PIA03156

In these pictures you can see that Saturn, like Jupiter, has bands of clouds. Saturn has more high-level haze and its cloud patterns are more muted, but they are definitely present. As with Jupiter, the bands of clouds lie along bands of latitude. Both planets also have fairly substantial winds, reaching ~100 m/s in Jupiter's upper atmosphere and ~500 m/s at Saturn. (For comparison, a gale-force wind on Earth would be ~ 20 m/s.) Jupiter's cloud patterns include the most famous storm in the solar system, the Great Red Spot. Other red spots have appeared and disappeared in Jupiter's atmosphere over the four-ish centuries we have had telescopes with which to observe them. The Great Red Spot is the longest-lived, although in recent years it has been shrinking somewhat and becoming a bit less red. The following montage of Hubble Space

Telescope images shows the Great Red Spot and the swirling clouds near it, from 1992 through 1999. One interesting characteristic of this storm is that it is a high-pressure system, rather than a low-pressure system like a hurricane or cyclone on Earth would be. The Great Red Spot's winds circle in the opposite direction from a terrestrial cyclone.

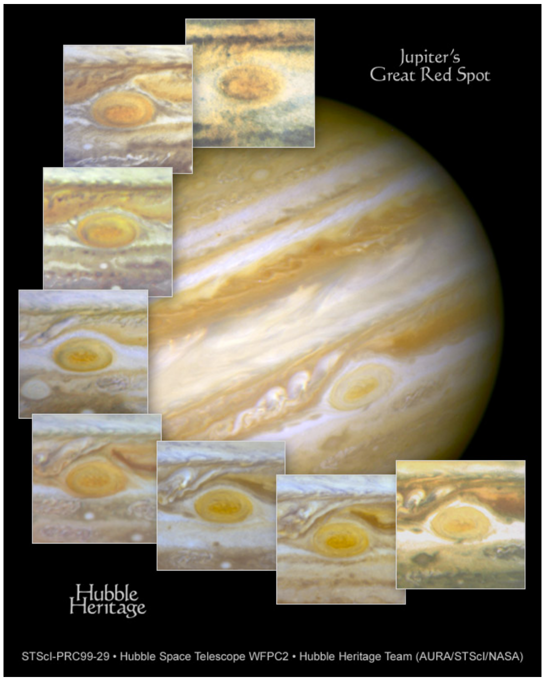


Figure 4.19: Great Red Spot

http://hubblesite.org/newscenter/archive/releases/1999/29/image/a/

Uranus and Neptune

The outermost two planets are considered ice or slush giants, because their atmospheres are less extensive than those of Jupiter and Saturn and because their atmospheric composition includes relatively more molecules of ices such as water (H_2O), ammonia (NH_3), and methane (CH_4), compared to hydrogen (H_2) and helium than we find at Jupiter or Saturn. Methane, which has absorption bands in the near IR, makes Uranus and Neptune look blue. Why Uranus tends more toward cyan while Neptune's blue color is much less green is not clear.

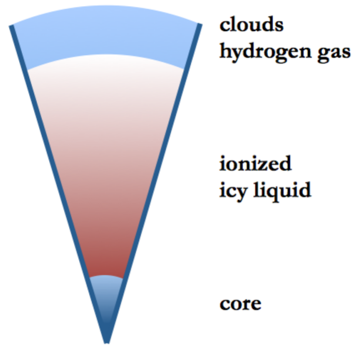
Uranus was discovered by William Herschel in 1781. It is, under good conditions, just visible to the naked eye, but it isn't very bright and it doesn't move very fast among the background stars. Herschel, having built a 6-inch telescope with excellent optics, was the first to be able to recognize it as a planet. Given that Saturn is at ~10 AU from the Sun and Uranus is nearly 20 AU, it's clear that with this discovery the solar system instantly got a lot bigger!

Like Venus, Uranus has an odd axial tilt: 98°. What's even odder is that the whole Uranian system, rings and moons as well as the planet, are tilted. The fact that the system is tilted played an important role in the discovery of Uranus' rings. In 1977, when the rings were discovered, Uranus was nearly pole-on to us. A team of planetary scientists was using an occultation of a star by Uranus to study the atmosphere of the planet. As the planet passes in front of a star, the starlight won't disappear immediately but will for a time be visible through the planet's atmosphere; how that atmosphere affects the starlight helps us understand the composition and structure of the atmosphere. Fortunately, they started recording their observations a few minutes before the actual occultation. As the star passed behind the previously unknown rings, it winked out briefly five times. At the end of the occultation, the pattern repeated. Uranus' rings had made their presence apparent. More rings, thinner and fainter, have since been discovered and there are now over a dozen distinct rings known.

Neptune, farther from the Sun, is fainter, smaller on the sky, and more slowly moving than Uranus. It is, nonetheless, visible in small telescopes and it is probable that Galileo observed it as early as 1612. He was not able to recognize it as a planet, though. Once Uranus had been discovered it made sense to search for still more distant planets. Uranus itself provided some clues. It was not easy, prior to the development of the computer, to calculate the expected position of a planet based on all the relevant gravitational influences that might cause it to deviate from a simple Keplerian solar orbit. Uranus had been observed and recorded for nearly a century before Herschel's discovery, so there were at least quite a few positions almost immediately available for analysis. In the mid-1800s Urbain Le Verrier, in France, and John Couch Adams, in England, both worked on the problem of the fact that the observed positions of Uranus were not lining up with the predicted positions. The deviations in position could be due to the gravitational perturbations of an as-yet-unknown object (initially assumed, in accord with the Titius-Bode rule, to lie 38 AU from the Sun). Both men calculated similar positions for where this 8th planet might be. In the summer of 1846 James Challis, at the Cambridge Observatory, searched the sky where Neptune was subsequently discovered but, lacking the latest star position maps he failed to realize that he had, in August 1846, observed the new planet. Le Verrier was able, in September, to convince Johann Gottfried Galle, at the Berlin Observatory, to search the relevant portion of the sky. On the night of 23 September, 1846, Galle, with the assistance of student Heinrich Louis d'Arrest, did so and found the planet almost immediately, only about one degree away from Le Verrier's predicted position. Adam's prediction was not quite as close; he was off by a bit more than 10 degrees. Not surprisingly, competition for the credit for the discovery ensued. Both Le Verrier and Adams did valuable work in using what we would today call perturbation theory to estimate how far out of position Uranus would be given a range of possible perturbing influences. Both were also very lucky in that both assumed too large an orbit for Neptune and it was a quirk of timing (i.e., where around its orbit Neptune happened to be) that produced a planet in the predicted direction. Today, the weight of historical opinion is that Le Verrier, able to motivate a more effective search, deserves relatively more of the credit for the discovery of Neptune.

Uranus and Neptune have been visited by one spacecraft, Voyager 2, in 1986 and 1989, respectively. Those flybys helped improve our understanding of these two distant planets. Uranus is the less massive of the two, ~14.5 times the mass of Earth compared to Neptune's 17 Earth masses. Neptune is on average a bit more dense, though – 1.64 g/cm^3 compared to Uranus' 1.27 g/cm^3 – with the result that Neptune has a slightly smaller radius than Uranus.

Neither planet is massive enough to have the layer of liquid metallic hydrogen that Jupiter and Saturn do; they do, though, have a layer of ionized liquid water, ammonia, and methane. Rotation plus the presence of a conducting liquid layer drive a dynamo that continually regenerates the planet's magnetic field. On Earth, it's liquid iron generating a magnetic field that is roughly aligned with our rotation axis. At Uranus and Neptune, those magnetic fields are wildly tilted (59° and 47°, respectively) and equally wildly offset from the center of the planet; for Uranus, the axis of the field misses the center of the planet by ~1/3 of Uranus' radius and at Neptune it's over half way out from the core. The interiors of these planets are not as well constrained as those of Jupiter or Saturn. The following rough sketch shows the general model for their interiors:



The core temperatures and pressures are not as extreme as in the gas giants, ~5,000 K and 7-800 Gpa. Models suggest that the rocky / metallic core of Neptune is a bit more than one Earth mass, while that of Uranus is a bit less.

Figure 4.20: Ice giant interior model

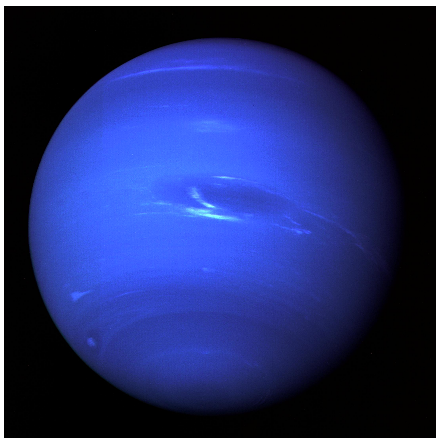


Figure 4.21: Neptune. Credit: NASA / JPL; Voyager 2
https://photojournal.jpl.nasa.gov/catalog/PIA01492

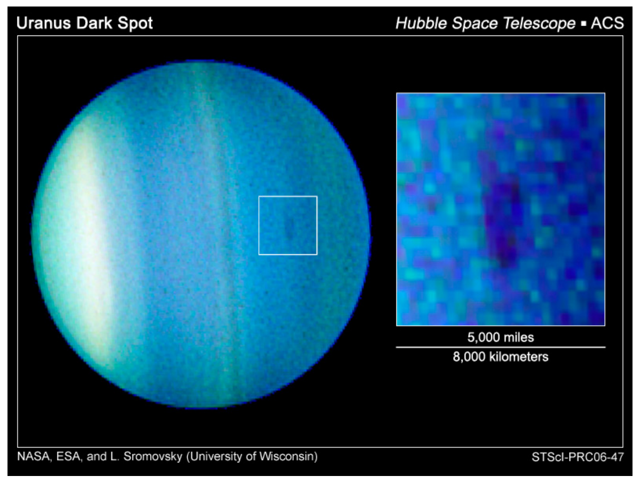


Figure 4.22: Uranus' dark spot
http://hubblesite.org/newscenter/archive/releases/2006/47/image/a/

Like the gas giants, both Uranus and Neptune have clouds and strong zonal (east-west) winds. Uranus' cloud patterns are generally quite muted; Neptune's are more obvious and at the time of the Voyager 2 flyby, Neptune, as seen above left, was sporting several storms, including one dubbed the Great Dark Spot. Hubble observations five years later, in 1994, showed that this dark spot had disappeared and a new one, in the northern hemisphere, had shown up. The supposition is that these storms may come and go every few years. In 2006, Uranus was observed with a dark spot of its own, as seen on the right. The storms are driven by strong winds. The strongest observed winds on Uranus have been ~240 m/s and on Neptune we have the highest measured winds seen on any planet, at ~580 m/s. The fact that Neptune's atmosphere is so dynamic was a bit surprising. At ~30 AU from the Sun, Neptune receives only 1/900th as much sunlight, per square meter, as the Earth does. Its upper atmosphere is only ~55 K, making it decidedly one of the colder places in the solar system. It's interesting that there is enough energy to drive such obvious weather patterns.

Uranus and Neptune have lots of satellites; Uranus has at least 27 and Neptune at least 14. As with the moons of the gas giants, several of these are fascinating objects in their own right and we'll look at several of them in more detail. Both planets also have rings, which, like Jupiter's ring, are composed of darker particles that make the rings much less obvious from Earth than those of Saturn.

Major moons of the outer solar system

The moons of the outer solar system are amazingly varied in their size and shape, composition, and level of geologic activity. You should be on a first-name basis with the six largest: Io, Europa, Ganymede, and Callisto, in the Jovian system; Saturn's moon Titan; and Triton, the largest of Neptune's retinue. Here, in order and to scale for size, are those six and, for comparison, our Moon and Mercury. Two immediate notes about these images: yes, Titan is fuzzy (it has an atmosphere), and no, we don't have a good full-disk image of Triton.

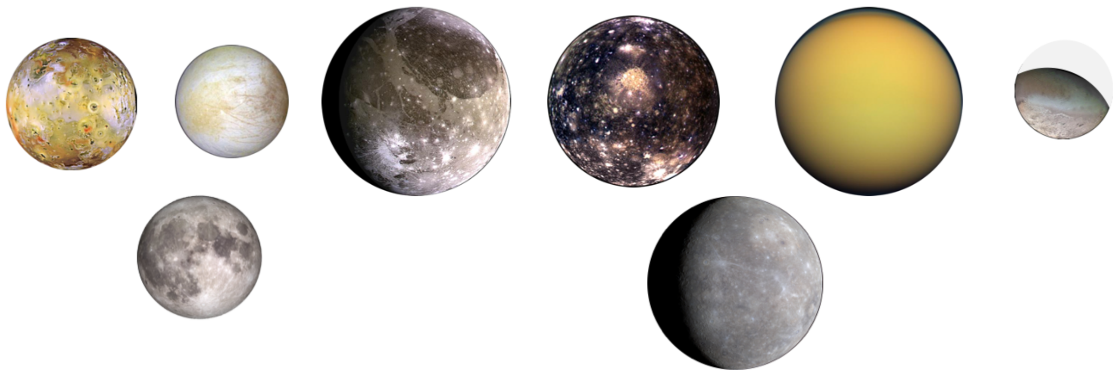


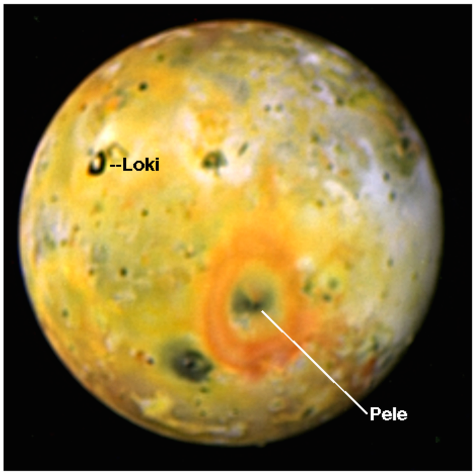
Figure 4.23: Major moons
Image credits: NASA/JPL/DLR (https://photojournal.jpl.nasa.gov/catalog/PIA01400, https://photojournal.jpl.nasa.gov/catalog/PIA01299); NASA/JPL-CalTech/Space Science Institute (https://photojournal.jpl.nasa.gov/catalog/PIA14602); NASA/JPL/USGS (https://photojournal.jpl.nasa.gov/catalog/PIA00317); NASA Scientific Visualization Studio (http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4404); NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington (https://photojournal.jpl.nasa.gov/catalog/PIA13840)

Io, Europa, Ganymede, and Callisto are often called the Galilean satellites, because Galileo noticed them in 1609-10 and, most importantly, noticed that they were in orbit around Jupiter. In Europe in 1600, whether the Sun, planets, and stars circled around Earth or whether the Earth was a planet in orbit around the Sun was an open question; to discover that these four new bright points of light moved with Jupiter was big news. In terms of sizes, Io and Europa are just larger and just smaller, respectively, than our Moon. Ganymede and Callisto (and Titan) are quite similar in size to Mercury, although less dense.

