Chapter 12: Formation of Galaxies and Stars

The previous chapter tells the story of how the universe developed from an initial ultra-hot, ultra-dense state filled with particles and force fields to a much lower density condition containing atoms of only the lightest few elements, photons, and other leftover particles. Our current universe contains massive collections of these atoms: planets, stars, galaxies, and clusters of galaxies. This chapter tells the story of how a universe composed of particles and gas created galaxies and stars.

Current Structure of the Universe

Before we discuss how the universe evolved to its present condition from a nearly uniform mixture of bare atoms, photons, and dark-matter particles, it is helpful to survey the structure of the universe that we now observe. Figure 6-5 of Chapter 6 displays the different types of galaxies: spiral (the Milky Way is of this type), elliptical, and irregular. Most galaxies reside in clusters of galaxies. The Milky Way lies in a small cluster known as the Local Group. The nearest large cluster is the Virgo Cluster (Fig. 12-1).

Figure 12-1. The central portion of the Virgo Cluster of galaxies . Image from the Hubble Space Telescope [Source: http://stsci.edu]

Exploration of the distribution of galaxies by obtaining their distances with the methods discussed in Chapter 6 reveals that clusters are organized in huge superclusters that extend across many tens of megaparsecs. Astronomers think that superclusters are the largest organized structures in the universe. That is, the universe contains essentially the same number of superclusters of galaxies in one huge chunk (with a radius greater than several hundred megaparsecs) of the universe as another. The pattern of superclusters (shown in Fig. 12-2) forms a "cosmic web" of elongated features interspersed with large voids where few galaxies reside. This structure is an important property that models of the evolution of the universe need to reproduce.

Evidence for Dark Matter

As mentioned in Chapter 11, most of the mass in the universe is composed of some form of non-luminous dark matter. The first observational evidence for dark matter was found in 1932 by Fritz Zwicky. He estimated the mass of all the galaxies in some clusters from the light we receive from them and their distances. This gave the total luminosity. The color and spectra of the galaxies indicate that stars similar

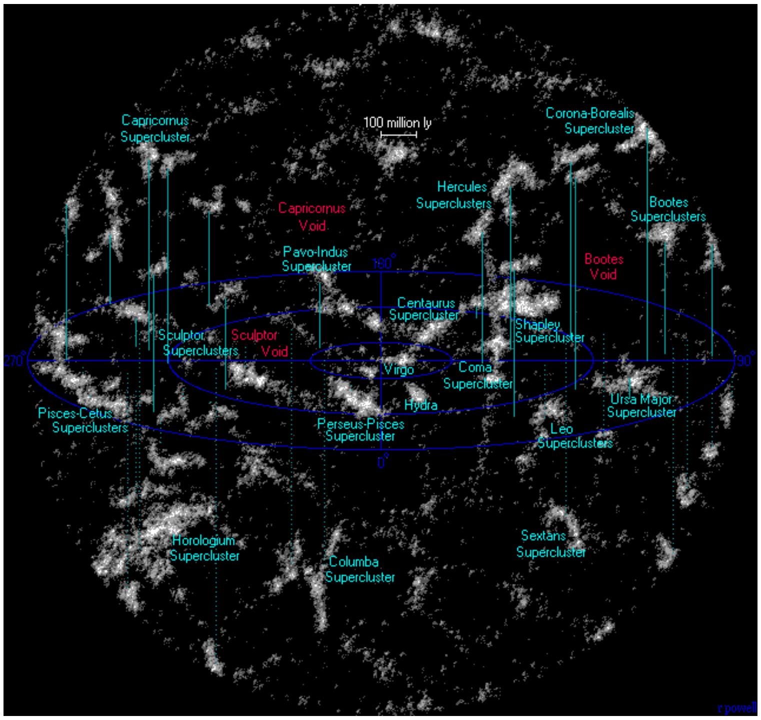


Figure 12-2. The structure of the universe within a few hundred megaparscecs of the Milky Way, which lies at the center of the diagram. Each dot represents a cluster of galaxies. The superclusters of galaxies are labeled. The black regions between the superclusters are "voids" where the density of galaxies is low [Source: http://stsci.edu]

