CHAPTER 5

Debris

Comets

Comets are balls of dirty ice from the outer solar system that follow elliptical orbits with high eccentricities, so that they are near to the Sun for only a small portion of their lives. As a comet comes near to the Sun at perihelion, the outer layers heat up and turn to gas, causing a coma (halo) and a tail to form. Very close to the Sun, the tail of a comet splits into two pieces, an **ion** or **plasma tail** and a **dust tail**. While both tails point away from the Sun, the dust tail curves ‘‘back’’ along the orbit, while the plasma tail is swept straight away from the Sun by the solar wind. These tails can be as long as 1 AU, making comets the largest objects in the solar system. However, comet tails are extremely diffuse; comet tails are more perfect vacuums than any we can make on Earth. The entire mass of a comet is less than 1 billionth the mass of the Earth.

The **nucleus** of a comet is a few kilometers across, and contains lots of water ice and carbon dioxide ice. This nucleus is surrounded by the **coma**—this is the ‘‘head’’ of the comet. The coma can be over 1 million km across. The coma shines both by reflected sunlight, and by the transitions of excited atoms and molecules in the gas (Fig. 5-1).

Comets can be divided into two types—long-period and short-period comets. This distinction is not quite as arbitrary as it sounds, since there are two different reservoirs for comets in the solar system. The long-period comets come from the **Oort cloud**, a swarm of comets 50,000–100,000 AU from the Sun. These comets have been in the Oort cloud since the solar system formed, and contain material that has remained the same since before the Sun formed. The Oort cloud is approximately spherical in shape, although there is probably a denser region near the plane of the solar system. An ice ball leaves the Oort cloud to become a comet when a star passes nearby (within 3 light years), and changes the ice ball’s orbit. The passage of a star slows the ice ball, so that it no longer has enough energy to maintain its orbit. These objects fall into long elliptical orbits around the Sun. It is rare for such an event to happen; about 10 stars per million years pass

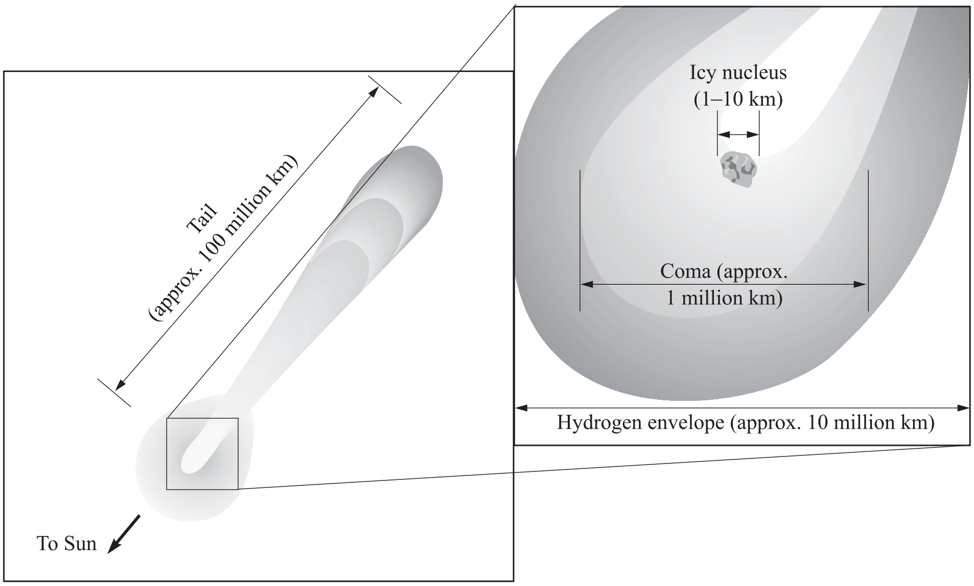

Fig. 5-1. Anatomy of a comet.

close enough to change the orbits in the Oort cloud. Each star may affect several ice balls, however. There are probably trillions of icy balls in the Oort cloud.

Short-period comets have periods less than 200 years, and originate in the Kuiper belt. The Kuiper belt is located just outside the orbit of Neptune, between about 30 and 50 AU from the Sun. These comets are distributed in a flat ring on the ecliptic. Extrapolating from known Kuiper belt objects indicates that there are probably about 70,000 comets in the Kuiper belt larger than 100 km across.

Each time a comet passes near the Sun, it sheds some of its mass, which remains in the orbital path. Eventually, the comet disintegrates entirely, unless, of course, it runs into the Sun, a planet, or receives a gravitational "assist" out of the solar system during one of its orbits.

Solved Problems

5.1. How could you find out how much of a comet's light is reflected, and how much is emitted?

The reflected sunlight will have the same spectrum as the Sun. It will be a blackbody, with Sun-like emission and absorption lines. Other emission lines may be present, and all of these will be from excited molecules and atoms in the comet itself.

5.2. In what part of the orbit can a comet travel with the plasma tail ''in front'? Draw a diagram to explain.

Just after the comet passes the perihelion of its orbit (closest approach to the Sun), the plasma tail will swing around because it always points away from the Sun. It is in this part of the orbit that the plasma tail can lead (Fig. 5-2).

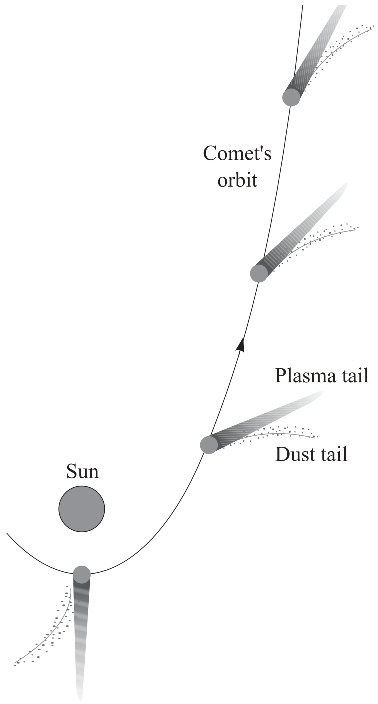

Fig. 5-2. Sometimes the plasma tail is in front of the comet.

5.3. Given that short-period comets come from just outside the orbit of Neptune, (a) how long is the period of a short-period comet? (b) Halley's comet has a period of 76 years. Is it a long- or short-period comet?

(a) If the comet comes from just outside the orbit of Neptune, at 30 AU from the Sun, and comes to within about 1 AU of the Sun, then the semi-major axis is *approximately* 15.5 AU. Using Kepler's third law,

$$P^2 = a^3$$
$$P = \sqrt{15.5^3}$$
$$P = 61 \text{ years}$$

(b) Comets from the Kuiper belt have periods less than 200 years. With a period of 76 years, Halley's comet is definitely a short-period comet.

5.4. From the orientation of an orbit, is it possible to determine whether a comet comes from the Oort cloud or the Kuiper belt?

Sometimes. If the orbit is highly inclined to the ecliptic, so that the comet cannot come from the Kuiper belt, then it is probably a long-period comet from the Oort cloud. However, if the orbit is on the ecliptic, it could have come from either source, and further observations are necessary (of the speed, for example, or the shape of the orbit) to determine the source of the comet.

5.5 Why do the plasma and dust tails usually point in different directions?

The plasma tail extends almost directly away from the Sun, while the dust tail is curved. Usually, the comet is not moving on a path which points directly toward the Sun. This is the only time that the two tails will point in exactly the same direction (Fig. 5-3).

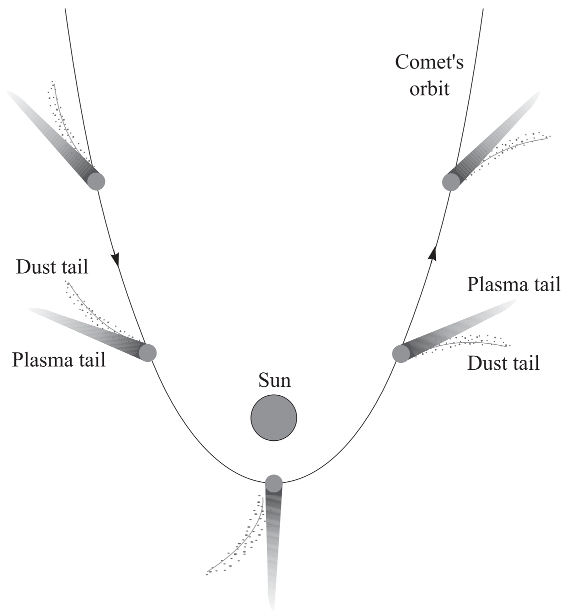

Fig. 5-3. The directions of the two comet tails. Note that far from perihelion, the comet will not have tails.

5.6. Which would hit the Earth at higher velocity: a prograde comet (one that orbits the Sun in the same direction as the Earth) or a retrograde comet (one that orbits oppositely)?

A retrograde comet would impact at higher velocity because the Earth and the comet would be heading towards each other. The prograde comet would be traveling in the same direction, so the relative velocity would be lower than the actual velocity. As an analogy, imagine two cars traveling at 60 mph and at 62 mph. In a head-on collision, the impact velocity is $60 + 62 = 122$ mph. If the faster car hits from behind, then the impact velocity is only 62 – 60 mph or 2 mph.

Meteorites

When a small rock or bit of dust is floating in space, it is a **meteoroid**. As it falls through the atmosphere of the Earth, it produces a bright streak of light, and is called a **meteor**. When it actually makes it to the surface of a planet or moon, we call the rock a **meteorite**. The brightest meteors are called **fireballs**. Sometimes these are as bright as the full moon. **Micrometeorites** are meteorites that are as small as sand grains. These are so small that the atmosphere slows them without heating them, and they drift to the surface of the planet. About 100 tons of micrometeorites accumulate on Earth every day. On the Moon, however, there is no atmosphere, and the micrometeorites are not slowed before they hit the surface. This is the main erosion process on the Moon, and the major contributor to the regolith.