The orbits of the inner three Galileans are locked in a 4:2:1 resonance, meaning that Io goes around Jupiter 4 times and Europa 2 times for every 1 orbit of Ganymede. Tides and tidal heating are discussed in more detail in chapter 2, here there are two things to note. First, there's a different in the strength of the gravitation force due to Jupiter from one side of a moon to the other side. The fact that the strength of the gravity due to our Moon differs from one side of Earth to the other is why we have ocean tides. The difference in the gravity across, say, Io, means that it gets pulled into an elliptical shape. For Io, being the closest to Jupiter, the effect is largest. The difference in the gravity across a moon matters less the farther away you are from the planet; the force of gravity is proportional to $1/r^2$ but the tidal force, being a difference, goes as $1/r^3$. Second, that stretching varies a bit with time because the orbits are not perfectly circular and stable (i.e., the distance r in the $1/r^3$ changes). Together these two factors mean that the interiors of these moons, and particularly Io, are heated by the continual slight changes in the gravitational stretching that they experience.

The tidal heating effect is strongest for Io, less strong for Europa, still present a bit for Ganymede, and not really a factor for Callisto. Io is the most rocky of the four (3.5 g/cm^3 density) and is very volcanic; Europa, a bit less dense (3.0 g/cm^3), has an ocean under its icy crust; Ganymede also has an icy ocean but is less dense than Europa (1.9 g/cm^3) and therefore must have a lower ratio of rock to ice; Callisto is the least dense of the four (1.8 g/cm^3) and has one of the oldest, most heavily cratered surfaces in the solar system.

The following images of Io were taken in December 2000 by the Galileo spacecraft. Three of Io's major volcanic regions (Loki, Pele, and Tvashtar) are labeled. In addition to basalt, Io's volcanic eruptions include enough sulfur to give Io its wild coloring. The whites indicate sulfur dioxide "frost". Reds and blacks are the most active eruptions. The fact that there are basically no visible impact craters – with no reason to suppose that Io has never been hit – combined with the observations of active volcanoes tell us that Io is continually resurfacing itself and is the most geologically active body in the solar system.



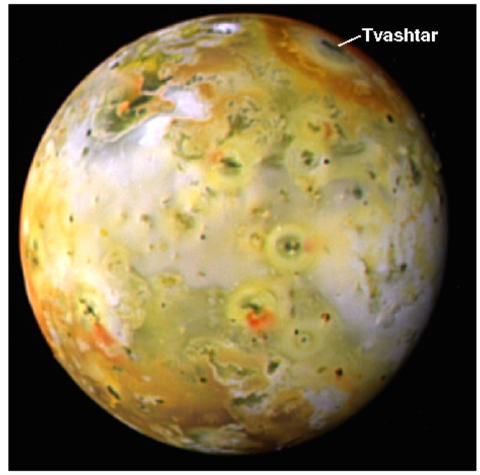


Figure 4.24: Io. Image credits: NASA/JPL/University of Arizona; Galileo spacecraft
https://photojournal.jpl.nasa.gov/catalog/PIA02588

Because of its proximity to Jupiter, Io interacts strongly with Jupiter's magnetic field. Cutting across the magnetic field lines sets up a current of ~3 million amps, producing lightning in Jupiter's atmosphere. Io contributes ~1,000 kg of dust and gas to Jupiter's magnetosphere every second, much of which will become ionized and add to a plasma torus around Jupiter. Due to the volcanic eruptions, Io has a tenuous atmosphere, primarily composed of SO_2. Observations suggest that much of this atmosphere freezes out when Io's orbit takes it into Jupiter's shadow; the frost sublimates and re-inflates the atmosphere when Io returns to the sunlight. Io is differentiated, with ~20% of its mass in an iron-rich core. Io's interactions with Jupiter's magnetic field produce an induced magnetic field in Io, which, along with the lava flows, tells us that at least 10% of Io's mantle must be molten.

Prior to the Voyager 1 flyby of Jupiter we were not sure that Io was actually volcanic. Three days after Voyager 1's closest approach to Jupiter, in March 1979, JPL engineer Linda Morabito was watching that day's images arriving from the spacecraft when she noticed the fuzzy plume above the limb of Io in this image. The bright spot near the center is a second volcanic plume; the ejecta in the plume, although erupted in darkness, rises high enough to catch the sunlight. It was quite exciting to have the first observational evidence of active volcanism on a body other than Earth.

Figure 4.25: Io - first images of volcanic eruptions.
Credit: NASA / JPL; Voyager 1
http://photojournal.jpl.nasa.gov/catalog/PIA00379

Europa's crust is icy, with cracks that very much resemble cracks in the ice in the Arctic Ocean. In November 2014 NASA released reprocessed images taken by the Galileo orbiter in the late 1990s. The image on the left is color balanced to try to give a good idea of what Europa would look like to our eyes. Overall, the icy surface is very reflective, giving Europa an albedo of 0.67. In 2012, spectra taken with the Hubble Space Telescope above the limb of Europa, shown below right, provided evidence for plumes / geysers of water ejected from some of the cracks in the ice.

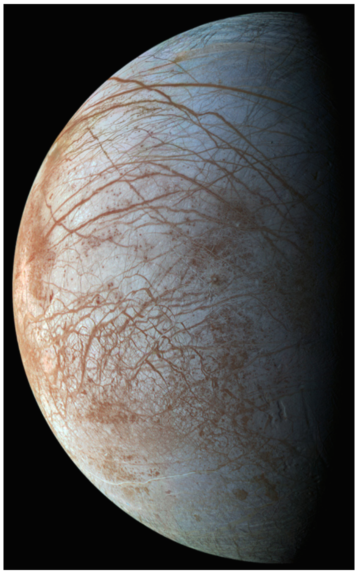


Figure 4.26: Europa. Credit: NASA/JPL-CalTech/ SETI Institute; Galileo spacecraft
https://photojournal.jpl.nasa.gov/catalog/PIA19048

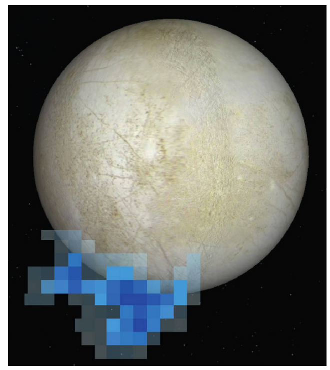


Figure 4.27: Europa's plumes. Credit: NASA/ ESA/L. Roth/SWRI/University of Cologne
http://www.nasa.gov/content/goddard/water-vapor-over-europa

Europa's surface shows *tectonic* activity, meaning that the cracks show evidence of faulting, where blocks of ice split or slide sideways with respect to each other. There are hints of *subduction*, where some block of ice may have subsided and sunk under other blocks. The ice, the cracks, the geysers, the fact that Europa is differentiated, that it also has an induced magnetic field, and that it receives some tidal heating from Jupiter, all suggest that Europa has an ocean under that icy crust. How thick the ocean is, and how deep below the surface it lies, are not yet well determined. Europa has a few impact craters; they don't show the vertical relief of lunar craters nor have they been totally flooded, and that partial relaxation lends support to a model in which the icy crust is several tens of kilometers thick. The following image is of the crater Pwyll.

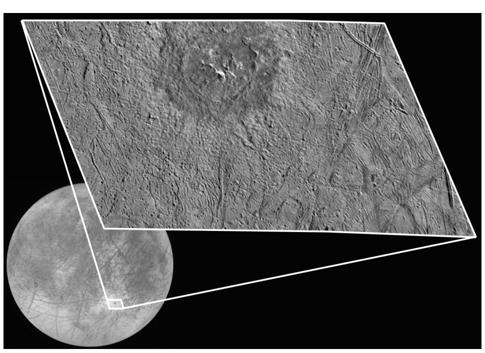


Figure 4.28: Europa and Pwyll crater. Credit: NASA / JPL / ASU; Galileo spacecraft, 1997
http://photojournal.jpl.nasa.gov/catalog/PIA01176

We find evidence of an ocean under an icy crust on several of the outer solar system moons; the evidence is particularly persuasive for Europa and Ganymede, at Jupiter, and Enceladus and Titan, at

Saturn. Those oceans can't be pure water, though, because the temperatures are too cold. One way to drive down the freezing point of water is to add salt. Regular sodium chloride salt is the original icy winter sidewalk de-icer because a solution of water and sodium chloride (~23% salt) has a freezing point that's ~20°C colder than water alone. "Ice" in the outer solar system doesn't mean just water, but a range of molecules that would be liquid or gas at Earth, such as water, ammonia, methane, and contaminants such as various salts.

That Europa has an ocean makes it an attractive candidate for places to search for life. It is quite an engineering challenge to design a mission to Europa that could make a way through the icy crust to sample the underlying ocean without contaminating it with microbes from Earth.

Next in line out from Jupiter, it should be no surprise that Ganymede experiences less tidal heating than Europa (and much less than Io). As you can probably tell from the comparison image introducing this section, Ganymede is actually larger than Mercury, although, having a significant complement of ices, it is a bit less than half as massive. Ganymede is massive enough, though, that it has its own magnetic field, in addition to a field induced by its interaction with Jupiter's magnetic field. Current models of the interior of Ganymede include a two-part core quite similar to Earth's, with an inner liquid region rich in iron, nickel, and iron-sulfide, inside a solid iron layer. The core is surrounded by a rocky mantle, above which are layers of liquid water and ice.

Ganymede's surface shows relatively more craters and relatively fewer cracks than Europa's surface. The craters and cracks are similar to those on Europa, though, indicative of an icy crust over a liquid ocean. Ganymede's surface is also darker, having a more substantial *regolith*, or buildup of dust, accreted over the ages. The darkest terrain on Ganymede has more, and larger, craters than the relatively bright regions, meaning that the darker terrain is older. In the following global image you can also see one of Ganymede's icy pole caps. On the right in are two images of bands on Ganymede and Europa; Ganymede is darker and more cratered. Bands on Europa form when the icy crust splits, cutting across pre-existing features. It is probable that some of Ganymede's features also indicate crust splitting. There are indications of slip-strike faulting, where markings on opposite sides of a band are offset.

Figure 4.29: Ganymede. Credit: NASA/JPL/DLR; Galileo spacecraft http://photojournal.jpl.nasa.gov/catalog/PIA01299

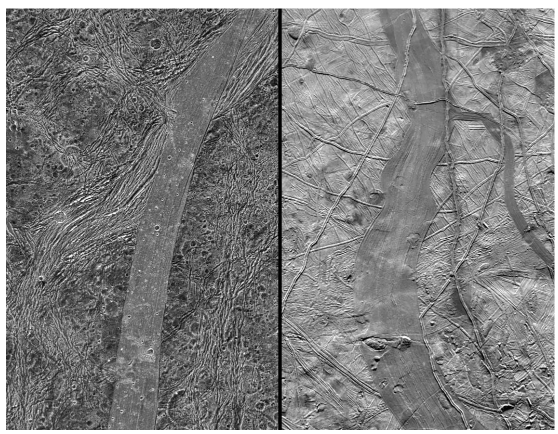


Figure 4.30: icy bands. Credit: NASA / JPL / Brown University; Galileo spacecraft.
Ganymede (left): 116 km wide
Europa (right): 275 km wide
http://photojournal.jpl.nasa.gov/catalog/PIA02575

Callisto, the outermost of the Galilean satellites, shows pretty much zero indication of tidal heating. Its surface is dark and heavily cratered with no evidence of resurfacing. Models suggest that it isn't even differentiated, which is odd for an object that's nearly the size of Mercury! Callisto's density, ~1.8 g/cm^3, indicates a nearly equal mix of rock and ice. The craters, in the image below left, are bright because impacts have punched through the dark surface regolith into the brighter ice beneath. One of the ancient impacts on Callisto, Valhalla, shown in the image below right, provides an excellent example of a multi-ring basin. We'll talk more about cratering in a later chapter. The white, near the image top, is a polar deposit of ice.

Figure 4.31: Callisto. Credit: NASA / JPL / DLR; Galileo spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA03456

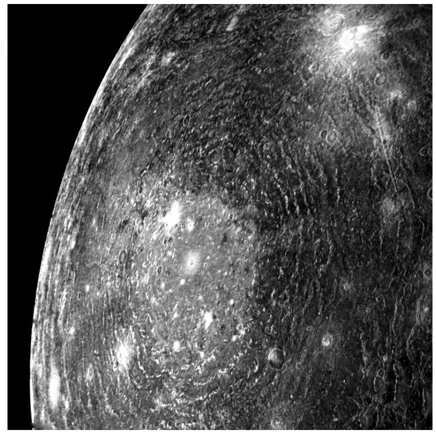


Figure 4.32: Callisto and Valhalla impact basin. Credit: NASA / JPL; Voyager 1
http://photojournal.jpl.nasa.gov/catalog/PIA02277

Titan, Saturn's largest moon, has the distinction of being the only moon with a substantial atmosphere. Titan's atmosphere is so substantial that the surface pressure is ~147 kPa, or nearly 1.5 times the surface pressure on Earth. Near the surface, the atmosphere is ~95% nitrogen (N_2); most of the rest is methane (CH_4). The surface is cold, ~94 K, and tough to see because, like Venus, the atmosphere is highly opaque in visible wavelengths. There's a hazy layer at the top at of the atmosphere and evidence of weather patterns and polar cloud formations, both of which can be seen in the image on the left-hand side, below.