to the Sun produce most of this light. So, by dividing the total luminosity of the cluster by the luminosity of the Sun, and multiplying the result by the mass of the Sun, we can estimate the mass in luminous objects — mostly stars. Then the force of gravity caused by these stars can be determined. Zwicky also measured the velocities of the galaxies in the clusters from their redshifts, after subtracting the velocity caused by the Hubble Law (eq. 10-4; the distances to the clusters were known). He found that the velocities exceed the escape velocity (eq. 4-14) calculated from the force of gravity supplied by the stars. The fact that the clusters have remained intact indicates that the escape velocity — and therefore the mass of each cluster — must be much larger than that calculated, thus implying that there is more mass in dark matter than in stars.

Later in the 20th century, astronomer Vera Rubin determined the speeds of orbits of stars and gas about the center of the galaxy in various spiral galaxies. She did this by measuring the Doppler shifts of spectral lines from opposite sides of each galaxy, at different distances from the center. The expectation was that, beyond the central region, the velocities should follow Kepler's 3rd Law (the version given in eq. 4-9), with velocity proportional to one divided by the square-root of the distance from the center. This is because most of the starlight – and therefore most of the stars – in galaxies comes from the central 1-2 kiloparsecs. Instead, the galaxies rotate with speeds that hardly vary at all out to the visible edge of the galaxy (Fig. 12-3). Later observations found the same to be true of the Milky Way Galaxy. Much more mass than seen in stars must be present in galaxies, extending even beyond their visible boundaries.

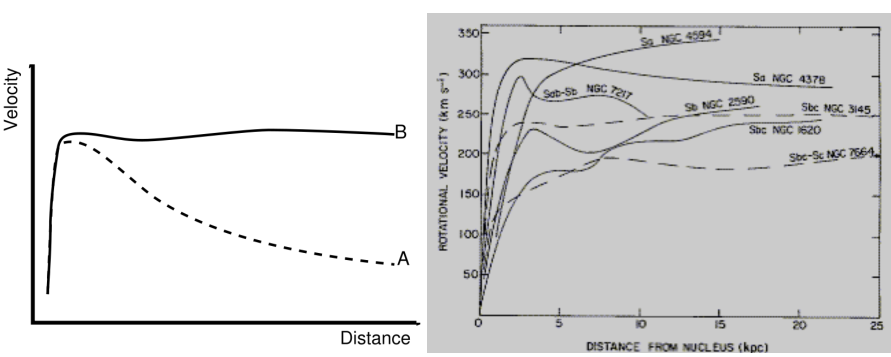


Figure 12-3. Orbital velocity of stars and gas around the center of a galaxy *vs.* distance from the center. *Left:* (A) Curve expected if the galaxy's mass is dominated by stars and (B) average observed curve. *Right:* Observed curves in 7 galaxies. [Sources: *left:* wikimedia.org; *right:* V. Rubin, et al., *Astrophysical Journal Letters*, vol. 225, L107 (1978)]

In the Milky Way Galaxy, gas and dust make up much less mass than do the stars. Planets and other small masses provide even less mass. Furthermore, the abundance of deuterium (^2_1H) relative to normal hydrogen (^1_1H) limits the density of matter that was made out of protons and neutrons a few minutes after the Big Bang started, to about what we now observe in the form of stars (see Ch. 11). The mass that supplies the extra gravitational force needed to explain both the high velocities of galaxy motions in clusters of galaxies and the high orbital speeds far from the center of a spiral galaxy must therefore be both dark and made out of something else besides protons and neutrons. Astronomers have concluded that this dark matter consists of a type of particle that has not yet been discovered in laboratories on Earth. Although the Standard Model of particle physics does not include such a particle, extensions to the model that try to unify gravity with the other forces predict the existence of massive particles that interact with other particles only through the weak interaction and gravity. Their presence is very difficult to detect with techniques that employ more familiar forms of matter, since a single particle would have a negligibly small gravitational force, and the weak interaction is also extremely difficult to measure.