There are three basic types of meteorites: iron, stony, and stony-iron. **Iron** meteorites are the easiest to recognize. They are overly heavy for their size, because they have a high proportion of iron. The so-called Widmanstätten patterns (Fig. 5-4) are observed in polished and etched slices of these meteorites and provide evidence that these meteorites come from planetesimal-sized chunks of rock. The size of the crystals indicates how slowly the rock cooled. If the meteorite was formed at its current size, it would have cooled quickly, and these crystals would not have formed. If the meteorite had formed in a large ($\sim$100 km) object, it would have been under higher pressures, and cooled much more slowly. These patterns imply that the meteorite cooled over millions of years, which is consistent with an object the size of a planetesimal.

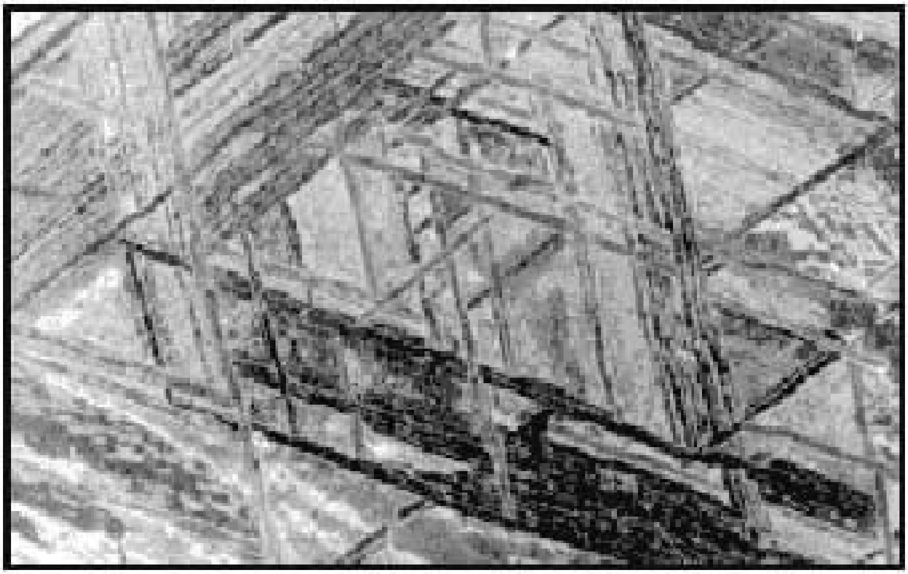

Fig. 5-4. Widmanstätten patterns in an iron meteorite.

Stony meteorites resemble ordinary rocks. Consequently, stony meteorites are much less likely to be found, even though they are much more common than iron meteorites (95% of the meteorites that fall to Earth are stony meteorites). Stony meteorites have about the same density as ordinary rock, and hence are more difficult to find. Most of these stony meteorites are found in places like Antarctica, or the Sahara desert, where there are few ordinary rocks on the surface. Most stony meteorites contain rounded particles imbedded in the rest of the rock (Fig. 5-5). These lumps are called **chondrules** and the entire stony meteorite is then called a **chondrite**. **Carbonaceous chondrites** are a special kind of chondrite that contain high levels of carbon and often contain amino acids, the building blocks of proteins.

Fig. 5-5. A meterorite with chondrules. (Courtesy of New England Meteoritical Services.)

Stony-iron meteorites, a hybrid in which pieces of metal are embedded in ordinary silicate rock, are less than 1% of the total number of meteorites that fall to Earth.

The majority of meteorites probably come from the asteroid belt. Asteroids are large enough to have held the heat of the early solar system for millions of years. This allowed them to differentiate, so that the iron fell to the center, surrounded by a thin stony-iron layer, and enveloped in a thick stone "crust." When two such objects collide, the fragments consist of lots of stony meteoroids, fewer iron meteoroids, and a very small number of stony-iron meteoroids. These fragments spray away from the collision site, and a few of them eventually find their way to planets. Other sources of meteorites are comets, the Moon, and Mars.

Meteor showers are caused by a different phenomenon. As comets disintegrate, they leave behind in their orbits dust and larger debris ranging in size from millimeters to centimeters. Some of the comet orbits intersect the Earth's orbit, so that the Earth passes through them once each year. The infall of the larger debris causes meteor showers, when the dust particles stream through the atmosphere more often than normal. These particles are not large enough, in general, to result in a meteorite. The meteors produced in a meteor shower all appear to come from the same point in the sky. This point is called the **radiant** (because the meteors radiate away from it). The location of the radiant gives the meteor shower its name. For example, the radiant of the Leonids is in the constellation Leo. The radial pattern of the meteors is a product of perspective, because the Earth is passing through the meteoroid swarm. Figure 5-6 shows a time-lapse picture of a meteor shower.

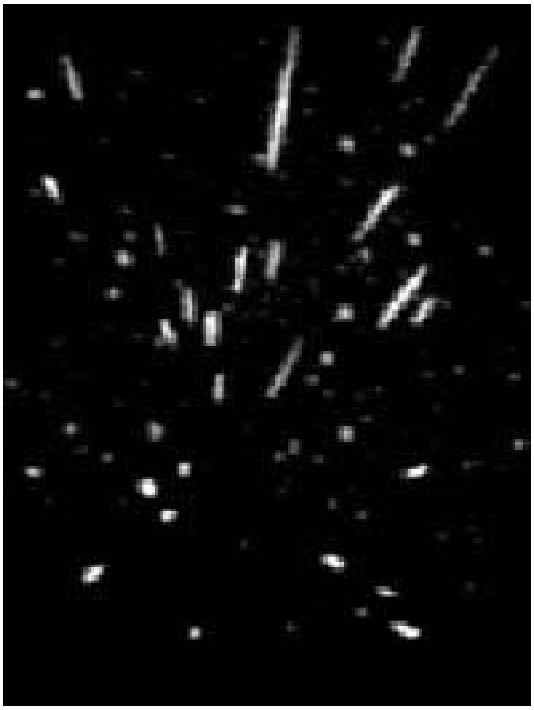

Fig. 5-6. A time-lapse photograph of a meteor shower. (Image courtesy of NASA.)

Solved Problems

5.7. Why do meteorite hunters search for fireballs, but ignore meteor showers?

Meteors in meteor showers are usually produced by small particles that generally burn up in the atmosphere at altitudes of 30–100 km. (The smallest ones produce no bright streak at all.) Fireballs are caused by larger objects, which may not completely burn up in the atmosphere.

The potential for finding a rock at the end of a fireball trail is much higher than the potential for finding a rock at the end of a meteor trail which is part of a meteor shower.

5.8. Why are carbonaceous chondrites fundamentally important to the question of the existence of extraterrestrial life?

Carbonaceous chondrites contain amino acids, commonly known as the building blocks of life. If these amino acids are extraterrestrial in origin, they indicate that there are amino acids in space. This means that life does not need to originate from scratch on every planet or moon independently, but could be assisted from the impact of these meteoroids.

5.9. What is the kinetic energy (KE) of a 1,000 kg rock traveling at 30 km/s? Express your answer in megatons of TNT (the usual unit of measure for nuclear warheads—1 megaton of TNT $= 4 \times 10^9$ joules).

Convert the velocity from 30 km/s to 30,000 m/s. Use the kinetic energy equation

$$\mathrm{KE} = \tfrac{1}{2}mv^2$$
$$\mathrm{KE} = \tfrac{1}{2}(1{,}000)(30{,}000)^2\ \mathrm{kg \cdot m^2/s^2}$$
$$\mathrm{KE} = 9 \times 10^{11}\ \text{joules}$$
$$\mathrm{KE} = \frac{9 \times 10^{11}\ \mathrm{J}}{4 \times 10^9\ \mathrm{J/Mton}}$$
$$\mathrm{KE} = 225\ \text{megatons of TNT}$$

There is equivalent kinetic energy in a rock of this size to a 225-megaton warhead.

5.10. Why are meteor showers predictable?

Meteor showers are caused when the Earth intercepts the dust left behind in the orbit of a comet. Since the Earth is at the same place in its orbit on the same day every year, it intercepts the orbit of a comet on the same day every year.

5.11. Draw a diagram of a differentiated asteroid (Fig. 5-7).

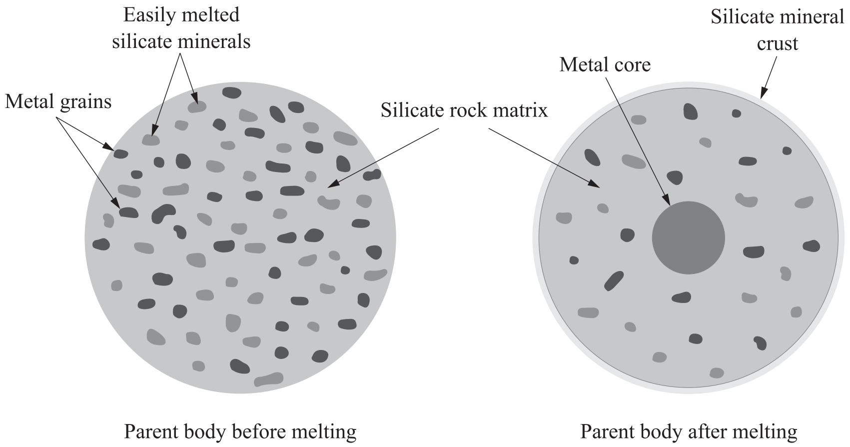

Fig. 5-7. A differentiated asteroid.

5.12. When observations are skewed in favor of objects which are easily observed, this is called a "selection effect." Explain how the distribution of known meteorites is biased by a selection effect.

On Earth, the easiest meteorites to find are the iron meteorites, because they are easily distinguished by their weight. Stony meteorites are more common, but difficult to find because they closely resemble ordinary rocks. Only in places where terrestrial rocks are scarce (Antarctica, the Sahara desert), are stony meteorites easily distinguished from terrestrial rocks. This makes it far more likely that any *identified* meteorite is an iron meteorite, independent of the actual numbers of iron versus stony meteorites that land on the planet.