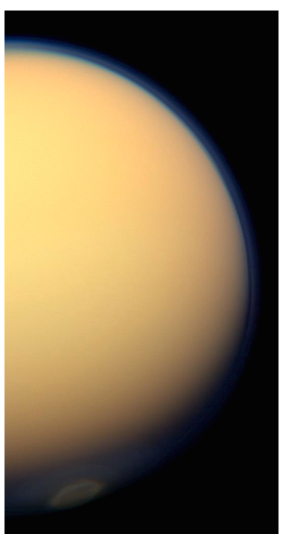


Figure 4.33: Titan. Credit: NASA / JPL / Space Science Institute; Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA14925

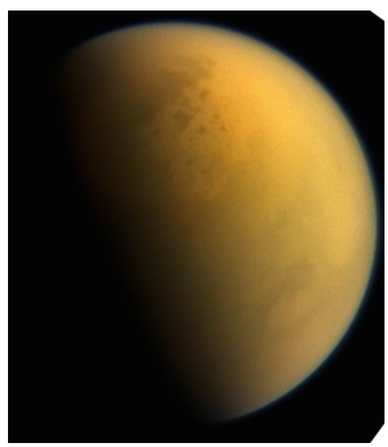


Figure 4.34: Titan

Credit: NASA / JPL / Space Science Institute; Cassini spacecraft.
North is up in this image
http://photojournal.jpl.nasa.gov/catalog/PIA17179

The dark features near the top, in the image above right, taken with filters that cut through the haze, appear to be lakes of liquid hydrocarbons. The pressure and temperature on the surface of the Earth are near the triple point for water, meaning that conditions are just right for water to be ice, liquid, or vapor. On Titan, conditions are near the triple point for methane. It is the only solar system object other than Earth known to have stable liquid seas on its surface. One way to tell that these are liquid is to bounce radar off the surface at an angle (side-aperture radar; we mentioned this briefly, above, in considering how we can tell what the surface of Venus is like). Radar that hits a rough surface will be reflected in lots of directions, including back toward an orbiting spacecraft. Radar that hits a smooth surface will predominantly reflect forward, with very little signal coming back to the spacecraft. The following image is a false-color radar map of regions around Titan's north pole, with the seas shown in dark blue. Analysis of Cassini spacecraft images over several years suggest that some of the smaller lakes may be ephemeral, shallow lakes that come and go with the seasons.

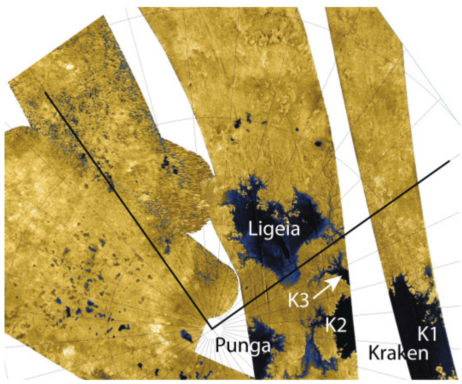


Figure 4.35: Titan.
Credit: NASA / JPL / University of Arizona; Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA16845

The regions labeled K1, K2, and K3 are all part of Kraken Mare, and would be connected if the data were complete.

Like Ganymede and Callisto, Titan is about the size of Mercury, but, being a mix of rock and ice, has a density of only about 1.9 g/cm^3. Titan's interior seems to be differentiated and there's evidence for a subsurface ocean. There's also evidence for some features that look like volcanoes. On Titan, and other icy outer solar system objects, that would be *cryovolcanism*, where what's erupting isn't a silicate-based magma but an icy magma of water, ammonia, various carbon-containing molecules, salts; in other words, when you're that cold, watery ices behave pretty much the way silicates do on Earth. Just before arriving at Saturn the Cassini spacecraft separated from the Huygens lander, which touched down successfully on the surface of Titan in January 2005. It sent back data during its descent through the atmosphere and also for about an hour and a half after landing. The following image is from the surface of Titan. The rocks or pebbles in this image are ice, probably a mix of water and hydrocarbons. The ones in the foreground range from ~4 cm to ~15 cm diameter. Just beyond the rocks is a region that appears to have been swept clear. Some of the rocks also appear to be undercut, suggestive of erosion by some fluvial process.

Figure 4.36: Titan
Credit: NASA / JPL / ESA / University of Arizona; Huygens lander, January 14, 2005
http://photojournal.jpl.nasa.gov/catalog/PIA07232

At Saturn, the trajectory of Voyager 1 took it close to Titan and, as a result, Voyager 1's path was bent to take it up out of the plane of the solar system. Voyager 2's path continued on past Saturn to Uranus and Neptune. At Neptune, Voyager 2 passed about 40,000 km above the frigid surface of the moon Triton. The pinkish ice at the bottom of the following image is Triton's south pole cap.

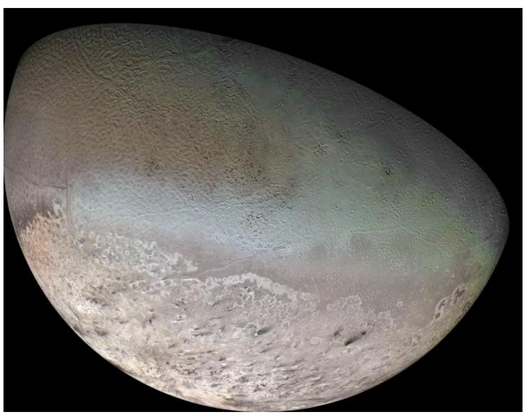


Figure 4.37: Triton. Credit: NASA / JPL / USGS; Voyager 2
http://photojournal.jpl.nasa.gov/catalog/PIA00317

With a diameter of ~2,700 km, Triton is smaller than our Moon, but still larger than the dwarf planets. Triton orbits Neptune retrograde. A number of small moons orbit retrograde, but Triton is the only major moon to do so. A retrograde orbit suggests that a moon was captured by the planet, rather than having formed with the planet. When a planet is forming, all the little bits of rock and ice that are going to wind up incorporated into the planet or its original retinue of satellites are expected to be swirling in the same direction. In physics' terminology, we expect all the material to have the same angular momentum vector. Triton is also relatively close to Neptune, with an orbit period of ~5.9 days. Some day it will probably collide with Neptune.

Triton's composition suggests that it formed farther out in the solar system. Its mottled surface is very cold, only ~38 K, and covered (at least in part, allowing that we haven't imaged all of the surface at decent resolution) in nitrogen ice. Nitrogen, possibly evaporated from the surface ices, is also the dominant component in Triton's tenuous atmosphere. The atmosphere is dense enough, though, to support a few thin clouds, and windy enough to move the gas and dust ejecta from geysers, observed in the south polar ice. The dark left-to-right streaks in the following image are fallout from the geysers; the particularly dark one was a geyser caught in the act of erupting.

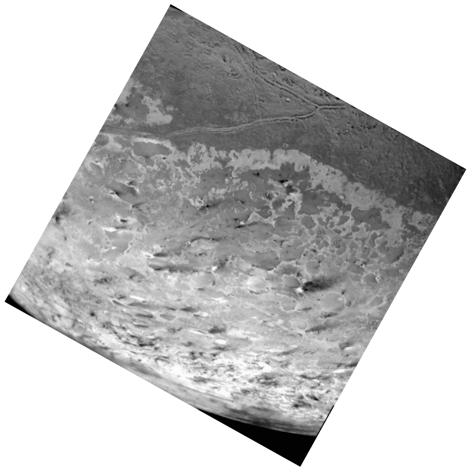


Figure 4.38: Triton
Credit: NASA / JPL; Voyager 2
http://photojournal.jpl.nasa.gov/catalog/PIA00059

Triton seems to be differentiated, with a relatively large rocky / metallic core, giving it an overall density of ~2.1 g/cm^3. It's possible that heating generated during the process of capture contributed to the differentiation of Triton. Despite its low temperature, Triton's surface shows evidence of persistent geologic activity, again, possibly fueled by internal heat deposited long ago. There are very few impact craters but lots of cracks and ridges and dimples, particularly visible in the regions shown in the following left-hand image, labeled the "cantaloupe terrain" because of its resemblance to the skin of a cantaloupe. The image on the right shows a region ~500 km across. It's possible we are seeing remnants of old impact basins.

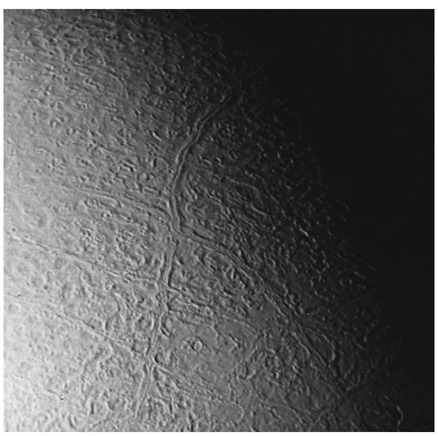


Figure 4.39: Triton
Credit: NASA / JPL; Voyager 2
http://photojournal.jpl.nasa.gov/catalog/PIA01537

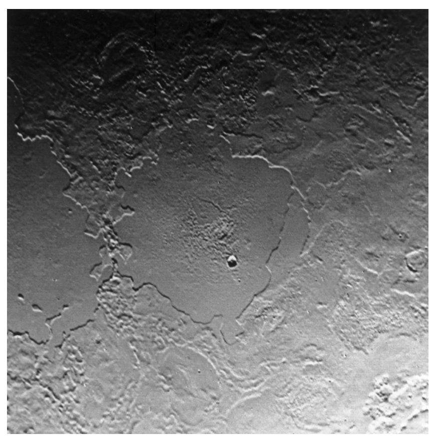


Figure 4.40: Triton
Credit: NASA / JPL; Voyager 2
http://photojournal.jpl.nasa.gov/catalog/PIA01538

Medium-sized moons of the outer solar system

As mentioned above, moons of the outer solar system come in a range of sizes, levels of cratering and geologic activity and, when we get small enough, shapes. As a bit of an arbitrary distinction, let's consider medium-sized moons to be those that are large enough to be round but distinctly smaller than the six considered above.

Here, for scale to size, are Saturn's moons Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Iapetus, along with our Moon for comparison.

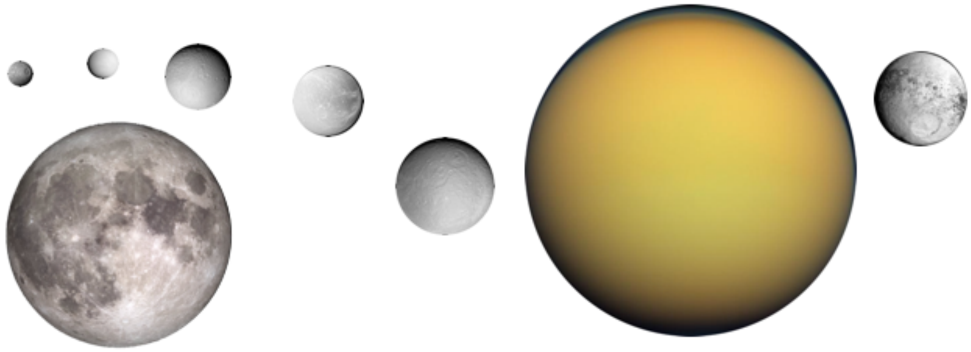


Figure 4.41: Medium-sized moons of Saturn (plus our Moon & Titan)
Image Credits: NASA / JPL-CalTech / Space Science Institute (http://photojournal.jpl.nasa.gov/catalog/PIA12570, http://photojournal.jpl.nasa.gov/jpeg/PIA14588.jpg, http://photojournal.jpl.nasa.gov/catalog/PIA07738, http://photojournal.jpl.nasa.gov/catalog/PIA12674, http://photojournal.jpl.nasa.gov/catalog/PIA07763, https://photojournal.jpl.nasa.gov/catalog/PIA14602, http://photojournal.jpl.nasa.gov/catalog/PIA09756); NASA's Scientific Visualization Studio (http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4404)

In the following brief descriptions of these moons the images are not to scale.

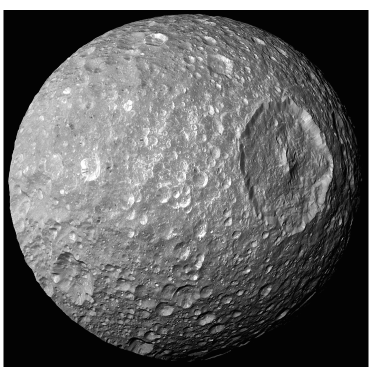


Figure 4.42: Mimas
Credit: NASA / JPL / Space Science Institute; Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA12570

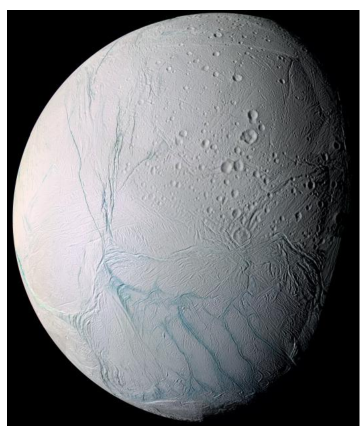


Figure 4.43: Enceladus. Credit: NASA / JPL / Space Science Institute; Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA06254

Mimas, above left, seen in detail for the first time about the same time the original *Star Wars* movie came out, distinctly resembles the "Death Star" satellite. At just under 400 km diameter, Mimas is about the smallest possible object with enough self-gravitation to be round. Enceladus, above right, is about 500 km across, and is surprisingly active. Those streaks in the southern hemisphere give rise to geysers and the evidence suggests that there is a sea under the icy crust in the south. Most of the medium-sized moons of Saturn are heavily cratered, so it's noteworthy that Enceladus' surface shows signs of current tectonically active regions along with a few ancient cratered regions. The reason the activity is surprising is that smaller objects lose internal heat faster than large ones. Internal heat is roughly proportional to volume, r^3, while heat loss is roughly proportional to surface area, r^2. Smaller objects have a larger ratio of area to volume and thus cool faster. Enceladus is trapped in an orbital resonance with Dione, below right, which contributes to its internal heating. Those geysers are the main source of material for Saturn's broad, diffuse E ring, which extends from just outside Mimas' orbit to beyond the orbit of Rhea.

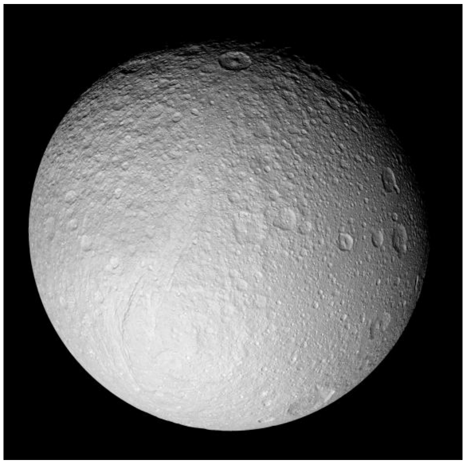


Figure 4.44: Tethys
Credit: NASA / JPL / Space Science Institute; Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA07738

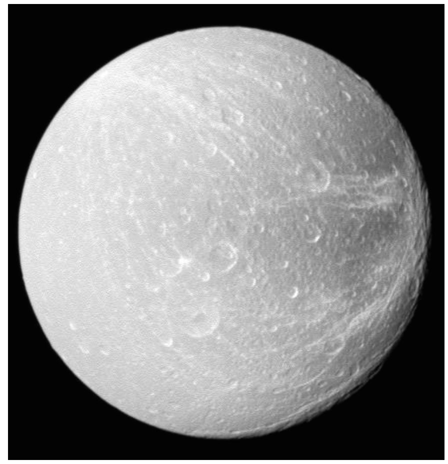


Figure 4.45: Dione
Credit: NASA / JPL / Space Science Institute; Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA12674

Tethys and Dione, above left and right, respectively, are about 1,100 km across. Tethys is heavily cratered but has a huge, old, rift running up-down in this image. Tethys' density is just under 1 g/cm^3, indicating that it is composed much more of ice than of rock. Dione, next out from Saturn, is also heavily cratered and also has some fractures. It is significantly denser than Tethys, at ~1.5 g/cm^3; it's not clear why the two are so different. Most of Saturn's moons are tidally locked on Saturn, meaning that they keep the same side toward Saturn as they orbit. Dione and Rhea, below, both have slightly brighter leading hemispheres. A number of Saturn's moons have some wispy cracked surface ice; in Dione and Rhea's case, that's on the trailing hemisphere. With several craters on Tethys and Dione, as well as with the major crater (named Herschel) on Mimas, you can see a central peak, which tells us that the crater has not relaxed or sagged, much, since its formation. These surfaces, although icy, must be quite rigid.