Formation of Superclusters, Clusters, and Galaxies

It may seem remarkable that anything at all could form from gravity when space is expanding, but the only requirement is that the expansion needed to be gradual enough for this to happen. Consider a volume of space that will condense because of gravity. In order to do this, the mass inside this volume needs to be high enough that the escape velocity (eq. 4-14) is greater than the speed of separation of opposite sides of the volume because of the Hubble Law. We can do a little bit of algebra to estimate crudely that this is true for densities greater than about 9.2×10^{-27} kg/m^3 if we assume that the Hubble constant has not changed very much since superclusters of galaxies started to form. This is about 4 times the current density of matter in the universe. Density is proportional to 1/volume and the volume of a region of space is proportional to the radius of that region raised to the power of 3. From these considerations, we can estimate that gravity could cause regions of higher-than-average density to collapse for billions of years after the Big Bang started. It is not clear whether any such over-dense regions are still collapsing.

Since the mass of the dark matter in the universe is about 8 times that made from protons and neutrons, the dark matter must have played a dominant role in the formation of massive structures in the universe. Computer simulations (*e.g.*, Fig. 12-4) have led cosmologists to conclude that gravity causes dark matter, if it is "cold" (average kinetic energy much less than the rest-mass energy), to clump together in long, tangled filaments. This pattern reproduces rather nicely the "cosmic web" structure of the universe represented by superclusters of galaxies (Fig. 12-2).

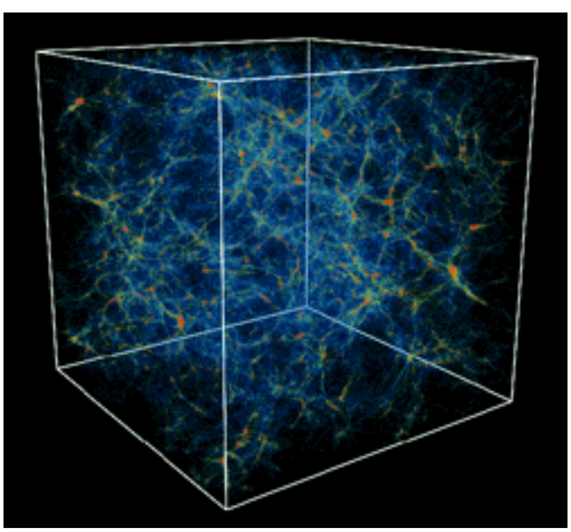


Figure 12-4. Computer simulation of a network of superclusters reproduced by a model in which cold dark matter provides most of the mass. Note the rough similarity with the atlas of superclusters in Fig. 12-2. [Source: cosmicweb.uchicago.edu/sims.html]

The order in which structures formed in the universe is rather controversial. Computer simulations, backed by observations of galaxies at high redshifts, suggest that massive stars (tens of solar masses) formed first and collected in congregations that were the seeds of modern galaxies. Regions where there were higher numbers of these primeval galaxies became clusters and superclusters of galaxies. Once gravity started the collapse of a region or section, the force of gravity became continually stronger as the size decreased. As a consequence, once the collapse of a region started, it proceeded relatively quickly.

Black Holes at the Centers of Galaxies

A large amount of the mass became concentrated in the centers of many of the galaxies as they were forming. Gravity became so strong that a massive, very compact object was created at the center (nucleus) of the galaxy. The object collapsed to the point that gravity was so intense that nothing could escape from its pull, not even light. We call such an object a **black hole**. We can imagine that a black hole could exist if the escape velocity from its surface were greater than the speed of light, the cosmic speed limit. We then use this to derive an equation for the maximum radius of a black hole, the Schwarzschild radius R_s:

$$R_s = \frac{2GM}{c^2} = 3.0\ (M/M_{sun})\ \text{km} \quad (12\text{-}1)$$

R_s = Schwarzschild radius, G = gravitational constant = 6.67×10^{-11} m^3/(kg s^2), M = mass of the black hole (in kg), c = speed of light = 3.0×10^8 m/s, M_{sun} = mass of the Sun = 2.0×10^{30} kg.

Einstein used a more geometrical approach: the bending of space-time caused by such a condensed mass is so severe that it creates a hole in space-time.

A black hole of one solar mass, *i.e.*, with a mass equal to that of the Sun, has a Schwarzschild radius of only 3.0 km. So, you would need to squeeze the Sun down to the size of a village before it would become a black hole. A black hole at the center of a galaxy, though, is much larger. For example, a black hole containing 100 million times the mass of the Sun has a Schwarzschild radius equal to the diameter of the Earth's orbit. Black holes at the centers of many galaxies have masses even greater than this.