5.13. Suppose an iron meteorite has no Widmanstätten patterns. What does this indicate about the formation of the meteoroid's parent body?

The presence of Widmanstätten patterns indicates that the parent body cooled very slowly. If there are no Widmanstätten patterns, the parent body of this rock must have cooled quite rapidly—too rapidly for these patterns to form. This in turn implies that the parent body must have been small, so that it gave up its heat quickly.

5.14. The Leonid meteor shower lasts about 2 days. The Earth moves 2.5 million km each day. How thick is the belt of meteoroids that causes the Leonids?

The Earth moves 5 million km in 2 days, so the belt of meteoroids must be 5 million km thick.

Asteroids

There are about 1 million asteroids larger than 1 km in the solar system. The vast majority of these orbit the Sun between Mars and Jupiter. Over 8,000 of these have been individually cataloged and named, and have well-determined orbits. Although it is common to depict the asteroid belt as a dense region, asteroids are actually quite well separated, rarely approaching within 1 million km of one another. (A few asteroids have moons of their own: these are certainly the exception to the rule.) All together, the asteroid belt contains about 0.1% of the mass of the Earth.

The asteroids are not uniformly distributed throughout the asteroid belt. The so-called Kirkwood gaps are regions avoided by asteroid orbits. If an asteroid orbits at a radius such that its period is 1/2, 1/3, 1/4, etc., of Jupiter's period, then after 2, 3, 4, etc., orbits, respectively, the asteroid will meet Jupiter in the same place, and get a gravitational tug towards the same direction in space. Because these tugs are not random, but occur over and over at the same location, the effect adds up, and the asteroid is pulled out of that orbit. This leaves gaps, where few asteroids exist. The asteroids in these gaps are generally in transit, either inward or outward.

In addition to the asteroids in the belt, some asteroids share Jupiter's orbit. Asteroids in this special group are called Trojan asteroids, and they orbit about 60° ahead or behind Jupiter. Their orbits are stabilized by the combined gravity of Jupiter and the Sun. Over 150 of these are known; the largest is about 300 km in size.

Finally, some asteroids are "Earth-crossing" and are potential impactors. These asteroids come from three different groups—the Apollo, Aten, and Amor asteroids. Most of these are small, less than 40 km across, and so they are difficult to find in the sky. About 500 are known. Most of these will strike the Earth some time over the next 20–30 million years. Near-misses are common, and are often unpredicted. In 1990, an asteroid came closer to the Earth than the Moon. The asteroid was previously undiscovered, and was not noticed until after it had safely passed the Earth.

Asteroids do not emit visible light, they only reflect it. Astronomers determine the compositions of asteroids by comparing the spectrum of the light reflected by the asteroid and the spectrum of the Sun. Absorption lines that are present in the asteroid's spectrum, but not in the solar spectrum, must be due to elements or minerals in the asteroid. Asteroids are classified in three major groups: carbonaceous (C), silicate (S), and metallic (M). Most asteroids are C-type asteroids, with very low albedo and no strong absorption lines. The rest are mainly S type, with an absorption feature due to a silicate mineral, olivine.

The amount of light reflected from an asteroid towards the Earth changes as the asteroid tumbles through space. We can use this information to determine how quickly the asteroids rotate. About 500 asteroids have been studied well enough to determine their rotation periods, which are generally between 3 and 30 hours. Smaller asteroids have irregular shapes. The shape of small asteroids can be determined from analysis of the amount of radiation received over time (light curve), which fluctuates with a period equal to the period of the asteroid. More radiation is received when the asteroid is viewed perpendicular to the longest axis than when viewed perpendicular to the shorter axes.

Solved Problems

5.15. Why are comets icy, but asteroids are rocky?

Comets formed in the outer solar system. From the section on solar system formation (Chapter 3), condensation temperatures were lower there, so that ices could form. Asteroids, however, formed in the inner solar system, where condensation temperatures were higher, keeping ices from forming.

5.16. Suppose that the Earth-crossing asteroids are evenly distributed, so that the impact rate is constant. How many years will pass, on average, between two impacts?

There are 500 Earth-crossing asteroids, all of which will impact in the next (approximately) 25 million years. This means that there are about

$$\frac{25 \times 10^6}{500} = 50{,}000$$

years between collisions.

5.17. Figure 5-8 shows a "light-curve" of an asteroid (a graph of the amount of light from the asteroid versus time). Label the portion of the curve where the longest axis is perpendicular to the line of sight. Label the portion of the curve where the shortest axis is perpendicular to the line of sight. What is the period of this asteroid?

The time between long-axis peaks is 705.75 − 705.55 days, or about 0.2 days. This is equivalent to 4.8 hours, but is only half of the period. So the period is about 9.6 hours.

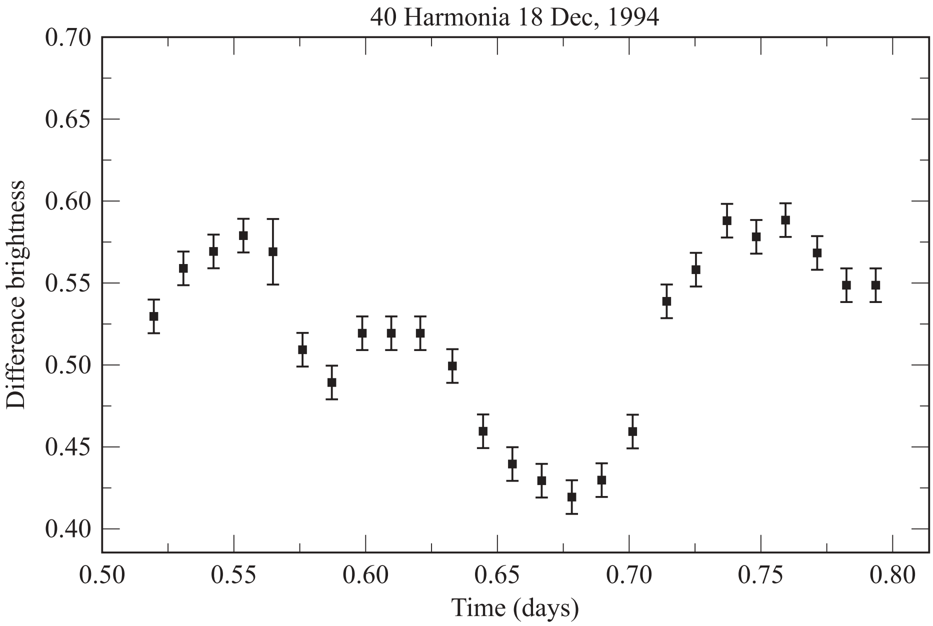

Fig. 5-8. Light curve of 40 Harmonia, an asteroid.

5.18. Sketch the distribution of asteroids in the solar system (Fig. 5-9).

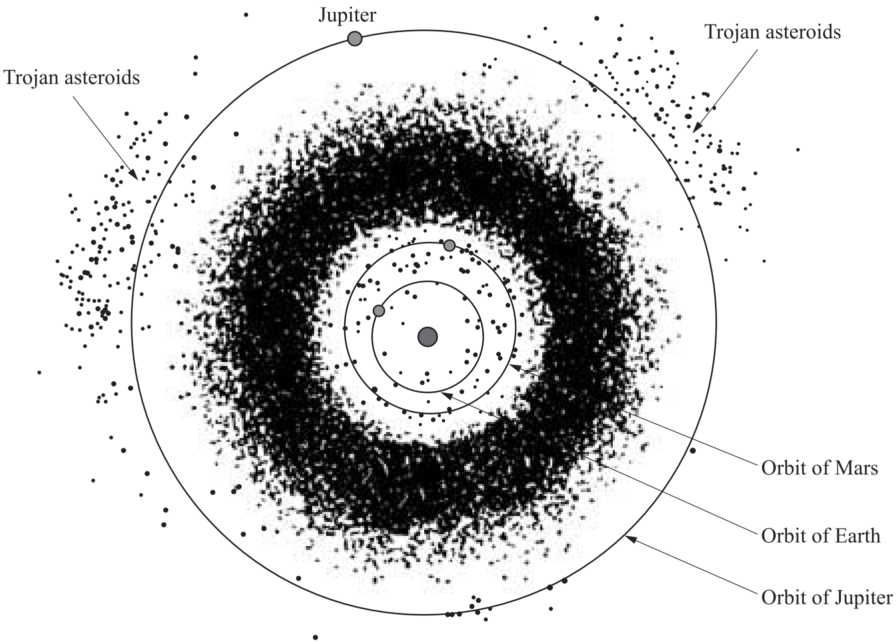

Fig. 5-9. The distribution of asteroids in the solar system.

5.19. Classify the following four spectra of asteroids into C type or S type (Fig. 5-10). How can you tell which are which?

C-type asteroids have no strong absorption lines. Asteroids A, C, and D are C-type asteroids, whereas asteroid B is an S-type asteroid because it does have a strong absorption line.

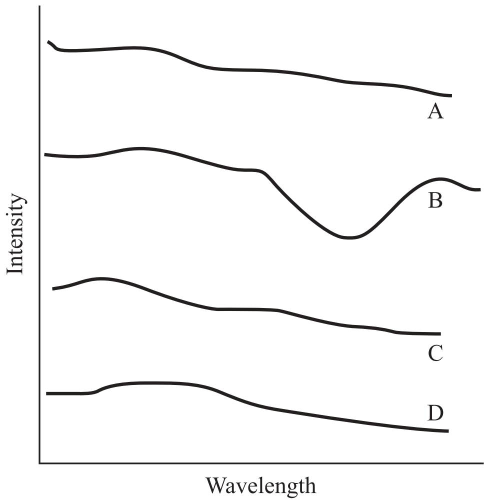

Fig. 5-10. Four spectra of asteroids—three C type and one S type.