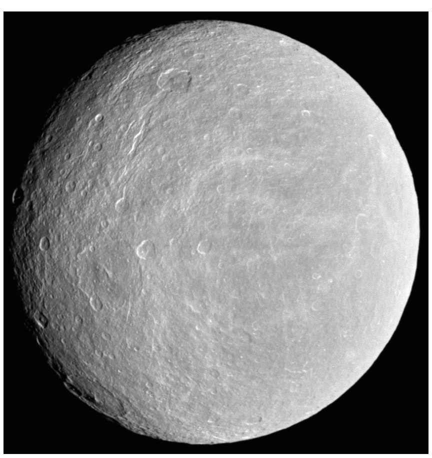


Figure 4.46: Rhea. Credit: NASA / JPL / Space Science Institute; Cassini
http://photojournal.jpl.nasa.gov/catalog/PIA12648

Rhea, at a bit more than 1,500 km diameter, is the second largest of Saturn's moons. Its overall density, 1.3 g/cm^3, implies that it is a mix of relatively more ice than rock. There is debate about whether Rhea is differentiated. Even if it is not, it's still possible that there could be seas under the icy crust. There are hints, also still being debated, that Rhea might have had its own ring.

Iapetus, just under 1,500 km diameter, has some intriguing features. First and most immediately obvious is the rather extreme albedo difference between its leading and trailing hemispheres. The leading hemisphere is dark, albedo ~0.04, and slightly reddish-brown in color. The trailing hemisphere is bright white, with an albedo ~0.55, which makes it almost as reflective as Europa. The bright material includes the poles, making the bright and dark regions fit together like the segments of a tennis ball. Some of the craters in the dark region punch through into cleaner underlying ice, suggesting that the dark material is not very thick. The low albedo region would absorb more sunlight, warming ice under the dark material. At very low air pressure ice won't melt; what happens is called *sublimation*, where the ice changes directly from solid to gas phase. That leads to a positive feedback, driving ice from Iapetus' dark regions to its whiter regions, making the dark regions even darker and even more likely to lose ice. The second noticeable feature is that part of Iapetus has an equatorial ridge. The ridge is ~1,300 km long and ~13 km high. Why the ridge exists is not completely clear; some models suggest a collision with another satellite that broke apart on impact, falling in a long line onto Iapetus.

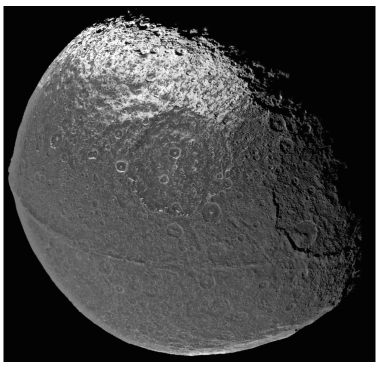


Figure 4.47: Iapetus
Credit: NASA / JPL / Space Science Institute; Cassini
http://photojournal.jpl.nasa.gov/catalog/PIA06166

Figure 4.48: Iapetus. Credit: NASA / JPL / Space Science Institute; Cassini
http://photojournal.jpl.nasa.gov/catalog/PIA08384

Uranus has five medium-sized moons, Miranda, Ariel, Umbriel, Titania, and Oberon. Uranian moons are all named for characters from Shakespeare's *Tempest* or Alexander Pope's *Rape of the Lock.* Here they are with our Moon, to scale. Miranda is a little less than 500 km across, Ariel and Umbriel are a little more than 1,100 km diameter, and Titania and Oberon are a little more than 1,500 km. Voyager scientists decided to maximize the quality of the observations we could obtain for Miranda, meaning that we don't have high-resolution images of the other four.

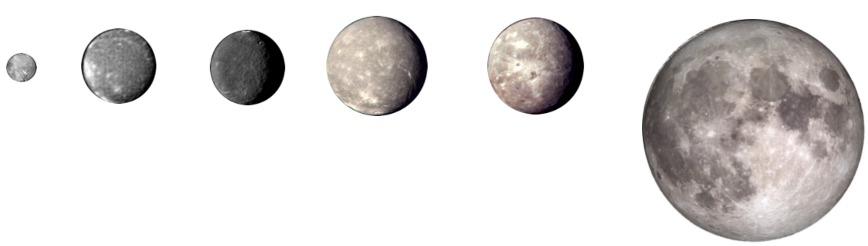
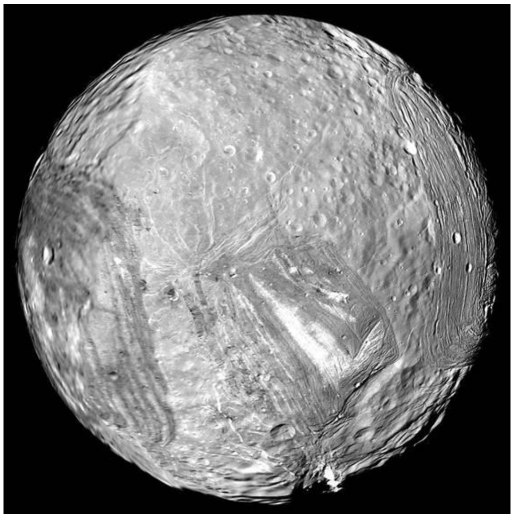


Figure 4.49: Our Moon with the medium-sized moons of Uranus
Image Credits: NASA / JPL (http://photojournal.jpl.nasa.gov/catalog/PIA18185, http://photojournal.jpl.nasa.gov/catalog/PIA01351, https://photojournal.jpl.nasa.gov/catalog/PIA00040, http://photojournal.jpl.nasa.gov/catalog/PIA00036, http://photojournal.jpl.nasa.gov/catalog/PIA00034); NASA's Scientific Visualization Studio (http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4404)

Miranda is the least dense, ~1.2 g/cm^3, implying that it is about 60% water ice. The other four are about 1.6 – 1.7 g/cm^3, suggesting compositions that are about half-and-half ice and rock. These four moons are, on average, more rocky than the medium-sized moons of Saturn. As you can tell from the images above, the albedos of these moons vary greatly. Ariel is twice as bright as Umbriel. The colors vary a bit as well. Oberon is a little on the red side, Umbriel a little bluish. On all five we can distinguish craters and cracks and some surface variation in albedo.



Miranda has amazingly varied terrain, including a 20-km-high cliff, seen near the bottom of this image. The weird chevron-shaped features are called "coronae", but in this case naming them doesn't necessarily mean that we have a convincing explanation of their origins.

Figure 4.50: Miranda
Credit: NASA / JPL; Voyager 2
http://photojournal.jpl.nasa.gov/catalog/PIA18185

Neptune's second-largest moon is Proteus, discovered by the Voyager science team. It is shown in the image below, to scale, with Triton. Proteus is ~420 km diameter, large enough that we would expect that it could be round. It has, though, clearly been hit often – the diameter of its largest impact crater is about half the size of Proteus itself! Proteus orbits inside the orbit of Triton and it's possible that it formed from debris that might have been involved in the capture of Triton. It has a low albedo and is relatively close to Neptune, which could explain why Proteus wasn't discovered by ground-based observers.

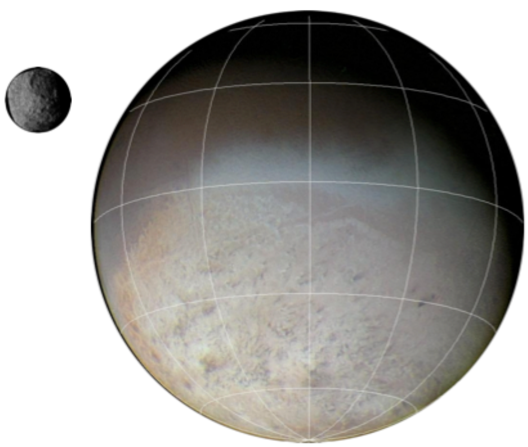


Figure 4.51: Proteus (left) Credit: NASA / JPL; Voyager 2; http://photojournal.jpl.nasa.gov/catalog/PIA00062
and Triton http://photojournal.jpl.nasa.gov/catalog/PIA00329
NASA / JPL / USGS; Voyager 2

Dwarf planets

In 1800 the logical object to look for was whatever was "missing" from the 2.8 AU spot in the Titius-Bode sequence. As mentioned above, that led to the discovery of Ceres, the largest object in the asteroid belt. In 1900, the logical object to look for was "Planet X", something beyond Neptune. Neptune was discovered in 1846 and, with an orbital period of 165 years, had moved far enough in the succeeding 50 years that several people felt confident that it, too, was showing evidence of being tugged on gravitationally by another, more distant, planet. While it turned out that these analyses overestimated the precision with which we were, at that time, able to measure the position and motion of Neptune, the tantalizing suggestion that there might be a ninth planet led several investigators to the telescopes to search.

One of those leading the efforts to find a ninth planet was Percival Lowell, a wealthy Bostonian who had founded Lowell Observatory in Flagstaff Arizona. Lowell had drawn some amount of skepticism for his conviction that he could see canals, clear evidence of an intelligent civilization, in the surface markings on Mars. Lowell and his observatory staff searched for the ninth planet from 1906 until his death in 1916, after which the search was suspended for a time because of protracted legal battles with Lowell's widow. Later analysis showed that Lowell Observatory astronomers and others actually had seen Pluto but, perhaps because it is so tiny and faint, had not recognized what they had recorded.

In 1929 Clyde Tombaugh, a young man from a Kansas farm who had some experience having built his own telescopes, was hired to resume the search. Tombaugh realized that there were ways to systematize the search. First, start the search by concentrating along, or at least near, the ecliptic. All the known planets lie along this plane and that makes it the most likely place for additional planets. Second, observe at the opposition point. That's the point in the sky opposite to the Sun; i.e., it's the point highest in the sky at midnight. Because any outer planet must be moving more slowly than we are, Earth is guaranteed to be pass regularly between the Sun and that outer planet. At that time the planet will be in opposition to the Sun *and*, assuming the planet has a normal prograde orbit around the Sun, it will be moving retrograde against the background stars. Seeing the motion against the background stars is key to catching the planet and also helps distinguish a very distant planet from a relatively close asteroid. The following sketch illustrates the apparent backward motion of an outer planet as it is lapped by the Earth:

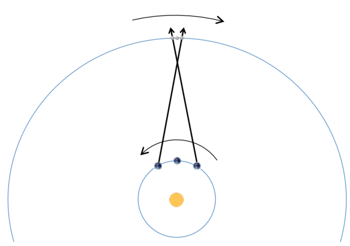
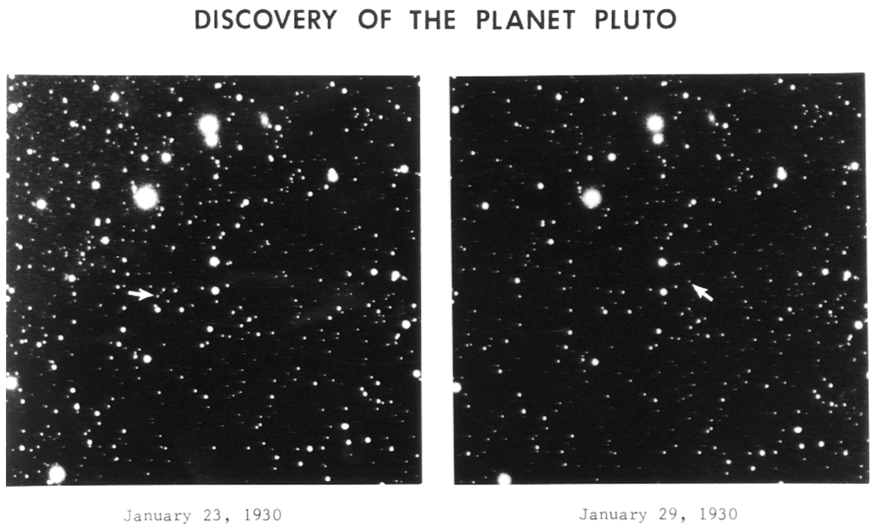


Figure 4.52: Retrograde motion

During the dark of the Moon, Tombaugh took photographs of the opposition point in the sky, always imaging the same point in the stars on pairs of plates (yes, a glass plate provided the substrate for the photographic emulsion) that were taken a few days apart, using a 13-inch diameter wide-field telescope. When the Moon was near full and the sky too bright for observing, Tombaugh compared the pairs of plates using a blink comparator. The stars on two well-aligned plates would stand still as the comparator flipped his view back and forth between the plates. Any object that moved from one plate to the other would "blink" as the view switched from one plate to the other. Variable stars might wink on and off. Asteroids, being closer to us, will move farther than a distant planet.

Math note: an asteroid at, say, 3 AU will have a speed that more closely matches Earth's orbital speed, so you might think that the angle it would move among the background stars over a few days might be less than the angle for an object at 30+ AU. The fact that the asteroid is so much closer to us in space, though, wins out and the angle an asteroid makes among the background stars is substantially larger than the angle for a Trans-Neptunian object.

Let's return to Clyde Tombaugh in Flagstaff in the winter of 1929-1930. His search had taken him into the constellation Gemini, where the ecliptic intersects the Milky Way, one of the most densely populated sections of the sky. On February 18^{th}, 1930, Tombaugh was blinking the plates he had taken on the nights of January 23^{rd} and 29^{th} when he found an object that moved the right amount for something beyond Neptune. Winter weather prevented him from taking a confirmatory plate for a few days. When the weather cleared, he was able to photograph the region again, and the object had duly moved the expected amount. Pluto had been discovered. The following image shows sections of the discovery plates, with Pluto helpfully indicated by the arrows.



https://en.wikipedia.org/wiki/Pluto#/media/File:Pluto_discovery_plates.png
Figure 4.53. Lowell Observatory

Pluto has at least five moons. Charon, the largest, was discovered by James Christy at the Naval Observatory outside Flagstaff in 1978. Pluto and Charon form a double system, in the sense that the center of mass lies in space outside the body of Pluto. The fact that there are moons helps us determine the mass of Pluto, which, at $1.3 \cdot 10^{22}$ kg, is only 0.18 times the mass of our Moon. Pluto and Charon are tidally locked on each other, rotating and revolving around each other with a period of 6.387 days. Pluto's axis is tilted ~123° to its orbit. The Pluto-Charon orbital plane was edge-on to our line of sight for ~5 years, from 1985 – 1990, during which time Pluto and Charon mutually eclipsed or transited each other many times. Observations of these eclipses and transits helped pin down the sizes of both objects. Charon's diameter is 1,212 km, or roughly half of Pluto's 2,372 km diameter.