Box 12-1. Black Holes

The Schwarzschild radius is the outer boundary of the event horizon. Once matter or energy passes the event horizon, it cannot escape. Recall from Chapter 9 that, according to Einstein's theory of General Relativity, massive objects cause a bending of space-time — see Fig. 9-6; such figures, of course, represent only three dimensions, whereas space-time involves four dimensions. The Sun makes only a minor depression in the "fabric" of space-time. An object that has collapsed inside its event horizon makes an infinitely deep hole in spacetime (see Fig. 12-5). The significance of this is that once anything — an atom, a spaceship, even light — is inside the event horizon, it cannot escape. An object that has shrunk to a radius smaller than its Schwarzschild radius is called a black hole because no light can come from the object. The infinite "depth" of the hole in space-time makes the region inside the event horizon special in a mathematical sense; this is termed a "singularity."

As was discussed in Chapter 9, time passes more slowly close to a massive object as measured by an observer far away from that object. (The opposite must be true, that an observer near a massive object observes time in the outside world to pass more rapidly.) Furthermore, light coming from a massive object is gravitationally redshifted. At the event horizon, time actually stops (again, as viewed by an outside observer) and the frequency of light coming from the event horizon is shifted to zero. It would then seem that a black hole could never actually form in the reference frame of an outside observer. Indeed, this is the case, although it has little practical importance: the outside observer sees the object collapse to a size just slightly larger than the Schwarzschild radius and the light from the object becomes so highly

Figure 12-5. Diagram representing the effect that a black hole has on space-time: it creates a bottomless hole. The sphere pictured at the center is inside the event horizon and cannot escape. It is a matter of conjecture what the hole in space-time might lead to.

redshifted that no further electromagnetic waves can be detected. Such an object would have the same appearance and seem to have the same properties as a true black hole.[1] An observer falling into a black hole, on the other hand, can pass through the event horizon rather quickly in his/her reference frame. Looking outside, that observer would measure time to pass extremely rapidly in the outside world and would see events from almost the infinite future of the universe just before passing through the event horizon. After this point, photons from the outside world could no longer catch up to the falling observer. Hence, he/she would therefore not be able to see events in the infinite future.

But, if such an observer falling into a black hole were to survive the plunge, where (and when) would he or she go? There is no unique answer to this, since the region inside the event horizon is a mathematical singularity. Einstein and others have speculated that the hole in space-time might connect to another region in space-time either in our universe or even in another universe. This hypothetical connecting tunnel is called a “wormhole” or an “Einstein-Rosen bridge”. Perhaps after a quantum theory of gravity is established, we will have a firmer basis to answer the question of where the hole in space-time goes.

Despite its not allowing any light to escape from inside it, a black hole can still be detected. This is because a black hole has a strong gravitational influence on nearby objects, such as another star. If the radius of a companion star in close orbit with the black hole is large enough, the black hole can draw matter from the outer part of that star toward the event horizon. In the case of a black hole at the center of a galaxy, gas that congregates at the center can fall onto the black hole. The gas usually forms a disk in the process (explained below in the section on formation of stars), which becomes very hot from compression (see Box 11-1) as the gas in the spinning disk falls toward the black hole. The temperature becomes so hot that the disk emits X-rays, which can be detected by space-based X-ray telescopes. In addition, if there is a companion star, it appears to revolve around a blank point at the center of mass of the star/black-hole system, but the second object in the system cannot be seen in visible light.

Both methods of detection have been used to infer the presence of about 20 black holes (with masses between a few and 15 solar masses) with stellar companions in the Milky Way Galaxy. The center of the Milky Way itself contains a black hole of 4 million solar masses, detected by its gravitational influence on the motions of stars and gas in the vicinity. The centers of other galaxies have similarly been found to contain black holes with masses as high as 10 billion solar masses. Astronomers have discovered that the mass of the black hole of a galaxy is proportional to the mass of the stars in the nearly spherical structure known as the “bulge” of a galaxy (Fig. 12-6).

[1]However, it would be possible for a “true” black hole to exist in our reference frame if it were present when the universe first came into existence. It is not known whether any such primordial black holes exist in the universe.