Pluto and Charon

Pluto is the smallest of the planets and fits neither the Jovian nor the terrestrial class. Pluto's orbit is highly inclined, about 17°, to the ecliptic, and has the most eccentric orbit of all the solar system planets. At its farthest, Pluto is 49.3 AU from the Sun; at its closest, 29.7 AU, it actually crosses inside the orbit of Neptune. This has led astronomers to believe that perhaps Pluto was an escaped Neptunian moon. Pluto's density is consistent with a composition of rock and ice. The thin atmosphere consists of nitrogen, with some carbon monoxide and methane. The surface temperature is about 40 K.

Pluto has a satellite, Charon, discovered in 1978. The tidal interaction between the two objects completely synchronized the motion of the pair, so that the two objects always show the same side to each other. One day on Pluto equals 1 day on Charon equals 1 synodic period. Astronomers now believe that both Pluto and Charon are Kuiper belt objects that were gravitationally perturbed (probably by Neptune), and drifted to the domain of the planets. Figure 5-11 shows Pluto and Charon superimposed on a map of the Earth in scale. The orbital and physical properties of Pluto and Charon are listed in Table 5-1.

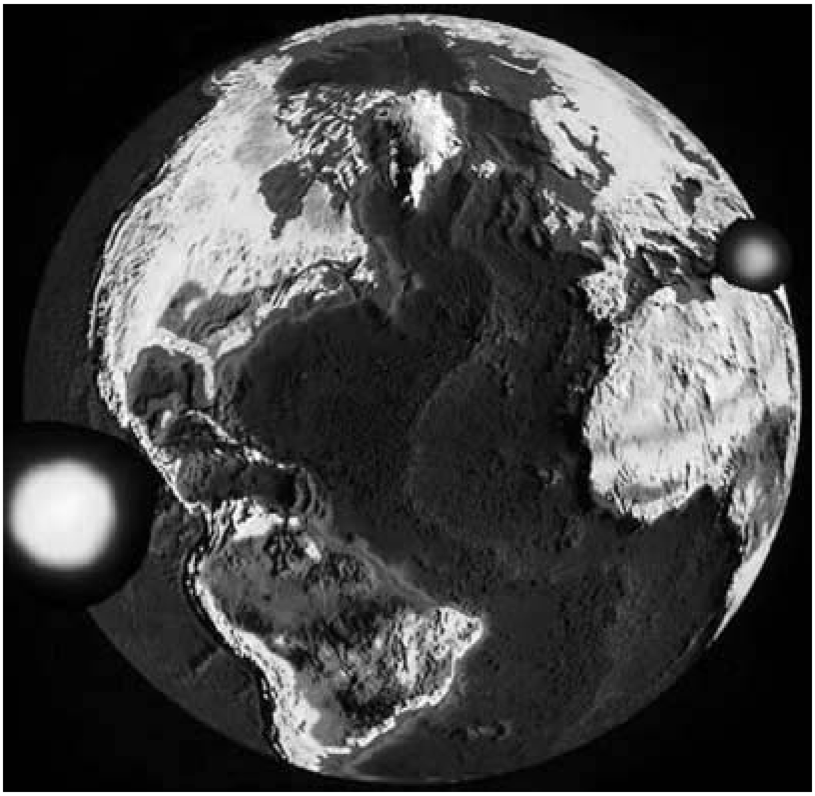

Fig. 5-11. Pluto and Charon superimposed on a map of the Earth. (Composite of NASA/STScI images.)

Table 5-1. Orbital and physical properties of Pluto and Charon

Property	Pluto	Charon
Mass (kg)	1.26×10^{22}	1.7×10^{21}
Radius (km)	1,150	~ 600
Mean orbit radius (km)	5.91×10^{9}	19.6×10^{3} (from Pluto)
Orbital period	249 years	6.4 days
Orbital inclination	17	
Orbital eccentricity	0.25	
Rotation periods (days)	6.4	6.4
Tilt of axis	122.5	

Solved Problems

5.20. Explain how the inclination of Pluto's orbit makes it impossible for Pluto to collide with Neptune, even though the orbits cross.

There are two reasons for this. First, the plots of orbits as usually shown are only two-dimensional. The statement that they intersect, or cross, is misleading. The orbits cross at a location when Pluto is far above the plane of the solar system. This makes it impossible for Pluto and Neptune to ever collide. In addition, Pluto and Neptune are in resonance, much like the Trojan asteroids, so that they remain always separated by the same amount at the same points in their orbits. They will always repeat the same pattern while orbiting the Sun, which does not include a collision.

5.21. What is Pluto's orbital period?

Pluto's major axis is $50 + 30 = 80\,\mathrm{AU}$. The semi-major axis, then, is about $40\,\mathrm{AU}$. Since Pluto orbits the Sun, we can use Kepler's third law,

$$
\begin{aligned}
P^2 &= a^3 \\
P &= \sqrt{a^3} \\
P &= \sqrt{(40)^3} \\
P &= 253\ \text{years.}
\end{aligned}
$$

The accepted orbital period of Pluto is 249 years. The 4-year discrepancy is largely due to the rounding in the distance from the Sun to Pluto at perihelion and aphelion, which each have only one significant digit.

5.22. Draw a sketch of Pluto and Charon at several times over one Plutonian day (Fig. 5-12). Be sure to identify particular locations on each body, so that the rotations are clear.

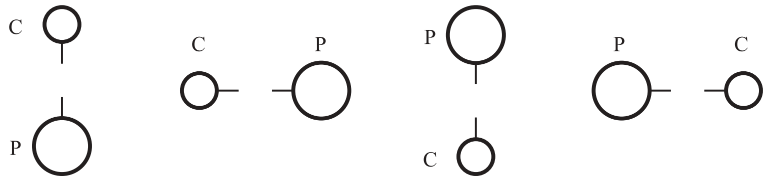

Fig. 5-12. Pluto and Charon over one Plutonian day.

Supplementary Problems

5.23. How long is the period of an average long-period comet?

Ans. 11 million years

5.24. Are the meteoroids in this year's Leonid shower located close (in space) to the ones from last year's meteor shower?

Ans. No, because the particles are orbiting too

5.25. Suppose a really spectacular comet approaches the Earth, with a coma of 1.5 million km in diameter. At closest approach, it is 0.9 AU from the Earth. What is the angular size of the coma?

Ans. 0.6°

5.26. Suppose this same spectacular comet has a tail 1.3 AU long. What is the angular length of the tail?

Ans. 83°, nearly halfway across the visible sky

5.27. What is the angular size of a 1-km diameter asteroid in the asteroid belt (at 3 AU)?

Ans. $5 \times 10^{-4}{}''$

5.28. The peak blackbody temperature of an asteroid is in the infrared. Why are they usually observed in the visible?

Ans. Because the majority of the light from an asteroid is reflected sunlight

5.29. The mass of Pluto is 0.0020 times the mass of the Earth. What is the mass of Pluto in kg?

Ans. 1.19×10^{22} kg

5.30. Charon orbits Pluto at a distance of 19,600 km. In Fig. 5-11, are Pluto and Charon shown at their greatest separation?

Ans. No

5.31. What is the orbital period of Charon (Charon's mass is 1.7×10^{21} kg)?

Ans. 6.47 days

5.32. What percentage of the asteroids larger than 1 km have been cataloged?

Ans. Approximately 1%

CHAPTER 6

The Interstellar Medium and Star Formation

The Interstellar Medium

The interstellar medium (ISM) is the dust and gas between the stars. The interstellar medium is seen as the dark dust lanes in the Milky Way (or in other galaxies), or by its effects on starlight: reddening and extinction. It is also observed more directly as reflection or emission nebulae.

Approximately 20% of the Galaxy's mass is ISM. The ISM absorbs visible light, but at the same time emits radio waves or infrared radiation. So, while we can't make an accurate map of the distant Galaxy in visible light, we can see distant pockets of interstellar dust and gas quite easily.

Ninety-nine percent of the ISM is gas, and only 1% of the mass is dust. Even in the nebulae, which have fairly high densities (Table 6-1), the density is lower than in the best vacuums that we can achieve in a laboratory.

GIANT MOLECULAR CLOUDS

Much of the mass in the interstellar medium is grouped into clumps called giant molecular clouds. These clumps are denser than the surrounding medium, and cool enough that they can contain molecular hydrogen (and trace amounts of other molecules). A typical giant molecular cloud is about 10 pc across, and contains about 1×10^6 solar masses. There are thousands of giant molecular clouds in the Milky Way Galaxy. The closest one is the Orion Nebula, shown in Fig. 6-1. The Orion Nebula is 450 pc away.

Table 6-1. Properties of components of the interstellar medium. Values are approximate, and are meant to be used only as a guide

Type of nebula	Density (g/cm^3)	Temperature (K)	Typical lifetime (yrs)	Typical size (pc)	Composition
HII region	10^{-25}–10^{-17}	10,000	10 million	few–100	Mostly hydrogen gas
Giant molecular cloud: cool clumps	10^{-20}–10^{-18}	10	Billions	0.1	Hydrogen, molecular gas, dust
Giant molecular cloud: hot clumps	10^{-25}–10^{-17}	30–100	Millions	0.1–3	Hydrogen, molecular gas
Reflection nebulae	10^{-25}–10^{-17}	$< 1{,}000$	Millions–billions	< 1–10	Dusty gas
Emission nebulae	10^{-25}–10^{-17}	1,000–10,000	Few thousand–100,000	0.01–a few	Atomic and molecular gas
Dark nebulae	10^{-25}–10^{-17}	$< 1{,}000$	Millions–billions	< 1–10	Dusty gas
Diffuse interstellar gas	10^{-27}	7,000–10,000	Not applicable	Not applicable	Hydrogen