The New Horizons spacecraft, launched in 2006, flew through the Pluto system successfully on July 14, 2015, subsequently spending 15 months downloading the observations made during that flyby. The image on the left below is of the anti-Charon-facing hemisphere of Pluto, the side for which New Horizons obtained the highest resolution images. It was taken on July 13^{th}, when the spacecraft was ~450,000 km away from Pluto; the resolution, i.e., the smallest features apparent in these images, is ~2.2 km. The color is enhanced to emphasize differences in surface texture and composition. The albedo variation across Pluto's surface is nearly as extreme as that of Iapetus. The New Horizons team is informally calling the heart-shaped region in the lower center-right of this image Tombaugh Regio, after Pluto's discoverer. The smoother western side of this region, which they are calling Sputnik Planitia, has no visible impact craters, but instead is divided into roughly polygonal features tens of kilometers wide that could be the tops of convective cells. Sputnik Planitia may be as young as ten million years. Most of Sputnik Planitia is bounded by higher terrain, suggesting that it is an ice-filled basin. Spectra are consistent with N_2, CO, and CH_4 ices, which would flow like terrestrial glaciers at Pluto's average surface temperature of ~38 K. The mountains around the edges of Sputnik Planitia must be more solid — Pluto's "bedrock" is likely water ice. The nitrogen, carbon monoxide, and methance ices contribute to Pluto's tenuous atmosphere — the New Horizons mission measured a surface pressure of about 1 Pa or 10 μbar, although the atmospheric pressure may vary considerably due to the large oribital eccentricity (~0.25) and thus large variation in solar insolation received over the course of Pluto's year.

Figure 4.54 Pluto. Credit: NASA / Johns Hopkins University Applied Physics Laboratory / Southwest Research Institute; New Horizons spacecraft
https://photojournal.jpl.nasa.gov/catalog/PIA19952

Figure 4.55: Sputnik Planitia Credit: NASA / Johns Hopkins University Applied Physics Laboratory / Southwest Research Institute; New Horizons spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA20726

Pluto's companion Charon has some interesting features of its own, including the mountain highlighted in the following image. The region shown in the inset is ~390 km from top to bottom and was taken from ~79,000 km, shortly before the closest point of the flyby. The fact that Charon has relatively few small craters (0.1 - 2-ish km) could suggest that there aren't as many small Trans-Neptunian objects as we might have thought.

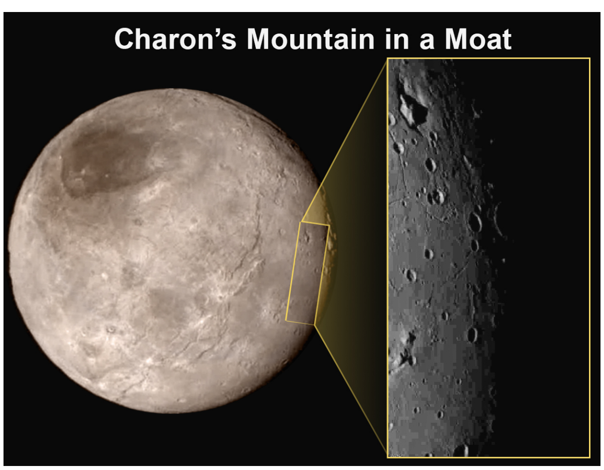


Figure 4.56
Credit: NASA / Johns Hopkins University Applied Physics Laboratory / Southwest Research Institute; New Horizons spacecraft
https://photojournal.jpl.nasa.gov/catalog/PIA19713

Pluto was the only Trans-Neptunian object known from 1930 until the discovery of (15760) 1992 QB_1, by David Jewitt and Jane Luu, observing from Mauna Kea. (Asteroids receive provisional designations based on the fortnight within which they were discovered; Q means the second half of August, because I isn't used, and B1 means the 27th object discovered in that fortnight.) Ceres was discovered in

1801, and the next three members of the asteroid belt were discovered in quick succession: 2 Pallas in 1802, 3 Juno in 1804, and 4 Vesta in 1807. Unlike Pluto, Ceres didn't have time to develop a popular image as an underdog planet. The development of the CCD camera in the 1980s contributed to the discovery of 1992 QB_1 and subsequent Trans-Neptunian objects. CCDs (charge-couple devices) are much more efficient (by ~10x) than traditional emulsion photography, and, producing digital output, allow for computerized analysis of images. The decade after 1992 QB_1 saw an order of magnitude increase in the number of catalogued minor planets (a generic term for asteroids, Kuiper Belt objects, and various other small Sun-orbiting objects scattered throughout the solar system). Bigger telescopes and faster computers also played important roles in that impressive discovery rate. In early 2005, analyzing images taken in late 2003, Michael Brown and his team identified the object subsequently named Eris. The name comes from the Greek and represents strife and discord, fitting for the object that motivated the creation of the new category, dwarf planet.

Eris' orbit is quite eccentric, with aphelion and perihelion distances of 97.7 and 37.9 AU, respectively. It has a moon, named Dysnomia, discovered in the fall of 2005. It rapidly became apparent that Eris is as large or larger than Pluto. There are several lines of useful observational evidence. These lines of reasoning require having enough positional points to determine Eris' orbit, and, specifically, its distance. First, consider its brightness. The smallest Eris could be can be estimated by assuming that its albedo is 100%, because we could receive a given amount of reflected light from either a larger darker object or a smaller, more reflective one. A second piece of evidence comes from looking at Eris in the infrared and observing not its reflected sunlight but what it is emitting. Here we are making assumptions about how cold Eris could be, how much light such a cold object could emit, and thus how bright Eris would be in the IR. A third piece of evidence comes from the angular size of Eris, which, granted, isn't much, as seen by a large telescope. Fourth, we can estimate its mass. This line of reasoning requires knowing the orbit period of its moon. Eris seems to be about the same size as Pluto, a bit more than 2,320 km across, but more than 27% more massive.

The International Astronomical Union voted in 2006 to create a new category of solar system object, the dwarf planet. In addition to Ceres, Pluto, and Eris, two more Trans-Neptunian objects are officially recognized as dwarf planets, Haumea and Makemake, whose orbits are a bit larger than Pluto's. Haumea is intermediate in mass between Ceres and Pluto, and has two moons and a narrow ring. Makemake is a little larger than Haumea; it has one satellite but the satellite's orbit is not well enough contrained to provide, yet, a definite mass for Makemake. Several astronomers argue for another dozen or so objects that should be called dwarf planets — for example, 2007 OR_{10}, a Trans-Neptunian object roughly 1,500 km in diameter; it has a moon but has yet to be given a formal name. Pretty much everyone agrees that more such objects remain to be found in the regions beyond Neptune.

So what's the distinction? Planets, both major and dwarf, orbit the Sun rather than another planet. Both are massive enough to pull themselves into round. The difference between the two is that dwarf planets do not gravitationally control the region near their orbits around the Sun. For example, Jupiter isn't the only object orbiting the Sun at 5.2 AU – it's accompanied by the Trojan asteroids which orbit at stable points 60 degrees ahead and behind Jupiter – but Jupiter is so much more massive that its gravity pretty much controls the motions of the Trojans. Other than the Trojans, and the occasional comet passing through, Jupiter has swept up any planetesimals that might have been in orbit near 5.2 AU. Ceres, on the other hand, although it is by far the largest object in the asteroid belt, is not so overwhelmingly more massive that it could control the motions of the asteroids nor has it been able to sweep them up into a planet. Pluck Ceres out of the asteroid belt and the rest of the objects there would just keep orbiting as they have for ages.

A few comments are in order. First, there are over 40 Trans-Neptunian objects known with diameters larger than ~500 km that are highly likely to be round, based on the assumption that they are mixes of rock and ice. Second, there are objects such as the asteroid / protoplanet 4 Vesta that probably were round and have suffered massive enough collisions since having solidified that they are no longer round; does that knock them out of the dwarf planet category? Third, astronomers have found several candidate “rogue” planets, planet-sized objects not in orbit around any star. In other words, like many human classification systems, our system for classifying planets is far from perfect.

Centaurs and Trans-Neptunian objects

Trans-Neptunian objects (TNOs) are any minor planets with orbits larger than ~30 AU, the size of Neptune’s orbit. It includes three primary subsets.

The Kuiper Belt, named for one of the several mid-twentieth century astronomers who pondered what might lie beyond Neptune, is sort of like an icy outer asteroid belt. It’s wider, extending out to ~50 AU, and more massive. To be a little more specific, objects with orbital semi-major axes at 39.5 AU, such as Pluto, are in a 2:3 orbital resonance with Neptune; Pluto orbits the Sun twice for every three orbits Neptune completes (one result is that whenever Pluto is at perihelion Neptune is on the opposite side of the Sun). Objects with orbits at ~48 AU are in a 1:2 resonance with Neptune. The majority of objects recognized as KBOs (Kuiper Belt Objects) have orbits in the range between these two resonances.

The New Horizons spacecraft, outward bound after its 2015 flyby of Pluto, passed within 3,500 km of the Kuiper Belt object (486958) 2014 MU_{69} on 1 January 2019, at a distance of 43.4 AU from the Sun. Since this is the farthest object we have visited, the New Horizons team have nicknamed it “Ultima Thule”, a reference to the farthest north lands, the borders of the world known to the ancient Greeks and Romans. As you might guess from the “2014” in its provisional designation, Marc Buie of the New Horizons team discovered this KBO *after* the New Horizons spacecraft was launched. Images returned by New Horizons show that Ultima Thule is a contact binary, roughly 35 km long. The larger of the two bits doesn’t seem to be spherical but rather a bit flattened; perhaps, early on, it was rotating rapidly. There are no obvious rings or satellites, which makes it difficult to estimate the mass and density of Ultima Thule. The surface color is a bit red, moreso than Pluto but not unlike other KBOs, and it has no detectable atmosphere. Downloading all the data taken during the flyby is expected to take until mid-2020 to complete. After that? According to team leader S. Alan Stern, New Horizons still has power, and should another suitable KBO be found, might have another encounter sometime in the 2020s.

Figure 4.57: 2014 MU_{69} / Ultima Thule
Credit: NASA / Johns Hopkins University Applied Physics Laboratory / Southwest Research Institute / Roman Tkachenko; New Horizons spacecraft
http://pluto.jhuapl.edu/Galleries/Featured-Images/image.php?gallery_id=2&image_id=606

Scattered disk objects are farther out than the Kuiper Belt and generally have higher orbital eccentricities and inclinations. Today’s models of the early solar system suggest that the giant planets didn’t form in their current locations but have migrated somewhat. In the process of migrating, the young giants interacted with icy planetesimals and gravitationally scattered many of them farther out in the solar system. Some of those objects have subsequently scattered back inward, and become the periodic comets. A half dozen of the scattered disk objects have orbits that are surprisingly aligned, leading to the proposal that a hypothetical Planet Nine, roughly ten times the mass of Earth and in a rather eccentric, distant, and highly inclined orbit, could be the culprit responsible for this statistically unlikely orbital alignment. In terms of searching, we probably aren't likely to find such an object by looking for its reflected sunlight. . .if you moved Neptune twice as far away, it would be 1/16 as bright — since sunlight falls off as $1/r^2$, only 1/4 as much light would get to Neptune-2x and the reflected light would fall off by another factor of 1/4 on the return trip. We're more likely to detect an object on the order of 100 AU away by looking in the infrared or microwave.

Gravitational scattering may play a role in producing the orbits of the objects known as Centaurs, whose paths take them across the orbits of one or more of the giant planets (i.e., they are related to, but are not themselves, TNOs). The first known is 2060 Chiron, which has an orbital aphelion of ~19 AU and a perihelion of ~8.5 AU. Chiron was discovered in 1977, and at the time held the title of most distant minor planet. As it approached its perihelion, a decade later, it developed a coma. That's probably not all that surprising, since outer solar system objects are likely to be icy and ices sublimate when the temperature gets high enough. It does serve to illustrate the fuzzy line between our various classification categories; asteroid? comet? a bit of both?

The Centaur 5145 Pholus, discovered in 1992, is quite reddish in color. Reddish is not unusual for outer solar system objects. Carbon-containing ices, such as methane or ethane, react with the UV in sunlight to produce more complex organic molecules, called tholins, which are reddish-brown in color. The following sketch, based on a 1996 paper by Luu and Jewitt, illustrates the differences in the reflectance spectra of Chiron and Pholus, normalized to 1.0 at 650 nm:

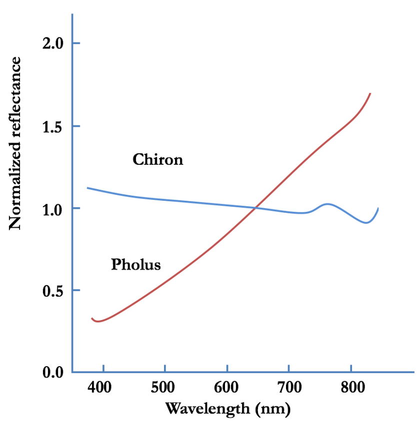


Figure 4.58: Spectra of Chiron and Pholus

The largest Centaur to have been discovered by late 2016 is 10199 Chariklo, whose diameter is estimated to be ~260 km, a bit larger than Chiron. Chariklo and Chiron also have the distinction of having rings, discovered during occultations of background stars.

Farthest out in the solar system is the Oort cloud, the third subset of TNOs. The Oort cloud is named for Jan Oort, who theorized that there might be a distant, roughly spherical distribution of small icy objects that could give rise to the long-period comets, which show a broad range of orbital orientations. If objects in the Oort cloud do have aphelia extending out to ~10^5 AU, that's half way to the next nearest star, Proxima Centauri.