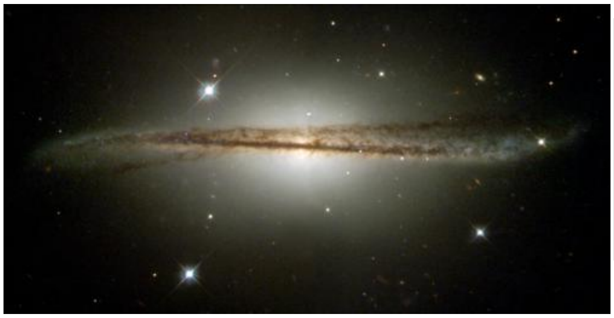


Figure 12-6. Hubble Space Telescope image of the galaxy ESO 510-G13. The image shows a twisted disk with dust (dark lanes) and a large bulge of stars. The mass of the black hole at the center of a galaxy is proportional to the total mass of the stars in the bulge. [Source: heritage.stsci.edu]

Quasars

Gas falling onto black holes with masses millions or billions times the mass of the Sun at the centers of galaxies is thought to be the energy source of quasars. These are cores of galaxies that display a range of extremely energetic activities, such as jets of ultra-hot, ionized, magnetized gas (perhaps partly composed of electrons and positrons) that shoot out of the galactic cores with flow velocities exceeding 99.5% the speed of light. Quasars are the most luminous type of active galactic nuclei.

Figure 12-7. Hubble Space Telescope image of the quasar 1229+204. The faint light in the image is the galaxy in which the quasar resides. The quasar (over-exposed on this image) is contained within a region less than 1 pc across at the center of the galaxy, yet it outshines the rest of the galaxy by thousands of times. The quasar's light comes mainly from a hot disk of ionized gas (much too small to see on astronomical images) orbiting around a super-massive black hole. [Source: hubblesite.org]

The ionized gas swirling around the black hole forms a hot disk that radiates visible and ultraviolet light with an extremely high luminosity, outshining the rest of the galaxy by thousands of times (Fig. 12-7). The matter in the disk follows Kepler's Laws (modified a bit by General Relativity very close to the black hole), so it orbits faster closer to the black hole. The ionized gas contains magnetic field that it drags in from the surrounding galaxy where the gas originated. Astronomers think that the orbital motion twists the magnetic field into a spiral shape. Similar to a wound-up spring, the magnetic field creates an outward force along the poles of the rotating system. A very small fraction of the gas is propelled out along the poles, accelerating to near-light speeds. These jets extend to well beyond the host galaxy's border. They shine with ultra-high luminosities at radio to γ-ray wavelengths, with the radiation changing in brightness in an irregular way. Astronomers (including the author) are studying such jets and their fluctuating levels of radiation in order to explore in detail how black hole systems produce such high-speed beams.

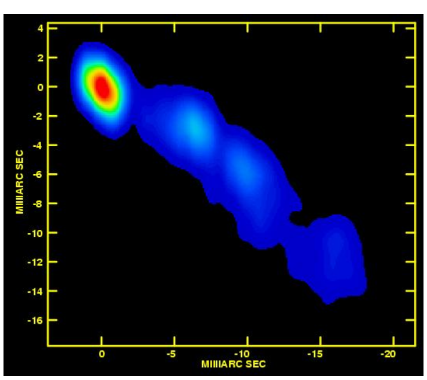


Figure 12-8. Ultra-fast jet of particles of the quasar 3C 273. The black hole (not visible) is near the upper left corner. This is a microwave image; the jet is bright also in infrared, visible, X-ray, and γ-ray light. The colors indicate brightness, with red being the brightest and dark blue the faintest level that can be detected on the image. The image was made with the Very Long Baseline Array, which consists of radio telescopes scattered around the US and its territories. [Source: www.nrao.edu]

Figure 12-9. Artist's sketch of a quasar. At the center of a galaxy, a black hole with a mass as large as billions of solar masses draws gas onto itself. The gas forms a disk, heats up, and radiates in visible and ultraviolet light with an extremely high luminosity. Magnetic fields are wound up by rotation of the disk and propel ultra-fast jets of high-energy particles along the spin axis of the black hole, an example of which is displayed in Fig. 12-8. [Source: www.sciencecodex.com]