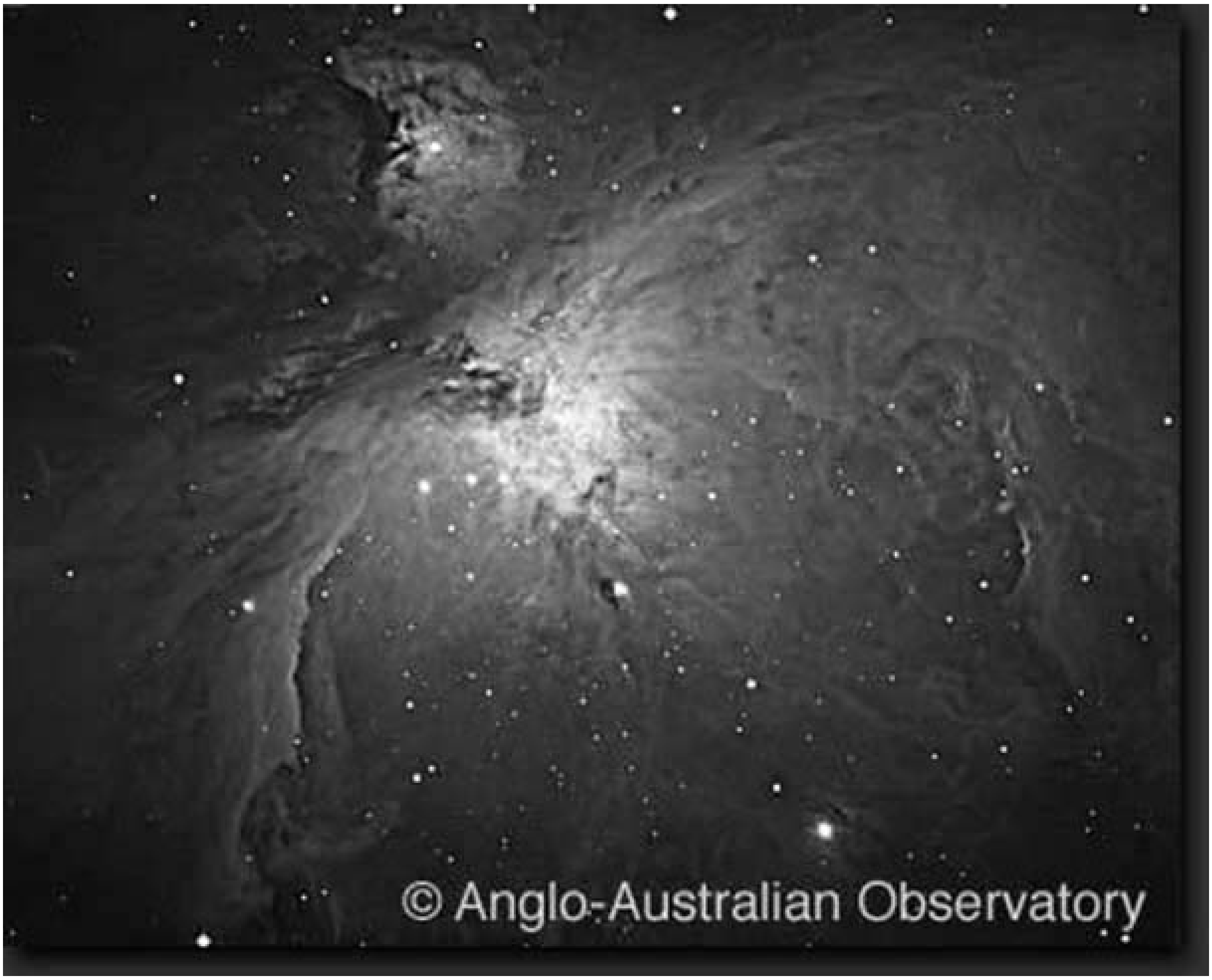

Fig. 6-1. The Orion Nebula in visible light. (Courtesy of the Anglo-Australian Observatory.)

INTERSTELLAR GAS

HII regions. These are usually parts of giant molecular clouds: specifically, the parts surrounding hot, young stars, such as O or B types (see Chapter 7). O and B stars emit UV light, which ionizes the hydrogen in the nebula. When the electrons recombine with the protons to form hydrogen, they emit photons at wavelengths characteristic of the hydrogen spectrum. The red color of HII regions is due to the 656 nm spectral line of hydrogen.

HII regions can be enormous, particularly if there is more than one O star producing UV radiation in the neighborhood. The O stars are massive, but have very short lifetimes. Consequently, the HII regions only exist for about 10 million years; when the O star exhausts its fuel, the HII region no longer has a source of ionizing photons and fades away.

Diffuse interstellar gas. The diffuse interstellar gas occupies the regions between the nebulae. It is extremely low density (therefore "diffuse"). Diffuse interstellar gas was discovered by observing the spectra of a binary star system. Astronomer J. Hartmann observed that there were really two sets of spectral lines from the binary (one from each star, see Problem 6.8), which shifted back and forth as the stars orbited each other. In addition to the shifting lines, there were spectral lines that did not shift. The fixed lines were narrow and were identified as lines of calcium in the intervening medium. Many other atoms have been found in the interstellar medium since the discovery of calcium.

In particular, neutral hydrogen has been identified by observing the 21 cm line. The 21 cm line results from a spin transition of the electron in the hydrogen atom. The electron and the proton each have a property known as the spin. When the spins of the two particles are parallel, they have more energy than when the spins are anti-parallel. The energy difference is very small, so that the photon emitted when the electron flips its spin is very low energy. That means that it has a long wavelength, 21 cm, and is observable as a radio wave.

Molecules have also been detected in the diffuse interstellar gas. The first molecules discovered were CH, CN, and CN^+, followed by H_2O (water) and NH_3 (ammonia). Currently, there are more than 80 known molecules in the diffuse interstellar gas, making up 0.002% of the interstellar gas. Some of these molecules are very complex, and contain as many as 16 atoms. Even amino acids have been found. Molecules are fragile, and are easily destroyed by UV radiation. For the most part, molecules only survive inside clouds, where they are protected by dust particles.

INTERSTELLAR DUST

There are three ways to detect the interstellar dust: infrared radiation from the warmed particles, extinction of visible light (dark patches), or reflection nebulae.

1. Dust is warmed by UV radiation, and therefore emits a blackbody spectrum that peaks in the infrared. Figure 6-2 shows the Milky Way Galaxy in the optical and the infrared. Dust emits in the infrared but blocks visible light. Therefore, the infrared image is bright whereas the optical image is dark, and vice versa.

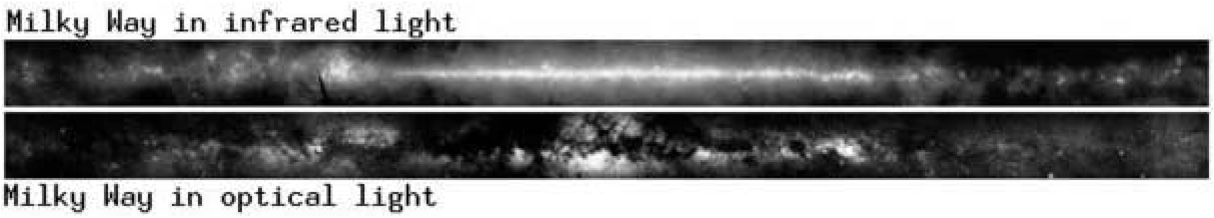

Fig. 6-2. Milky Way in optical and infrared light. (Courtesy of NASA.)

2. Dark nebulae: the dark patches in the Milky Way and dark clouds observed in other places (such as the Horsehead nebula). These dark nebulae are often called dust clouds even though they consist mostly of gas. These clouds range in size from less than 1 pc to more than 10 pc. Most nebulae absorb 75% of the starlight from background stars—a few absorb more, nearly 95% in some cases.
3. Reflection nebulae: these shine by scattered starlight, in much the same way that the blue sky shines by scattered sunlight. These nebulae are always bluish in color, and so are easily distinguished from HII regions that are always reddish in color. The line spectrum of these nebulae resembles the spectrum of the stars whose light they scatter.

Diffuse interstellar dust. Analogous to the diffuse interstellar gas is the diffuse interstellar dust. This dust is difficult to detect, and can only be found by looking at very distant clusters and comparing them to nearby clusters. The distant clusters will appear redder and fainter than they should at their distances. This is the result of two phenomena caused by the diffuse interstellar dust: extinction and reddening.

Extinction. On average, the diffuse interstellar dust dims starlight by one magnitude (= 2.51 times) per 1,000 pc in the plane of the Milky Way.

From a star at a distance of	Percent of light lost due to extinction
1,000 pc	60
2,000 pc	84
5,000 pc	99
10,000 pc	99.99

The Milky Way is about 60,000 pc across, so most of the starlight from distant stars has been extincted before reaching the Earth. This extinction is caused by both scattering and absorption. Determining which effect is more important is impossible without a detailed knowledge of both the composition and the size of the dust grains. As most of the interstellar dust is in the plane of the Milky Way, we can only see the galaxies that are "above" or "below" the Milky Way. On average, the Milky Way is about 2,000 pc thick.

Reddening. Dust scatters blue light more effectively than red light. As a result stars appear redder than they would if there were no dust in the line of sight. From a distance of 3,000 pc through the disk, only 2.5% of the blue light will reach us, whereas 6% of the red light will get through. The scattering efficiency decreases with decreasing frequency of light. This means that we can see deeply into the Milky Way using radio waves or infrared radiation, but not in ultraviolet radiation.

Solved Problems

6.1. What is the peak wavelength of the emission from cool (100 K) dust?

Recall Wien's law from Chapter 1, which relates the peak wavelength and the temperature:

$$\lambda_{\max} = \frac{k}{T}$$
$$\lambda_{\max} = \frac{2.9 \times 10^{-3}\ \mathrm{m \cdot K}}{100\ \mathrm{K}}$$
$$\lambda_{\max} = 2.9 \times 10^{-5}\ \mathrm{m}$$

The peak wavelength of 100 K dust is about 30×10^{-6} m, or 30 microns. This is in the infrared part of the spectrum.