Our census of the outer solar system is far from complete. We have detected very few objects with orbits lying entirely beyond ~50 AU. The first to be found is 90377 Sedna, discovered in 2003. We know that it's icy and a bit reddish; its orbit takes it from 76 AU out as far as 937 AU. That's an eccentricity of 0.85, and an orbit period of ~11,000 years. It's also a bit far out for the scattered disk and a bit too close to be an Oort cloud object. Again, like the discovery that the Centaur Chiron could behave both like an asteroid and a comet, Sedna challenges out attempts at categorizing solar system objects.

Comets

The principal definition of a comet is the development of a coma, the fuzzy atmosphere that forms when the comet gets close enough to the Sun for ices to become gas. Comets are traditionally named for their discoverers.

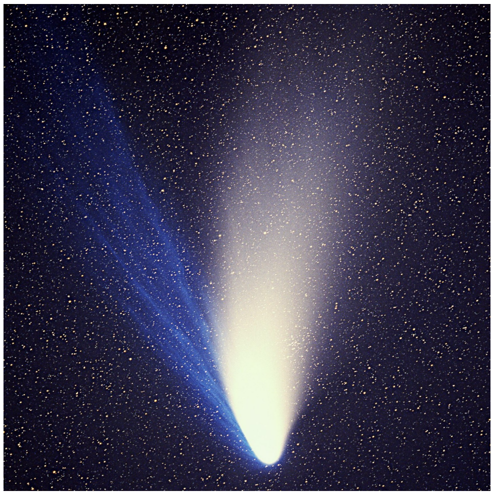


Figure 4.59: Comet Hale-Bopp.

Image credit: By E. Kolmhofer, H. Raab; Johannes-Kepler-Observatory, Linz, Austria (http://www.sternwarte.at) - Own work, CC BY-SA 3.0 https://commons.wikimedia.org/w/index.php?curid=6756556

Substances that become gas at relatively low temperatures, such as the watery ices we expect to find in outer solar system objects, are called *volatiles*; those that stay solid until very high temperatures are described as *refractory*. Most comet nuclei aren't very large, perhaps half a kilometer up to a few tens of kilometers. Halley's comet is on the large size, about 15 km long. They also seem, by and large, to be loose rubble piles of ice and rock, or "dirty snowballs", as astronomer Fred Whipple called them. They don't have very high surface gravities, so it's easy for molecules of gas, heated by sunlight, to acquire enough energy to exceed the escape speed of the comet nucleus. If enough gas molecules and bits of dust escape from the nucleus, the comet may develop a tail. If the comet's perihelion takes it close enough to the Sun, say, inside ~1 AU, and if the comet still has lots of ice and hasn't lost too much in prior visits to the inner solar system, the comet may become bright enough to be naked-eye visible. Comet Hale-Bopp, discovered in the summer of 1995, nearly two years before its April 1997 perihelion, was visible to the naked eye for ~18 months, but that comet was quite bright for an exceptionally long time. Very roughly, about one comet per year is naked-eye visible and about one a decade is really outstanding and may warrant being called a Great Comet.

Short-period comets usually have orbital periods of a few years and paths that tend to lie not too far off the ecliptic, suggesting that they originated in the outer solar system disk. Halley's comet, with a period of ~76 years, is a rough dividing mark between the short-period comets and the more eccentric long-period comets (although a period of 200 years is also often used as the dividing mark). Long-period comets' orbits are often also highly inclined. Halley's orbital inclination is 162°; an inclination greater than 90° means that it orbits the Sun retrograde. Some long-period comets, having had their energies boosted by interactions with one or more of the outer planets, will escape from the Sun's gravity entirely. Some comets have perihelia that are so small that they graze or crash into the Sun.

Humanity has undoubtedly been noticing comets for as long as we've been noticing stars and planets. What comets were thought to mean, though, was far from clear. Chinese astronomers had collected a record of "broom stars" by ~500 B.C.E., and had noticed that comet tails, regardless of their somewhat varying shapes, always point away from the Sun. They were seen as portents of bad events to come. Europeans acquired the idea that, as Shakespeare wrote in *Julius Caesar*,

> When beggars die there are no comets seen;
> The heavens themselves blaze forth the death of princes. (II, ii, 30-31)

Thus there must have been a comet preceding the death of Charlemagne in the year 814; that that comet didn't happen to be naked eye visible doesn't seem to have struck many people as problematic and chroniclers recorded that there had been one anyway. Halley's comet legitimately makes an appearance at the death of English King Harold in 1066, and is recorded in the Bayeux Tapestry:

Figure 4.60: Halley's comet in the Bayeux tapestry
Credit: By Myrabella - Own work, Public Domain; https://commons.wikimedia.org/w/index.php?curid=25336523

The artist Giotto may have seen Halley's comet during its 1301 apparition and that may have inspired his use of a comet to represent the star of Bethlehem in his painting "Adoration of the Magi"; why he used a comet to depict a birth rather than a death is not clear.

Aristotle, 4th century B.C.E., thought that comets, like meteors, had something to do with our atmosphere, and his views held sway in Europe for many centuries. Tycho Brahe, one of the last great pre-telescopic astronomers, observed that the Great Comet of 1577 failed to display parallax when observed from significantly different locations on Earth. That shot down the atmospheric model because anything that's relatively nearby, as an object must be if it's part of our atmosphere, would have to be seen in different locations among the background stars when observed from different locations on the ground. The first-century C.E. Roman writer Seneca did succeed in predicting a bit more modern view, expressing the view that comets had orbits like planets and that someday we might be able to demonstrate the nature of those orbits. That had to wait a while.

Edmond Halley didn't observe the comet that bears his name, but he did predict its return. Halley was a contemporary of Isaac Newton, and actually arranged the publication of Newton's epic *Philosophiae Naturalis Principia Mathematica* (usually just called the *Principia*) in which he lays out the principles we today call classical mechanics. Halley was interested in orbits, and comets, and was astute enough to realize that records of a comet in 1531, 1607, and 1682 sounded very much as if they must be the same object, returning to the inner solar system with an orbit period of ~76 years. Based on orbital calculations Halley performed, including estimations of the perturbing effects of Jupiter and Saturn, Halley predicted that this comet would reappear in 1758. Halley didn't live to see the 1758 apparition, but the comet dutifully returned as he predicted it would. His comet's perihelion distance is ~0.6 AU and its aphelion is ~35 AU.

Every time a comet passes close to the Sun it loses some of its volatiles. A burned-out comet, which no longer has enough ices to produce a coma or tail, is hard to distinguish from an asteroid. Halley's comet is interesting in that it has been around the Sun so many times and still has ice; it has been observed and recorded at least since 240 B.C.E.. Halley's should return next in 2061. Several space probes passed relatively close to Halley's comet during its last visit, in 1986, and gave us the first good images of the nucleus of a comet. The European spacecraft Giotto, named for the artist, flew past the nucleus at a distance of ~600 km.

Figure 4.61: Comet Halley
Credit: NASA / ESA / Giotto Project
https://photojournal.jpl.nasa.gov/catalog/PIA17485

Comet orbits are aligned in various directions. Here, for example, is a figure showing the orientation of Halley's orbit and the fact that Earth was not well positioned to see Halley's comet when it was at perihelion during its 1986 apparition. Prograde orbits are counterclockwise when seen from above. Halley's spends most of its time south of the ecliptic. It was above the ecliptic at perihelion on ~February 5th, 1986, at which time the Earth was on the other side of the Sun.

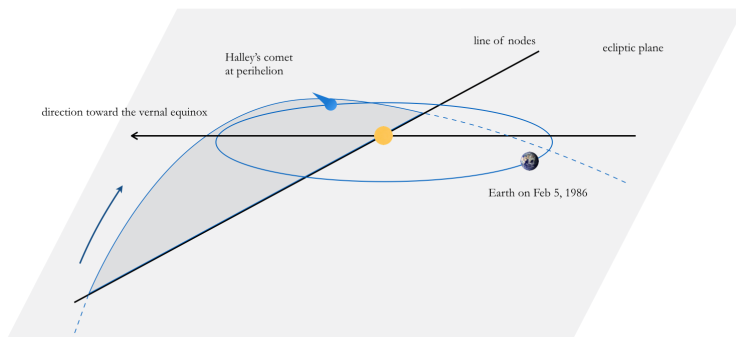


Figure 4.62: Geometry of Halley's 1986 apparition.
Earth image:
NASA / Visible Earth (https://visibleearth.nasa.gov/view.php?id=57723)

We've used several words – nucleus, coma, tail – but not yet looked at the overall anatomy of a comet. The following sketch shows the basic parts:

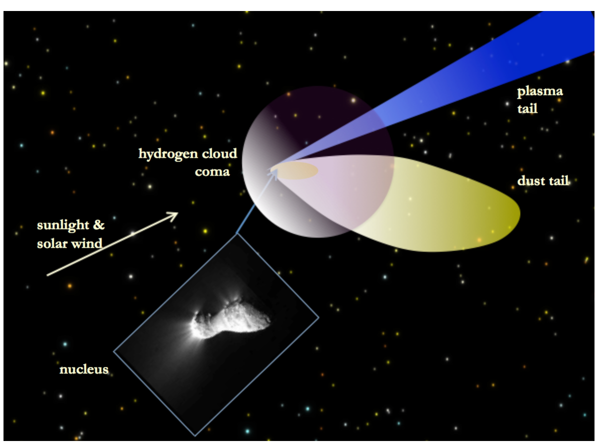


Figure 4.63: Anatomy of a comet

Inset: Comet Hartley 2; credit: NASA / JPL / UMD
http://www.nasa.gov/mission_pages/epoxi/images/version1/IINMVUAXF_6000002_001_001_crop.html

The nucleus is the few-kilometer-long (or oblong) object that is the actual body of the comet itself. Comet nuclei tend to be very dark, with albedos of 3-4%. As you can see in the inset image of Comet Hartley 2, when a comet nears the Sun, patches on the surface warm and create jets. The hypothesis is that the sunlight warms dark patches enough that ice under the dark surface turns to gas and the pressure in the bubble of gas gets high enough to blast out through the crust. Jets can make the nucleus tumble, so it's often the case that a comet doesn't have a stable rotation period. The visible head of the comet, made of a combination of dust and gas, is the coma. A more extensive cloud of hydrogen gas, e.g., created by photodissociation of water molecules, usually surrounds the coma, but it's only visible in the ultraviolet, in Lyman-α emission. The coma of the comet will likely vary in size during its passage through perihelion because as the comet nears the Sun, radiation pressure and the solar wind act to blow material backward into the comet's tails. At its peak, the coma can be larger than the Sun.

There are two types of comet tails. The gas molecules often get ionized (becoming a plasma) by ultraviolet sunlight. The plasma tail tends to be bluish because several of the dominant species of ions emit in the blue. Once they acquire a net electric charge particles will interact with the solar wind, which is an outflow of charged particles from the Sun, which is why the plasma tail, following the magnetic field lines of the solar wind, points pretty much straight away from the Sun. Plasma tails can extend millions of kilometers.

Moving charged particles create and interact with magnetic fields. If the magnetic field lines downstream from the comet nucleus get pinched together (called magnetic reconnection) a lot of energy can be released and the tail can actually get disconnected from the comet. That happened to Periodic Comet Encke in 2007, when it got smacked by a coronal mass ejection from the Sun. The following images were taken by one of the NASA STEREO satellites.

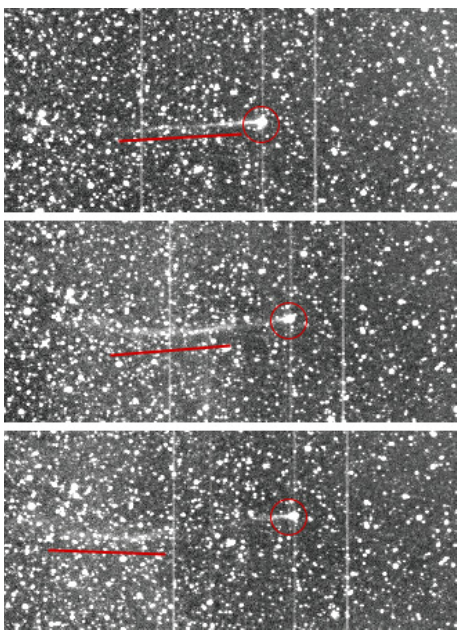


Figure 4.64: Comet Encke
Credit: NASA / STEREO
http://www.nasa.gov/mission_pages/stereo/news/encke.html#.VZGwnBNVhBd

Dust particles emitted from the comet nucleus get pushed back by the radiation pressure of the sunlight. Dust tails are not usually as long as the plasma tails but they can appear quite a bit brighter. The dust particles spread out quite a bit, curving and roughly following the comet orbit, and they are reflecting sunlight. From our perspective, our line of sight will occasionally catch a dust tail on the far side of the Sun curved around so far that it looks as though the comet has sprouted an "anti-tail" pointing back toward the Sun, but this is just a projection effect. Comets are fragile; chunks will occasionally break off, move a bit away, and sprout tails of their own, leading to extensive fan-shaped tails.

There are also some neutral gas atoms, such as the sodium discovered not just in the coma of Hale-Bopp but also flowing backwards as a third, if fainter and less well understood, type of tail. Here are a few more comet images.

Figure 4.65: Comet McNaught over the Pacific Ocean. Image taken from Paranal Observatory in January 2007.