There is a limit to the luminosity of light (at all wavelengths) produced by a system consisting of material falling onto a black hole. At ultra-high luminosities, the photons hit the electrons falling toward the black hole, which knocks the electrons back outward. The electrons take the protons and ions with them, since they are attracted strongly to each other from the electromagnetic force. The highest steady luminosity of a quasar or other black-hole powered system is the Eddington luminosity,

$$L_{\text{edd}} = 1.3\times10^{31}\ (M/M_{\text{sun}})\ \text{W} \tag{12-2}$$

L_{edd} = Eddington luminosity (in watts or W), M = mass of the black hole (in kg), M_{sun} = mass of the Sun = 2.0×10^{30} kg.

The luminosity is less than the maximum if the black hole has a short supply of "fuel" — matter falling into it.

Influence of Black Holes on Gas in the Universe and on the Growth of Galaxies

Black holes at the centers of galaxies played an important role in the state of the gas in the universe and perhaps in the development of galaxies. When massive black holes first formed from gravitational collapse of the gas (and perhaps stars) at the centers of galaxies, they created quasars as gas fell into them. The quasars then produced so many ultraviolet and X-ray photons that they ionized and excited the atoms that resided between galaxies. The gas containing these atoms then began to glow in emission lines. This glow, plus light from the early generations of stars, ended the "dark ages" that had existed when atoms first formed and the photons from the Big Bang cooled from visible to infrared wavelengths.

The formation of quasars at the centers of some galaxies may have slowed down the galaxies' development. The jets, as well as ultra-fast winds, can ram into gas that is falling toward the galaxy and keep the gas from adding to the mass of the galaxy. However, after millions of years the material feeding the black hole becomes exhausted, the jets and winds turn off, and more gas can fall in to make the galaxy grow. This can fuel another quasar episode if enough gas falls into the center of the galaxy and onto the black hole. Such a "feedback" process could explain why the mass of the black hole ends up being proportional to the total mass of stars in the bulge of the galaxy.

"Cannibalism": Merging of Galaxies

Images of the largest galaxies seen at great distances (high redshifts) — and therefore viewed as they existed early in the universe's history — appear less well-developed than the spiral and elliptical galaxies that we find at the current time. It therefore appears that galaxies — especially the largest elliptical ones — have grown by merging with other, smaller galaxies. Support for this "galactic cannibalism" is found in clusters of thousands of galaxies, which contain giant elliptical galaxies near their centers (two of which can be seen in Fig. 12-2, upper right quadrant). The relatively dense environment of such clusters causes many close encounters of galaxies with each other so that gravity can cause the galaxies to merge.

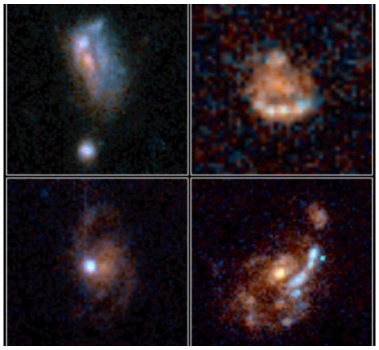


Figure 12-10. Hubble Space Telescope images of galaxies at great distances (high redshifts) and therefore viewed as they existed billions of years ago. Compare these with the more symmetric galaxies we see at the current time (Figs. 12-1 & 12-6). [Source: nasa.gov]

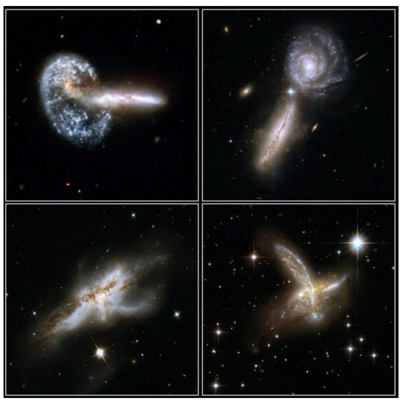


Figure 12-11. Hubble Space Telescope images of four pairs of galaxies that are so close to each other that the gravity of one is distorting the shape of the other. These galaxies may end up merging to form a single larger galaxy. [Source: nasa.gov]

The most massive galaxies at the current stage of the universe are either spiral or elliptical. The reason for the differences (see Fig. 6-5) among these large galaxies is not fully established. There is, however, significant evidence that giant elliptical galaxies formed from many mergers so that the various rotational directions averaged out to zero net rotation. Spiral galaxies, on the other hand, have a well-organized sense of rotation, so perhaps they have not undergone as many mergers as have elliptical galaxies.