6.2. How do astronomers determine the chemistry of a cool dust cloud?

As in many other applications, astronomers determine the presence of atoms and molecules in dust clouds from their emission and absorption lines. Most of the molecular lines that it is possible to observe occur in the infrared, millimeter, or radio wavelengths. Astronomers observe dust clouds with these types of telescopes, and compare the lines observed with lines formed in laboratory experiments.

6.3. What limits the age of an HII region?

HII emission is produced by gas which has been excited by UV photons. For this gas to be excited, there must be stars in the vicinity which are also producing lots of UV photons. These stars are in general of the O and B type, and so are massive and have short lifetimes. Once these stars end their lives (in about 10 million years), the HII region fades, and becomes non-luminous.

6.4. Describe the difference between reddening and extinction.

Interstellar dust absorbs and scatters starlight, dimming it. This is called extinction. Reddening depends on wavelength. Blue wavelengths are removed by scattering more than red wavelengths. This makes objects appear redder than they would if there were no dust in the way.

6.5. Figure 6-3 shows a spectrum of a dust cloud around a star. How hot is it?

The peak of the blackbody emission in this figure occurs at approximately 25 microns (25×10^{-6} m). Using Wien's law,

$$\lambda_{\max} = \frac{k}{T}$$

or

$$T = \frac{k}{\lambda_{\max}}$$
$$T = \frac{0.0029\ \mathrm{m \cdot K}}{25 \times 10^{-6}\ \mathrm{m}}$$
$$T = 120\ \mathrm{K}$$

The dust cloud is 120 K.

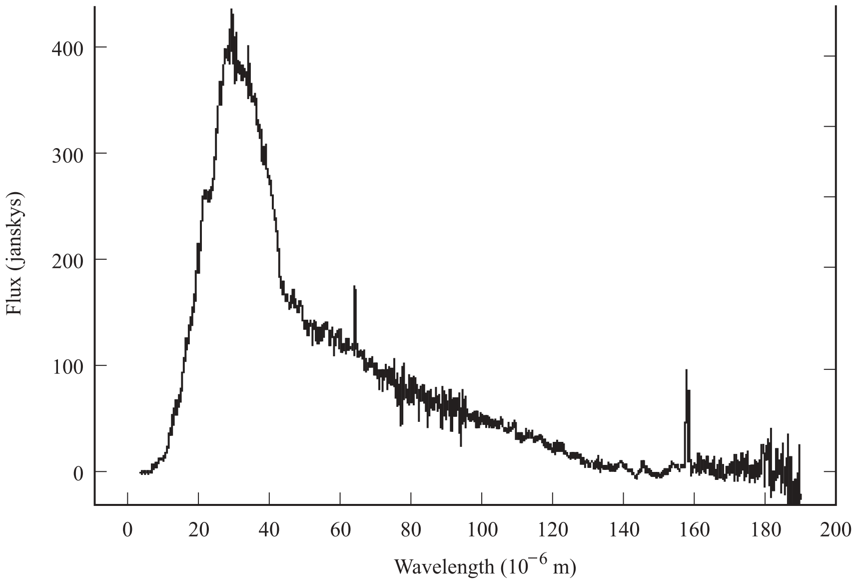

Fig. 6-3. A spectrum of circumstellar dust cloud.

6.6. How can you determine the difference between an emission and a reflection nebula?

There are two ways to determine the difference between an emission and a reflection nebula. The first method is to simply look at the color of the nebula. Since nebulae are made primarily of hydrogen, which has red emission lines, emission nebulae tend to be red. Reflection nebulae, however, shine by scattering starlight, and will be the color of the stars nearest them, usually much bluer than the emission nebulae. The second method is to look more closely at the spectra of the objects. A few sharp emission lines will dominate spectra of emission nebulae, while, in general, spectra of reflection nebulae look like the spectra of the stars whose light they are scattering.

6.7. What fraction of the Galaxy's mass is interstellar dust?

The interstellar medium is approximately 20% of the Galactic mass. Only 1% of this is dust. Therefore, $0.01 \cdot 0.2 = 0.002$ or 0.2% of the Galaxy's mass is interstellar dust. This is an extremely small component, yet it dominates our ability to see through the disk of the Galaxy.

6.8. Figure 6-4 shows several spectra of a binary star system. Label each line A, B, or C, depending on whether it came from star A, star B, or the interstellar medium.

6.9. How many solar-type stars could be made from a giant molecular cloud of diameter $D = 10\,\text{pc}$ and density $\rho = 1.6 \times 10^{-17}\,\text{kg/m}^3$? Assume the cloud is spherical, and about half of it is used to form stars.

The volume of the giant molecular cloud is

$$V = \frac{4}{3} \cdot \pi \cdot \mathrm{R}^3$$

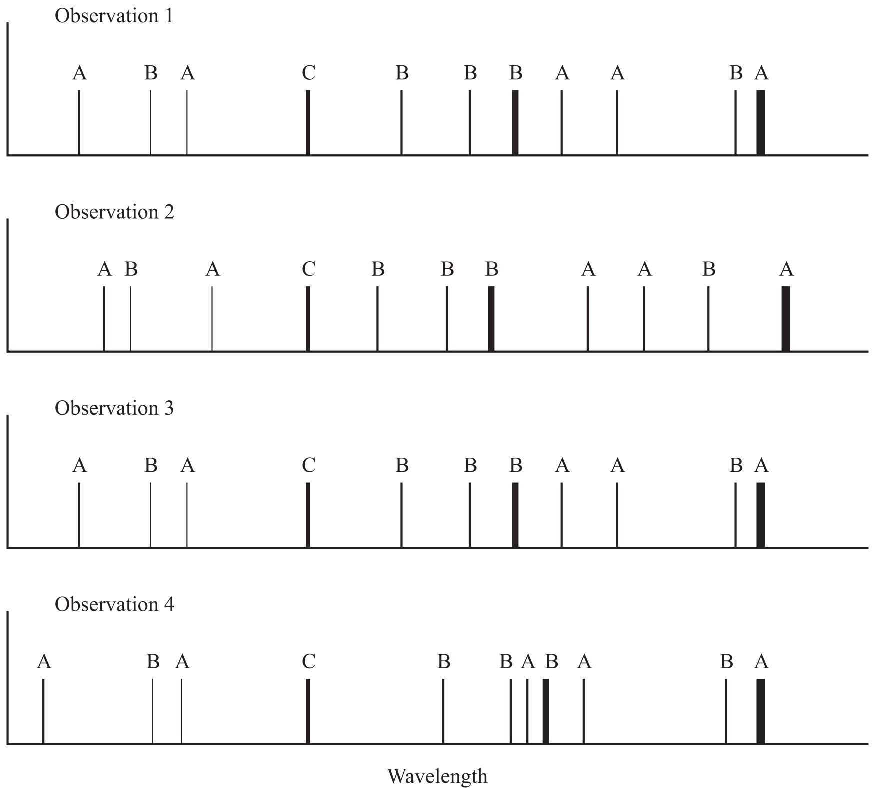

Fig. 6-4. Spectra of a binary star system, including interstellar lines, over several years.

The mass of the giant molecular cloud is found by multiplying the density by the volume,

$$M = \rho \cdot V$$

If only half of this mass forms stars, then we must divide by two to find the mass of all the stars formed. Substituting the first equation into the second gives

$$M = \frac{1}{2} \cdot \rho \cdot \frac{4}{3} \cdot \pi \cdot \left(\frac{D}{2}\right)^3$$

$$M = \frac{2 \cdot \pi}{3 \cdot 2^3} \cdot \rho \cdot D^3$$

$$M = 0.26 \cdot 1.6 \times 10^{-17}\,\text{kg/m}^3(10\,\text{pc})^3$$

$$M = 4.2 \times 10^{-15}\,\text{kg/m}^3 \cdot \text{pc}^3$$

$$M = 4.2 \times 10^{-15}\,\text{kg/m}^3 \cdot \left(\text{pc} \cdot \frac{3.08 \times 10^{16}\text{m}}{\text{pc}}\right)^3$$

$$M = 4.2 \times 10^{-15} \cdot (3.08 \times 10^{16})^3\,\text{kg}$$

$$M = 1.2 \times 10^{35}\,\text{kg}$$

To find out how many solar mass stars could be produced, divide by the mass of the Sun (2×10^{30} kg) to find $M = 61{,}000\,M_{\text{Sun}}$. About 60,000 stars with the same mass as the Sun could be formed from this average-sized molecular cloud.

6.10. What is the difference in energy of the two spin states of the hydrogen atom?

Recall from Chapter 1 that the energy of a photon is given by

$$E = hf$$

and that the relationship between wavelength and frequency is

$$f = \frac{c}{\lambda}$$

Substituting the second equation into the first, and knowing that the wavelength of the photon is 21 cm gives an energy of

$$E = \frac{hc}{\lambda}$$
$$E = \frac{6.626 \times 10^{-34}\,\mathrm{W \cdot s^2} \cdot 3 \times 10^8\,\mathrm{m/s}}{0.21\,\mathrm{m}}$$
$$E = 9.4 \times 10^{-25}\,\mathrm{W \cdot s}$$
$$E = 9.4 \times 10^{-25}\,\text{joules}$$

This is about 0.5×10^6 times smaller than the energy difference corresponding to the emission of visible light.

6.11. A radio spectrum of an interstellar cloud shows the 21 cm line shifted to 21.007 cm. Is the cloud approaching, receding, or remaining at the same distance from us? If it is traveling, what is its speed?

Because the wavelength increases, the emission is red-shifted, so the cloud must be moving away from us. To find its radial velocity, use the Doppler equation

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$$
$$v = \frac{\Delta\lambda}{\lambda} \cdot c$$
$$v = \frac{(21.007 - 21)}{21} \cdot 3 \times 10^8\,\mathrm{m/s}$$
$$v = 100{,}000\,\mathrm{m/s}$$
$$v = 100\,\mathrm{km/s}$$

The cloud is moving away from us at 100 km/s.

6.12. Suppose that a cool clump of a giant molecular cloud has a size of 0.1 pc. Given the density range from Table 6-1, what is the possible range of masses contained in this clump?