Credit:
S. Deiries/ESO

http://www.eso.org/public/images/mc_naught34/

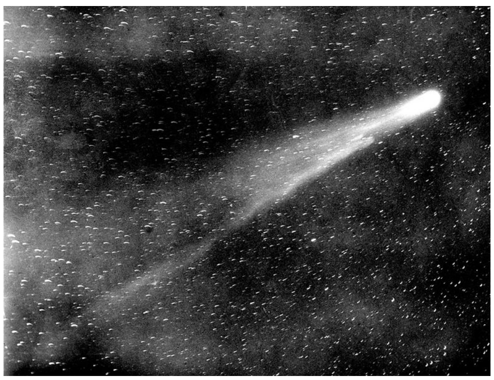


Figure 4.66: Yerkes Observatory photo of Halley's Comet, 1910
https://commons.wikimedia.org/wiki/Category:Comet_Halley#/media/File:Halley%27s_Comet,_1910.JPG

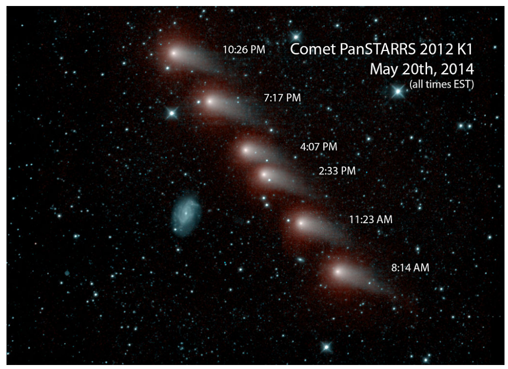


Figure 4.67: NEOWISE images of Comet Pan-STARRS and galaxy NGC 3726.
Credit: NASA / JPL-CalTech
http://www.nasa.gov/jpl/neowise/pan-starrs-20140703

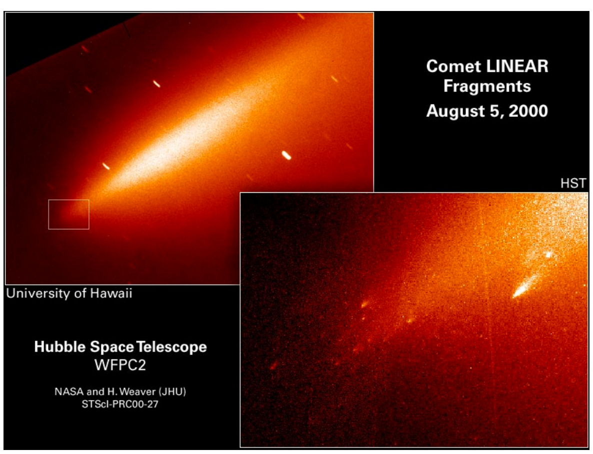


Figure 4.68: Comets occasionally disintegrate. C/1999 S4 (LINEAR) is, or was, a long-period comet discovered by Lincoln Labs Near-Earth Asteroid Research (LINEAR) project. It broke up as it passed perihelion in July 2000.

http://hubblesite.org/newscenter/archive/releases/2000/27/image/a/

In August 2014 the Rosetta spacecraft arrived at the short-period comet 67P / Churyumov-Gerasimenko for an extended orbit. An attempt to deploy a lander, called Philae, in November has had mixed results. The probe landed, but bounced into shadows where its batteries were quickly depleted. Seven months later, as the Rosetta, the comet, and the Philae lander got closer to the Sun, the changing orientation of the Sun has recharged the lander's batteries and Philae re-established some (but not consistent) communication with Earth for several weeks in the summer of 2015, before falling silent for good. The Rosetta mission ended in September 2016 with the spacecraft landing (intentionally) on the comet.

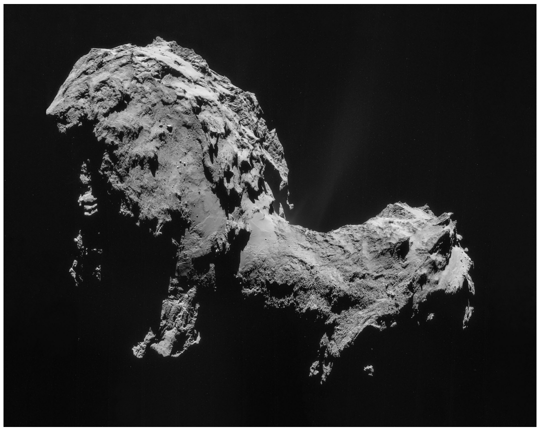


Figure 4.69: Comet 67P / Churyumov-Gerasimenko by Rosetta's navigation camera on 19 September 2014 from a distance of 29 km.
Credit: ESA / Rosetta / NAVCAM
CC BY-SA IGO 3.0 https://commons.wikimedia.org/w/index.php?curid=36603034

Churyumov-Gerasimenko has a 6.5-year orbit period; it reached perihelion, ~1.2 AU from the Sun, in mid-August, 2015. Around the time of perihelion the comet was quite active; note the jets in this image taken on 7 July:

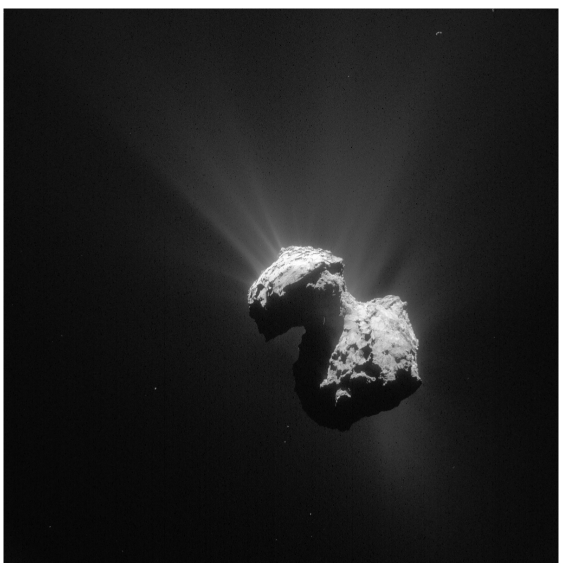


Figure 4.70: Comet 67P/Churyumov-Gerasimenko jets.
Credit: ESA / Rosetta /NAVCAM, CC BY-SA IGO3.0 https://commons.wikimedia.org/w/index.php?curid=41733207

The dust from a comet can get spread out along the comet's path. If Earth's orbit intersects that trail of dust, we get a meteor shower. If the dust is clumpy and hasn't had time to spread out along the orbit, you could get a meteor storm, with many more meteors seen per hour than usual. The Perseid meteor shower (associated with comet Swift-Tuttle), every August, or the Leonids (associate with comet Tempel-Tuttle), every November, are among the most famous. The 1833 Leonids produced an impressive storm, with many thousands of meteors per hour. Some come from asteroids: the parent body of the mid-December Geminid shower is the Apollo asteroid 3200 Phaethon. Meteor showers are named for the constellation in which we find the radiant point, the point from which all the meteors seem to be coming at us. The dust pieces are small, mostly tinier than a grain of sand; Earth runs into a cloud of dust and the little bits of rock burn up in our atmosphere. We mostly see the streak of hot gas produced by the friction and shock as the fast-moving dust grain slows and disintegrates. Just like more raindrops hit your front windshield when you driving into a rainstorm than hit the rear windshield, we are more likely to see meteors during a shower if we are on the leading edge of the Earth. That's why meteor showers are best observed after midnight.

Figure 4.71: An engraving of the 1833 Leonids by Adolf Vollmy.
http://star.arm.ac.uk/leonid/Meteor-Shower.jpg

Figure 4.72: A Perseid meteor from above, photographed from the International Space Station on August 13th, 2011. Credit: NASA
http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=15363

Dust and meteoroids

Some of the solar system's tiniest residents have the biggest stories to tell. Some of the dust and small bits of rock have been very little changed since the beginning of the solar system; some are fragments of asteroids and tell us about the conditions in the interiors of these larger objects.

Briefly mentioned above, the zodiacal light gives evidence of dust along the plane of the solar system. The image at the left was taken near Cerro Paranal and the European Southern Observatory's Very Large Telescope. The zodiacal light is best seen at times of year and/or locations where the ecliptic, the plane of the solar system, will intersect the horizon at steep angle. It is caused by the reflection of sunlight off the dust particles.

Figure 4.73: zodiacal light.
Credit: ESO / Y. Beletsky
http://www.eso.org/public/images/zodiacal-light/

Earth gets hit by ~$10^{7\text{-}8}$ kg of space rocks and dust every year, or on the order of fifty to a hundred tons every day. Most of that material is dust. The pieces that are small, like a sand grain or up to a small marble, will be vaporized in our atmosphere. The pieces that are really small will rapidly reach terminal velocity in the atmosphere and float down like snowflakes. Space dust is steadily accumulating on every outdoor surface. Larger chunks, in the few centimeter range, will lose some material to ablation (the term for heating the outside layers to vapor and shedding them) but survive to hit the ground. Pieces that hit the ground are called meteorites.

Terminology note: the smallish objects in space, usually less than ~100 m diameter, are called meteoroids; the streak of light in our atmosphere is the meteor; the rock on the ground is the meteorite. You might also see fireball or bolide used to describe a particularly bright meteor.

We will consider meteorites in more detail later, but as an introduction at this point note that they are divided into three main subtypes: Irons are chunks of iron and nickel that were once part of the core of a differentiated asteroid; stones are mostly rocky, which could either be because they came from the outer layers of a differentiated asteroid or because they are primordial rocks that never participated in differentiation; stony-irons are, as the name suggests, a mix. Stones are most common; irons are the most notably different from terrestrial rocks.

Let's return to the bits in space for a moment. In addition to lunar samples returned by the Apollo astronauts and the Soviet robotic Luna missions, there have been several sample return space missions designed to catch dust or molecules or collect samples from larger objects and bring them safely back to Earth. NASA's Genesis mission succeeded in returning samples of the solar wind in 2004, despite a parachute failure and a crash landing. The Stardust mission returned dust samples in 2006, collected from Comet Wild 2 using an incredibly low-density material called aerogel that can snag particles by slowing them gently enough that the fragile dust grains don't disintegrate. In 2010 the Japanese Hyabusa mission successfully returned asteroid samples. Hyabusa landed on 25143 Itokawa, an S-type asteroid, retrieved surface samples, and returned to Earth.

Interstellar interlopers

One newly recognized category of solar system objects, including long-term residents and those just passing through, are those determined to be interstellar in origin. 'Oumuamua, or 1I / 2017 U1, was discovered in October, 2017, about a month after it passed perihelion. That "1I" designation indicates that this is the first minor planet known to have come in to the inner solar system with such a high velocity that it cannot have originated in the solar system. Some solar system objects can get boosted into hyperbolic orbits, e.g., by an encounter with Jupiter, but that's not the case here. 'Oumuamua arrived from the direction of the constellation Lyra and its outbound trajectory is carrying it toward Pegasus at about 26.3 km/s. 'Oumuamua is long (about 230 by 35 meters), dark, and tumbling. Observations during its brief swing through our neighborhood show that its color is a fairly neutral gray. Its shape and rotation suggest that it has a relatively high density, similar to a metal-rich asteroid. It doesn't show obvious evidence of outgassing, but observers following it as it headed away found the object deviating slightly from its expected path, behavior that might be expected of an outgassing comet being pushed somewhat by jets of released gas and dust. To the extent that we might have expected visitors from beyond the solar system, based on the orbits and numbers of asteroids and comets in our own solar system, we would reasonably have expected to be visited by a comet, not an asteroid.

Once it became clear that we could be visited by extrasolar objects, several astronomers began examining records of meteors bright enough to have had observations of their paths catalogued (fireballs, or 'bolides'), looking for any whose trajectories might indicate an origin outside the solar system. One possible candidate, identified in 2019, disintegrated in the the atmosphere over the south Pacific in 2014. Models suggest that it was roughly 0.9 m in diameter and moving at ~ 60 km/s from a direction well out of the ecliptic when it hit. The high speed, as well as the direction, tentatively suggest that this meteoroid was not a bound solar system object.

An interstellar interloper could get captured by the gravity of the Sun and/or Jupiter and become a long-term resident. One candidate for this category is the obscure little asteroid 2015 BZ_{509}, which has the odd property of revolving around the Sun retrograde. That's not so odd for a comet, but not something we'd expect for an asteroid. 2015 BZ_{509} is about 3 km across, caught in a resonant orbit with Jupiter, meaning that its orbital semi-major axis is nearly the same as Jupiter's. Its orbit is sufficiently eccentric and inclined that it's not going to be plowing headlong into Jupiter any time soon. It's clearly possible for an outer solar system object to acquire a retrograde orbit, Halley's comet being one obvious example, so it's not yet clear whether 2015 BZ_{509} has an interstellar origin.

Surface temperatures

This section assumes that you've read about light and spectra in Chapter 1 (Introduction). Here let's add a bit about the factors that influence the surface temperatures of solar system bodies.

First, a description of the geometry: light from the Sun spreads out in all directions (i.e., *isotropically)*. A planetary body will intersect some of the light; how much depends on its size and distance from the Sun. Of what it intersects, a fraction will be absorbed and the rest reflected. What's absorbed will warm the surface. So will internal heat. Planetary bodies of any substantial size, i.e., those that are large enough not to have cooled off in the age of the solar system, are going to be warmer in their centers than at their surfaces. Warm opaque objects such as planets will radiate as roughly black bodies (not quite, but it's close). Unlike the Sun, moons and planets are not going to radiate isotropically. Think about the Earth – it's definitely cooler at the poles than at the equator and any given patch of ground isn't going to be the same temperature at night as it was in early afternoon. If we want the total amount of energy radiated by a planetary body we are going to have to make a few approximations about how much it deviates from being a black body, how much the temperature varies with location, how much it varies with time of day, and, for objects with substantial atmospheres, how much the surface layer temperature is modified by a greenhouse effect.

We can say that we expect all moons and planets to radiate in the infrared; none are hot enough to emit significantly in the visible. This means that when we observe the spectrum of a planetary body we expect to see the spectrum of reflected sunlight at visible wavelengths + the spectrum of emitted IR. At higher resolution, we'll also expect to see lines in the spectrum due to particular molecules at the surface or in the atmosphere – more on that bit in subsequent chapters. For now, let's look at the overall, low-resolution spectrum. The following sketch shows what the spectrum might look like.

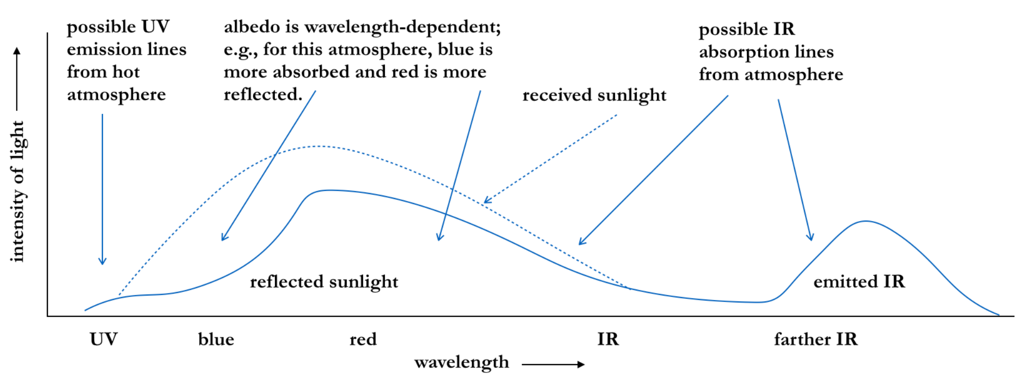


Figure 4.74: Planetary spectrum

The peak wavelength of the part that's emitted in the IR can give us an estimation of the surface temperature of the object. We can compare that to the expected surface temperature to get an estimation of the role of internal heating.