Quasars were most common between about 1.8 and 3 billion years after the Big Bang started. They are much rarer now. This is probably the consequence of gas being more plentiful 11-13 billions of years ago than it was later, after much of it formed stars. Although quasars are now rare, the black holes that powered them are still present in the centers of galaxies. These "monsters" are dormant because they are poorly fed. New gas falling in as the result of a merger with another galaxy occasionally turns them on again.

The Formation of Stars

In 1755, the philosopher Immanuel Kant proposed the idea that, although the universe as a whole might be in a steady state, individual stars are born and later die. New stars then form from the debris of previous stellar generations. Although it appears that he was wrong about the constancy of the universe, he was on the mark with regard to the second part. Stars are indeed still forming today, and stars eventually die – sometimes in spectacular fashion by exploding as supernovae – with the remains becoming part of the material out of which later generations of stars are born. The remainder of this chapter discusses the process of star formation.

The Formation of Stars from Gravitational Collapse of Clouds of Gas and Dust

The Milky Way and many other galaxies contain not only a multitude of stars, but also large clouds composed mainly of hydrogen and helium gas, with a small percentage of the heavier elements. The basic process for forming a star is the gravitational collapse of such a gas cloud. (See the upper left panel of Fig. 6-1 for an illustration of how the net force of gravity causes a region of finite size to contract toward the center of mass.) However, in the case of a cloud gravity is balanced by gas pressure, caused by the motions of the atoms and molecules in the cloud. Only in relatively cold clouds does the inward force of gravity exceed the resistance of gas pressure. Therefore, ironically, only initially cold clouds can form stars (except, perhaps, if the gas is compressed by an external force).

The first stars that formed in the universe probably were made from relatively small fragments of the gas that collapsed to form galaxies. These first-generation stars contained only hydrogen and helium (plus a very small amount of lithium and beryllium) left over from the first few minutes of the Big Bang. The most massive of these stars fused these light nuclei together to form heavier elements. Within a few million years, they then exploded as supernovae, scattering these heavier elements across their galaxy. (The evolution of stars is the topic of Chapter 13, where these processes are discussed more thoroughly.) As time went on, the material in galaxies became ever more enriched in elements heavier than helium as generations of massive stars formed and exploded.

After the first stars formed, the process of star formation became more difficult. Galaxies contain many very hot stars (these make up a small yet significant fraction of all the stars), which are luminous radiators of ultraviolet light. This ultraviolet light ionizes atoms, with the escaping electrons often possessing high velocities; collisions of these electrons with other atoms and electrons heat the cloud. Because of this, a gas cloud can only remain cold if this ultraviolet light is blocked from entering the cloud. This can be accomplished by dust inside the cloud. The dust grains, which have roughly the same size as particles of cigarette smoke, are composed of molecules — *e.g.*, graphite (carbon), water ice, and hydrocarbons — that stick together through the electromagnetic force. Such molecules and dust grains form naturally inside the denser clouds in galaxies. Clouds of gas and dust appear dark on images of the sky, because they block out the light from stars that lie behind them from our vantage point (see Fig. 12-12).

After enough dust has formed inside the cloud to allow the cloud to cool (by emitting electromagnetic radiation, first mostly at visible and then at infrared wavelengths), gravitational contraction can occur. Massive clouds separate into fragments during this process, forming many stars that congregate in a cluster of stars. Less massive clouds can form single or binary stars (or sometimes systems with as many as four stars).