The mass in a clump is given by the density times the volume,

$$M = \rho \cdot V$$
$$M = \rho \cdot \frac{4}{3}\pi \cdot R^3$$
$$M = \frac{4}{3}\pi \cdot 10^{-20}\,\frac{\mathrm{g}}{\mathrm{cm}^3}(0.05\,\mathrm{pc})^3$$
$$M = 5.2 \times 10^{-24}\,\frac{\mathrm{g} \cdot \mathrm{pc}^3}{\mathrm{cm}^3}$$
$$M = 5.2 \times 10^{-24}\,\mathrm{g} \cdot \left(\frac{\mathrm{pc}}{\mathrm{cm}} \cdot \frac{3 \times 10^{18}\,\mathrm{cm}}{\mathrm{pc}}\right)^3$$
$$M = 5.2 \times 10^{-24} \cdot (3 \times 10^{18})^3\,\mathrm{g}$$
$$M = 1.4 \times 10^{32}\,\mathrm{g}$$
$$M = 0.1 \times 10^{30}\,\mathrm{kg}$$
$$M = 0.1 \text{ solar masses.}$$

The mass in a low-density clump of this size is 0.1 solar masses, not enough to form a star.

If the clump has the maximum density for a cool clump, the density increases by a factor of 100, but all else stays the same, so that the mass is

$$M = 100 \cdot (\text{cool clump mass})$$
$$M = 100 \cdot 0.1 \text{ solar masses}$$
$$M = 10 \text{ solar masses}$$

Therefore, the mass in a high-density clump could form approximately 10 solar systems, even though it is about the same volume as the low-density clump which could not form any solar mass systems.

6.13. What are the temperatures, in degrees Fahrenheit, of cool and warm clumps of giant molecular clouds? Do non-astronomers usually call these temperatures "cool" and "warm"?

To convert from degrees Kelvin to degrees Celsius, subtract 273.

Cool clumps: -263°C

Warm clumps: (-243) to (-173)°C

To convert from degrees Celsius to degrees Fahrenheit, multiply by 9/5, and add 32: Cool clumps:

$$T(^\circ\mathrm{F}) = T(^\circ\mathrm{C}) \cdot 9/5 + 32$$
$$T(^\circ\mathrm{F}) = -263 \cdot 9/5 + 32$$
$$T(^\circ\mathrm{F}) = -441$$

Warm clumps:

$$T(^\circ\mathrm{F}) = T(^\circ\mathrm{C}) \cdot 9/5 + 32$$

for warmer warm clumps,

$$T(^\circ\mathrm{F}) = -173 \cdot 9/5 + 32$$
$$T(^\circ\mathrm{F}) = -279$$

for cooler warm clumps,

$$T(^\circ\mathrm{F}) = -243 \cdot 9/5 + 32$$
$$T(^\circ\mathrm{F}) = -405$$

These are all very cold.

Star Formation

Clumps in giant molecular clouds are often sources of intense infrared radiation, the product of heated dust. If the cloud is collapsing, the dust heats up because as the dust falls in towards the center, the potential energy is released as heat. This idea of big, warm, collapsing clouds is at the center of star formation theory.

The mechanism that triggers the collapse into clumps is not well understood. Two mechanisms are commonly proposed. The first is that the cloud is simply turbulent to begin with, with some clumps and some thin parts, and then gravitational attraction and collisions make the clumps grow. The second is that winds from a supernova in the vicinity sweep up dust and gas, causing denser regions to form. Again, gravity does the majority of the work in making these clumps collapse.

For a clump to collapse, it must be large enough and dense enough so that the average velocity of a particle is less than the escape velocity.

Under the influence of gravity alone, clumps should take approximately 100,000 years to collapse. But we know from star counts that it must take much longer for stars to form; otherwise, there would be many more of them. The galactic magnetic field, which threads the cloud, slows the collapse. Charged particles, such as protons, have a very hard time crossing magnetic field lines. When a charged particle interacts with a magnetic field line, it begins to orbit the line, and can travel easily *along* the field line, but not *across* it (Fig. 6-5). Neutral particles (like neutrons) do not have this problem, and can cross the field lines to gather in the center of the clump. After a few million years, the gravitational force due to the neutral particles in the center overwhelms the magnetic field's resistance, and mass accumulates rapidly in the core. From this point to the formation of an actual star is only 100,000 years.

A **protostar** is a clump of a giant molecular cloud that is collapsing rapidly, but has not yet formed a star. Protostar is the stage from shortly before the gravity overcomes the magnetic field to the time that the star ignites. Recently, astronomers have been able to acquire direct images of some of these objects with the Hubble Space Telescope (Fig. 6-6). Several things happen during the protostar stage.

1. **Material falls onto the protostar**. As the material falls onto the star, it becomes denser and therefore more opaque. As objects become denser and more opaque, energy/photons require longer time to escape. As a result, the temperature of the protostar begins to rise rapidly.
2. **A disk forms**. Rotation causes the cloud to flatten as it collapses. Also, because of conservation of angular momentum, the rotational speed of the disk increases as the material spirals inward. These disks are made of warm dust that emits in the infrared.

   Friction in the disk causes the material of the inner part of the disk to spiral in and the material in the outer part of the disk to spiral out. These disks will eventually disappear because of:

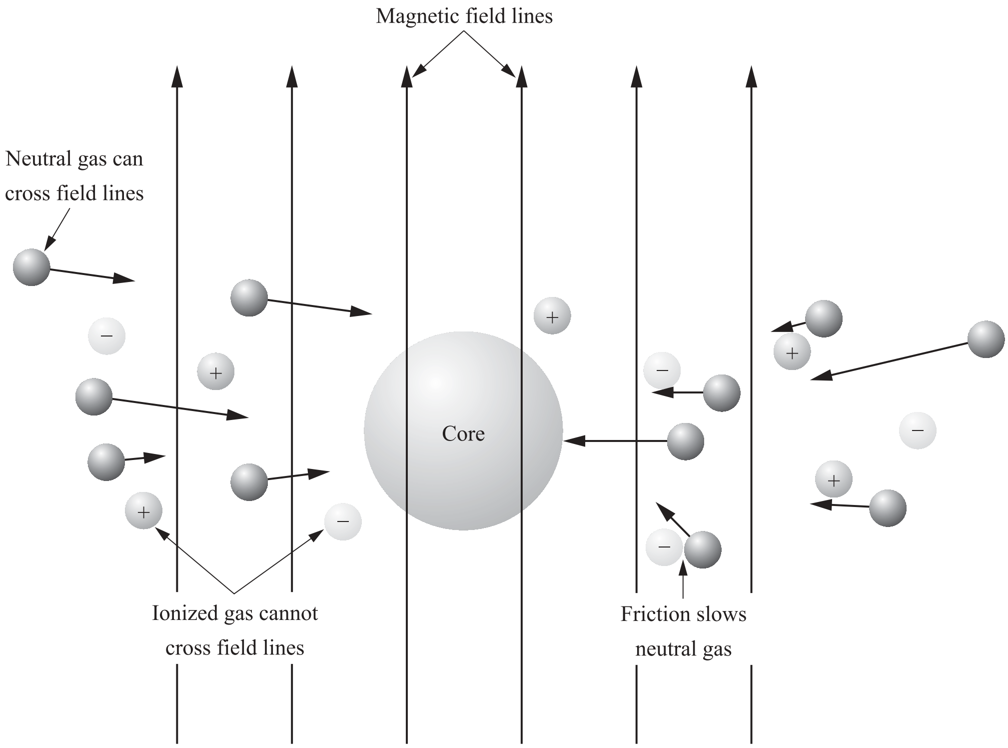

Fig. 6-5. Charged particles cannot cross magnetic field lines easily.

(a) evaporation by a nearby object—if a bright star is nearby, it can evaporate the materials of the disk, and disperse it back to the interstellar medium;

(b) wind dispersal—once the wind from the central star begins, it can transfer momentum to the disk particles, and disperse them back to the interstellar medium (see point 4 below); and

(c) planet formation—planets may form from the disk; see Chapter 3 for more details on planet formation.

3. **Temperature and pressure increase**. Once the protostar becomes opaque, it can no longer radiate away the energy produced by the infalling material. This energy is trapped inside the protostar, and causes the temperature to rise. As the mass falls inward, the density increases. From the ideal gas law (Chapter 1), the result is an increase in the pressure. The pressure increase in the interior slows, but does not quite stop the collapse.
4. **A wind develops**. Astronomers are not quite sure why, but at this stage in the evolution, the protostar begins pushing mass away. This stops the infall of more mass. The winds produced are very massive, about 10^{-7} solar masses per year, and carry with them not only energy and mass but also angular momentum. If the Sun were losing mass this quickly, it