In Chapter 1 you saw the relationship between wavelength of the peak of a black body spectrum and the temperature of the object:

$$\lambda_{\max}(\mathrm{m}) = \frac{2.898 \cdot 10^{-3}\,\mathrm{m} \cdot \mathrm{K}}{T(\mathrm{K})}.$$

You also saw the expression for the luminosity of a black body:

$$L = 4\,\pi\,r^2\,\sigma\,T^4.$$

Example: Ceres's emitted spectrum peaks at ~17.3 microns; what's its average surface temperature? Solve the above for temperature:

$$T = \frac{2.898 \cdot 10^{-3}\,\mathrm{m} \cdot \mathrm{K}}{17.3 \cdot 10^{-6}\,\mathrm{m}} \approx 168\ \mathrm{K}.$$

How does this compare to the expected temperature? Ceres is rocky and it's not unreasonable to assume that its albedo is ~10%; that means that 90% of the incoming sunlight is absorbed. Ceres' average distance from the Sun is ~2.77 AU. Ceres' radius is ~473 km. We also need the Sun's luminosity: $3.828 \cdot 10^{26}$ J/s. First let's calculate how much energy gets to Ceres, per second:

$$\frac{L_{\mathrm{Sun}}}{4\pi d^2} = \frac{3.828 \cdot 10^{26}\,\mathrm{J/s}}{4\pi(2.77\ \mathrm{AU} \cdot 1.5 \cdot 10^{11}\,\mathrm{AU/m})^2} = 176.4\ \mathrm{J} / (\mathrm{s} \cdot \mathrm{m}^2).$$

Of that, Ceres absorbs ~90%, or ~160 J / (s m^2). That is the received flux (recall that luminosity is J / s and flux is J / (s m^2)) over the Sun-facing hemisphere. The Sun sees Ceres as if it were a disk of area πr^2. Ceres rotates fairly rapidly (~9 hours) so it's not unreasonable to assume that the received energy gets spread over the entire surface, or $4\pi r^2$. That means we should divide by 4, giving us ~40 J / (s m^2), to get the amount that will be emitted by each square meter of the surface. This flux = $\sigma\,T^4$. Solve for the temperature:

$$T = \sqrt[4]{\frac{F}{\sigma}} = \sqrt[4]{\frac{40\ \mathrm{J} / (\mathrm{s} \cdot \mathrm{m}^2)}{5.67 \cdot 10^{8}\,\mathrm{J} / (\mathrm{s} \cdot \mathrm{m}^2 \cdot \mathrm{K}^4)}} \approx 163\ \mathrm{K}.$$

That's not bad.

Let's put this together into one, simplified expression:

$$T \approx 300 \cdot \sqrt[4]{\frac{(1-A)}{(d\ \mathrm{AU})^2}}.$$

All the physics – the solar luminosity, σ, the conversion from AU to meters – lives in that factor of 300, out front. Inside the 4th root is (1 – A), where A is the Bond albedo, and the distance from the Sun, either the orbital semi-major axis or the instantaneous distance for objects with more eccentric orbits.

The factor of 300 is an approximation; it *matters* whether a planetary body is radiating over its entire surface or only the sunward side, e.g., whether it is rapidly rotating or not or perhaps has an atmosphere that evens out the temperature. Think about Mercury: it rotates very, very slowly, and the Sun-facing side is *hundreds* of degrees hotter than the anti-Sun side! Roughly speaking, that factor of 300 is closer to 280 for rapid rotators and about 380 for slow rotators.

A note about albedo: Albedo is a measure of how reflective a surface is. There is not one set way to express albedo. It varies with color; e.g., a solar system body might not reflect the same percentage of sunlight in the visual, say ~500 nm, as it does in the near infrared. If we know the reflectivity over all wavelengths, we have a *bolometric* albedo. Albedo also depends on the relative positions of the Sun, object, and observer. The Bond albedo is the percentage of light reflected in all directions. The geometric albedo is the percentage of light reflected at zero phase angle, where the phase angle is the angle between the Sun and the observer as seen from the object. For instance, Full Moon is nearly zero degrees phase angle because if you were on the Moon looking back toward us, Earth and Sun would be almost in the same direction in your sky. Very few things reflect absolutely symmetrically and, to make matters a bit more complicated, water droplets in a cloud, the surface of an ocean, the minerals in surface rocks, etc., etc., all reflect somewhat differently as a function of phase. The geometric and Bond albedo are not usually going to be the same number. As an example of this, you might have noticed that the Full Moon looks relatively brighter than you might have expected based on seeing it near First Quarter. You'd think that the brightness would go up linearly as we saw more and more of the illuminated side of the Moon. It doesn't. There's a spike, called the opposition effect, when the Moon is (almost) directly opposite the Sun in our sky. The dust on the surface is really good at reflecting straight back.

Table 4.1: **Summary of orbital and physical properties of selected solar system objects**

Object	semi-major axis (AU or km)	revolution period (days or years)	orbit eccentricity	& inclination to ecliptic or planet equator (°)	rotation period (hours or days)	obliquity (°)
Sun	_	_	_	_	25 – 34 d	7.25
Mercury	0.387	87.97 d	0.206	7.0	58.65 d	0.003
Venus	0.723	0.615	0.007	3.39	–243 d	177.4
Earth	1.0	1.0	0.017	7.2 to Sun eq.	23.93	23.44
Moon	384,400 km	27.32 d	0.055	5.15 to ecl.	27.32 d	6.69
Mars	1.52	1.88	0.094	1.85	1.026 d	25.19
Phobos	9,376 km	0.32 d	0.015	1.09	0.32 d	0
Deimos	23,463 km	1.26 d	~0	0.93	1.26 d	
4 Vesta	2.36	3.63	0.09	7.14	5.34	
Ceres	2.77	4.60	0.08	10.59	9.07	~3
2 Pallas	2.77	4.61	0.23	34.84	7.81	~78?
10 Hygiea	3.14	5.56	0.12	3.84	27.62	
Jupiter	5.20	11.86	0.05	1.31	9.93	3.13
Io	421,700 km	1.77 d	0.004	0.05	1.77 d	
Europa	670,900	3.55 d	0.009	0.47	3.55 d	0.1
Ganymede	$1.070 \cdot 10^6$ km	7.15 d	0.0013	0.20	7.15 d	
Callisto	$1.883 \cdot 10^6$ km	16.69 d	0.0074	~1	16.69 d	0
Saturn	9.58	29.46	0.056	2.49	10.55	26.73
Mimas	185,539 km	0.94 d	0.02	1.57	0.94 d	0
Enceladus	237,948 km	1.37 d	0.005	0.019	1.37 d	0
Tethys	294,619 km	1.89 d	~0	1.12	1.89 d	0
Dione	377,396 km	2.74 d	0.002	0.019	2.74 d	0
Rhea	527,108 km	4.52 d	0.001	0.345	4.52 d	0
Titan	$1.222 \cdot 10^6$ km	15.95 d	0.029	0.35	15.95 d	0
Iapetus	$3.561 \cdot 10^6$ km	79.32 d	0.029	15.47	79.32 d	0
2060 Chiron	13.71	50.76	0.38	6.93	5.92	
Uranus	19.19	84.02	0.05	0.77	–17.24	97.8
Miranda	129,390 km	1.41 d	0.0013	4.23	1.41 d	0
Ariel	191,020 km	2.52 d	0.0012	0.26	2.52 d	?
Umbriel	266,300 km	4.14 d	0.0039	0.21	4.14 d	0?
Titania	435,910 km	8.71 d	0.0011	0.34	8.71 d	?
Oberon	583,520 km	13.46 d	0.0014	0.06	13.46 d	?
5145 Pholus	20.36	91.85	0.57	24.65	9.98	?
Neptune	30.07	164.8	0.0087	1.77	16.11	28.32
Proteus	117,647 km	1.122 d	~0	0.52	1.122 d	~0
Triton	354,759 km	– 5.88 d	~0	157	5.88	0
Pluto	39.26	247.7	0.25	17.16	6.387 d	122.5
Charon	19,591 km	6.387 d	0	0	6.387 d	
Haumea	43.22	284	0.19	28.19	3.92	?
Makemake	45.72	309	0.16	29.00	7.8	?
Eris	67.78	558	0.44	44.04	25.9	?
90377 Sedna	524.4	~11,400	0.85	11.93	10.3	?

Summary of orbital and physical properties of selected solar system objects, continued

Object	mass (kg)	diameter (km)	ave. density (g/cm^3)	albedo (Bond or geom.)	surface temp. (K)	atmosphere or color
Sun	$1.99 \cdot 10^{30}$	$1.39 \cdot 10^{6}$ (eq.)	1.41	_	5780	H, He
Mercury	$3.30 \cdot 10^{23}$	4,879	5.43	0.068 Bond	80 – 700	trace
Venus	$4.87 \cdot 10^{24}$	12,104	5.24	0.90 Bond	737	CO_2, N_2, SO_2
Earth	$5.97 \cdot 10^{24}$	12,742	5.51	0.31 Bond	184 – 330	N_2, O_2, Ar, H_2O
Moon	$7.35 \cdot 10^{22}$	3,474	3.35	0.12 geom	70 – 390	trace
Mars	$6.42 \cdot 10^{23}$	6,779	3.93	0.25 Bond	130 – 308	CO_2, Ar, N_2, O_2
Phobos	$1.07 \cdot 10^{16}$	27 x 22 x 18	1.88	0.071 geom	~233	
Deimos	$\cdot 10^{20}$	15 x 12 x 11	1.47	0.068 geom	~233	
4 Vesta	$2.59 \cdot 10^{20}$	~525	3.46	0.42 geom	85 – 270	V-type
Ceres	$9.39 \cdot 10^{20}$	938	2.17	0.09 geom	168 – 235	C-type
2 Pallas	$2.11 \cdot 10^{20}$	544	~2.8	0.16 geom	~164	B-type
10 Hygiea	$8.67 \cdot 10^{19}$	~431	2.08	0.07 geom	~164	C-type
Jupiter	$1.90 \cdot 10^{27}$	139,822	1.33	0.34 Bond	165 @ 1 bar	H_2, H2, CH_4, NH_3
Io	$8.93 \cdot 10^{22}$	3,643	3.53	0.63 geom	110	trace SO_2
Europa	$4.80 \cdot 10^{22}$	3,122	3.01	0.67 geom	102	trace
Ganymede	$1.48 \cdot 10^{23}$	5,268	1.94	0.43 geom	110	trace O_2
Callisto	$1.08 \cdot 10^{23}$	4.821	1.83	0.2 geom	134	trace O_2, CO_2
Saturn	$5.68 \cdot 10^{26}$	116,464	0.69	0.34 Bond	134 @ 1 bar	H_2, He, CH_4, NH_3
Mimas	$3.75 \cdot 10^{19}$	396	1.15	0.86 geom	~64	
Enceladus	$1.08 \cdot 10^{20}$	504	1.61	0.99 Bond	75 (ave)	trace H_2O, N_2, CO_2
Tethys	$6.17 \cdot 10^{20}$	1,062	0.98	0.80 Bond	86	
Dione	$1.10 \cdot 10^{21}$	1,123	1.48	0.99 geom	87	
Rhea	$2.31 \cdot 10^{21}$	1,527	1.24	0.95 geom	53 – 99	
Titan	$1.345 \cdot 10^{23}$	5,150	1.88	0.2 geom	93.7	N_2, CH_4, H_2
Iapetus	$6.5xx \cdot 10^{19}$	1,470	1.09	~0.6 geom	90 – 130	
2060 Chiron	?	~166 km	?	~0.15 geom	~75	
Uranus	$8.68 \cdot 10^{25}$	50,724	1.27	0.30 Bond	76 K @ 1 bar	H_2, He, CH_4
Miranda	$6.59 \cdot 10^{19}$	471	1.20	0.32 geom	~60	
Ariel	$1.35 \cdot 10^{21}$	1,158	1.59	0.23 Bond	~60	
Umbriel	$1.17 \cdot 10^{21}$	1,169	1.39	0.10 Bond	~75	
Titania	$3.53 \cdot 10^{21}$	1,577	1.71	0.17 Bond	70	
Oberon	$3.01 \cdot 10^{21}$	1,523	1.63	0.14 Bond	70-80	~0 atm
5145 Pholus	?	185	?	0.046	~62	red
Neptune	$1.02 \cdot 10^{26}$	49,244	1.64	0.29 Bond	72 K @ 1 bar	H_2, He, CH_4
Proteus	$4.4 \cdot 10^{19}$	~420	~1.3	0.096 geom	~51	
Triton	$2.14 \cdot 10^{22}$	2,706	2.06	0.719 geom	38	N_2
Pluto	$1.303 \cdot 10^{22}$	2,377	1.86	0.49 – 0.66 geo	33 – 55	N_2, CH_4, CO
Charon	$1.586 \cdot 10^{21}$	1,212	1.66	0.37 geom	53	
Haumea	$4.0 \cdot 10^{21}$	~1,400	2.6	~0.8	< 50	neutral
Makemake	$<4.4 \cdot 10^{21}$	~1,470	?	0.81	~38	reddish
Eris	$1.66 \cdot 10^{22}$	2326	2.52	0.96	~ 42-55	reddish
Sedna	?	~1,000	?	0.32 geom	~12	red

Sample questions

1. Estimate the expected subsolar surface temperature for the Moon.

2. Verify that Saturn receives ~1% as much sunlight per square meter as Earth does.

3. Mercury's rotation period is 58.65 days. That can be determined observationally by bouncing radar off the surface of Mercury and measuring the frequency difference between the signal returned from the approaching and the receding limbs of Mercury. (In reality there's too little signal returned from right at the limb and we'd have to use signals from longitudes much closer to the disk center, but for purposes of this problem assume you can bounce your radar off the limb.) Suppose you were transmitting your signal at 500 MHz. Ignore Mercury's obliquity; in other words, assume you are hitting the limb at Mercury's equator. What's the frequency difference between the return signals received from the approaching and receding limbs? Hints: Don't forget that both the side of Mercury coming toward you and the side going away are doing so at the equatorial ground speed. Also, when we bounce our radar off a surface it behaves as if there are two actions taking place, hitting the moving surface and reflecting from the moving surface; this will introduce another factor of two into your calculation.

4. Explain briefly
   a) why smooth surfaces are likely to be younger than heavily cratered ones
   b) why objects near the Sun are less likely to have atmospheres than those farther out
   c) why small objects are less likely to have atmospheres than larger ones
   d) the difference between refractory and volatile
   e) what albedo means
   f) what the ecliptic is
   g) the distinction between major and dwarf planets

5. Make a table of the major planets, several dwarf planets, the planet-sized moons, and a few smaller objects you find interesting. Jot down a few properties your found interesting for each object.

For instance, for Uranus you might say: ~20 AU, tilted on its side, boring blue weather;
or for Enceladus you might say: orbits Saturn, icy crust with liquid water underneath, geysers;
or for Io: orbits Jupiter, active volcanoes, SO_2 frost

Answers to selected problems are on the next page:

1. Assuming $A = 0.12$ and the Moon rotates slowly, $T \sim 370$ K.

3. ~ 20 Hz.