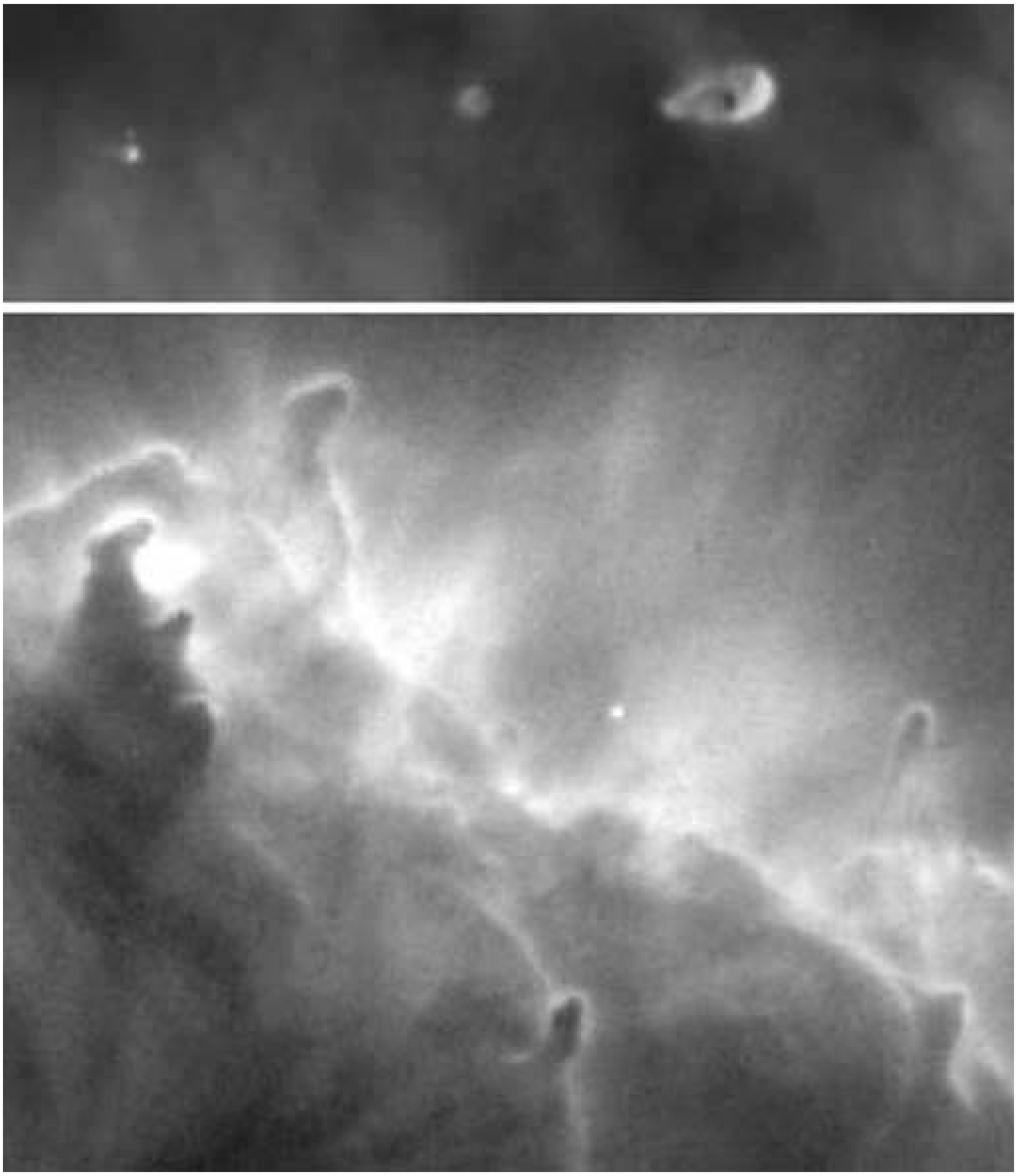

Fig. 6-6. An image of protostars in the Orion Nebula and in the Eagle Nebula. (Courtesy of STScI.)

would lose all of its mass in only 10 million years—an astronomically short period of time.

5. **Pressure and temperature increase further**. The pressure and the temperature continue to rise in the central portion of the protostar. Eventually hydrogen fusion begins, and the protostar moves onto the main sequence, and is finally a star.

Solved Problems

6.14. How do astronomers know that stars are formed in giant molecular clouds?

There are three key pieces of evidence that stars are formed in giant molecular clouds. First, these clouds are often the source of significant infrared radiation, implying that there are hot, bright stars shrouded by dust deep within the cloud. Secondly, astronomers often observe young stars very near to giant molecular clouds (i.e., in the center of HII regions). Since the stars are young, they have not yet had time to move far from where they formed, and so probably formed in the molecular cloud. Thirdly, the Hubble Space Telescope pictures of giant molecular clouds yield direct evidence for the presence of protostars, collapsing clouds, and evaporating gaseous globules (EGGs), which are dense star-forming pockets being excavated by brisk winds from hot young stars.

6.15. When is evaporation an important phenomenon in disk evolution? Was this mechanism important in the formation of the solar system?

Evaporation is important only when there is a nearby hot, young star to evaporate the disk material. This was probably not important in the formation of our solar system because the Sun has no nearby neighbors. This is not conclusive, however, since the Sun is older than the entire lifetime of some massive stars.

6.16. What is the significance of the development of a stellar wind?

The onset of the stellar wind effectively stops the infall of more mass onto the protostar. The stellar wind is also responsible for sweeping out the last of the gas remaining in the disk (see Chapters 3 and 7 for more on the topic of stellar winds).

6.17. What happens to turn a protostar into a star?

A protostar is simply a clump of dense hydrogen gas and dust. It does not become a star until it begins to fuse hydrogen in the core, and thus to produce energy.

6.18. Use what you have learned about single star formation to explain how binary stars and clusters of stars might be formed?

These are actually two different processes. Binary stars might be formed from the same clump, in much the same way that Jupiter and the Sun formed from the same cloud. Alternatively, if the cloud had two smaller clumps within it, they might form a binary system.

Clusters of stars, on the other hand, are formed by groups of many clumps in giant molecular clouds, with single or binary stars forming from each clump. All of the clumps are bound together by gravity, however, and so are all the stars that are formed.

6.19. Suppose a clump of a giant molecular cloud rotates once every million years, and has a radius of about 0.05 light years. What is the rotation period of this clump when it has collapsed to the size of the solar system (radius $= 40$ AU)? (Assume that the mass remains constant.) How does this compare to the orbital periods of Neptune and Pluto? (This method is an estimation, using a simplified model. The situation can be more correctly handled using the moment of inertia of the clump.)

The speed, v, of a rotating body is given by the rotation speed, ω, times the radius, r,

$$v = \omega r$$

The initial angular velocity is

$$\omega_1 = \frac{2\pi}{T_1} r_1,$$

where T_1 is the period of rotation (10^6 years).

This can be substituted into the angular momentum equation, and set equal to a constant, because angular momentum must be conserved.

$$L = m\omega r^2 = \text{a constant}$$
$$m_1\omega_1 r_1^2 = m_2\omega_2 r_2^2$$

but m remains constant,

$$\omega_1 r_1^2 = \omega_2 r_2^2$$
$$\omega_2 = \omega_1 \frac{r_1^2}{r_2^2}$$
$$\omega_2 = \frac{2\pi}{1\times 10^6\,\text{yr}} \frac{(0.05\,\text{ly})^2}{(40\,\text{AU})^2}$$
$$\omega_2 = \frac{2\pi}{1\times 10^6\,\text{yr}} \frac{(0.05\,\text{ly}\cdot 63{,}000\,\text{AU/ly})^2}{(40\,\text{AU})^2}$$
$$\omega_2 = \frac{2\pi}{1\times 10^6\,\text{yr}} \frac{(3{,}163)^2}{(40)^2}$$
$$\omega_2 = \frac{2\pi\cdot 6{,}255}{1\times 10^6\,\text{yr}} \cong 2\pi/160\,\text{yr}$$

So the rotation period, finally, is 160 years. This is very close to the orbital period of Neptune (165 years), but much less than the orbital period of Pluto (249 years).

6.20. Why does a collapsing cloud begin to heat up more rapidly as it becomes opaque?

For the gravitational energy released in the collapse to escape the cloud, the photons carrying that energy must be able to escape. As the cloud becomes opaque, the photons become trapped inside the cloud. Thus the energy remains in the cloud and the temperature increases.

6.21. Suppose a cool clump of a giant molecular cloud is exceptionally large, about $r = 10$ pc across, and has a mass, M, of 1×10^3 solar masses. Will this clump collapse to form stars?

For a cloud to collapse, the average velocity must be less than 1/6 the escape velocity. In a cool clump of a giant molecular cloud, most of the particles are hydrogen molecules, and so have a mass of two protons, or 3.4×10^{-24} g. These particles are at a temperature of about 10 K.

$$v_{\text{avg}} = \sqrt{\frac{8kT}{\pi\cdot m}}$$
$$v_{\text{avg}} = \sqrt{\frac{8(1.4\times 10^{-23}\,\text{kg}\cdot\text{m}^2/\text{s}^2/\text{K})(10\,\text{K})}{\pi\cdot(3.4\times 10^{-27}\,\text{kg})}}$$
$$v_{\text{avg}} = 324\,\text{m/s}$$

The escape velocity is given by

$$v_{\rm esc} = \sqrt{\frac{2GM}{r}}$$

$$v_{\rm esc} = \sqrt{\frac{2 \cdot 6.67 \times 10^{-11}\,{\rm m^3/s^2/kg} \cdot 10^3 \cdot 2 \times 10^{30}\,{\rm kg}}{10 \cdot 3 \times 10^{16}\,{\rm m}}}$$

$$v_{\rm esc} = 943\,{\rm m/s}$$

1/6 of the escape velocity is about 157 km/s. The average velocity is greater than 1/6 the escape velocity, so this clump will not collapse to form stars.

Supplementary Problems

6.22. How many solar mass stars could be formed from a molecular cloud that has a density of 10^{-19} g/cm^3 and a diameter of 0.1 pc? (Assume all the mass is converted to stars.)

Ans. 18

6.23. Suppose a cool clump of a giant molecular cloud has a radius of 1 pc, and a mass of 100 solar masses. Will the clump collapse to form stars?

Ans. Yes

6.24. Suppose a cool clump of a giant molecular cloud has a radius of 10 pc, and a mass of 100 solar masses. Will the clump collapse to form stars?

Ans. No

6.25. The Orion Nebula is about $3'$ on the sky. What is its linear diameter?

Ans. 0.4 pc

6.26. The Eagle Nebula contains dust pillars as much as 1/3 pc high. How large is this in miles?

Ans. 6×10^{12} miles, or 6 trillion miles

6.27. In Fig. 6-6, the protostars are not round. Why?

Ans. The accretion disk has begun to form

6.28. Suppose a 10 solar mass protostar developed a stellar wind of 10^{-7}solar masses/year. If this wind continued, how long could the star survive?

Ans. 10^8 years

6.29. Suppose a clump of a giant molecular cloud rotates once every million years, and has a radius of 0.1 light years. What is the rotation period of this clump when it has collapsed to 40 AU?

Ans. 40 years

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