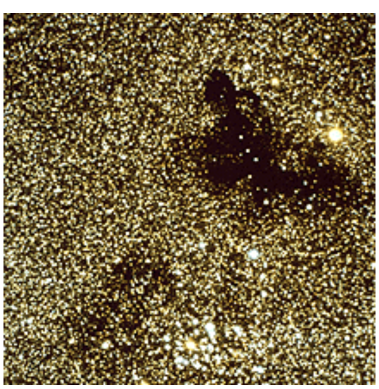


Figure 12-12. The dark splotch is the Coalsack Nebula, a cold cloud of gas and dust. The cloud is closer than most of the stars in the image. The dust in the cloud blocks starlight from behind the cloud from reaching us. Stars can form from the gravitational collapse of such a cloud. [Source: http://www.psrd.hawaii.edu]

We will discuss the simplest case of the formation of a single star. Contracting gases heat up (see Box 11-1), so the temperature of the cloud increases. Eventually, the density and temperature of the central region reach such high values that it becomes a luminous, opaque emitter of electromagnetic radiation. At this stage, astronomers refer to the object as a protostar since the core is not yet as hot or dense as that of a normal star. The source of energy that drives the luminosity of the protostar is the heat from the contraction. When, after further contraction, the density and temperature in the core increase to the point that nuclear fusion (see Ch. 8) produces most of the energy, the object becomes a normal star.

Gas clouds in the Milky Way usually rotate very slowly; however, as they contract, they spin more rapidly. The basic principle behind this is conservation of angular momentum. Angular momentum (symbol p_{ang}) is similar to momentum, but applies to rotating objects or systems (such as the solar system or a galaxy). For a ring-shaped section of a cloud, it is equal to the mass m of the ring times the speed[2] of rotation v times the distance r of that mass from the axis of rotation, or

$$p_{\text{ang}} = mvr \tag{12-3}$$

p_{ang} = angular momentum (in kg m^2/s), m = mass (in kg), v = rotational velocity (in m/s), r = radius or distance from rotational axis (in m).

Since the mass of the contracting cloud does not change, as the radius shrinks the rotational velocity v increases such that mvr remains constant. This is how a figure skater is able to spin faster as she pulls her arms in toward the rest of her body: she decreases the average distance (r) of her mass from the axis of rotation, which causes her speed of rotation (v) to increase.

In the case of an initially spherical contracting cloud, this increase in the rotation speed causes a resistance to the contraction because of the inertia of the rotating mass. However, this effect is stronger along the equator than along the poles, since near the poles most of the velocity of infall is perpendicular to the equatorial plane. The gas along the poles therefore falls toward the center more freely than does the gas along the equator, and the cloud forms a disk as it contracts (see Fig. 12-13).

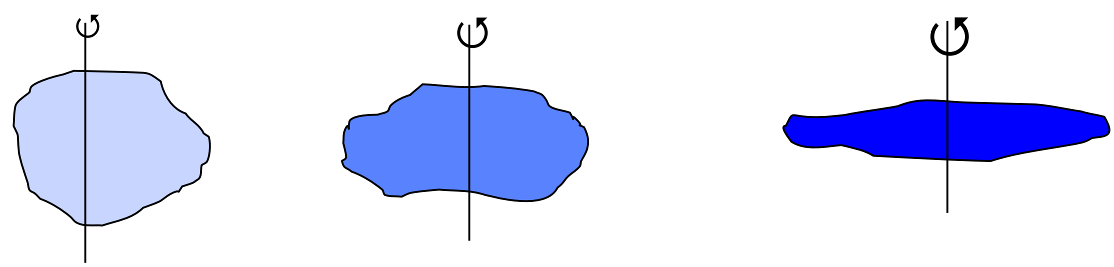
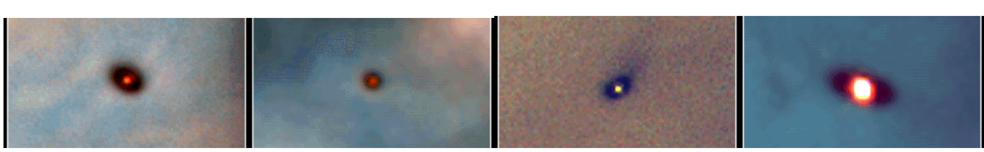


Figure 12-13. A cloud that is initially rotating slowly spins faster as it contracts from gravity. Gas can fall freely parallel to the rotation axis, but can only do so slowly along the equator. As a consequence, the infalling gas flattens until it forms a disk. Examples of disks surrounding newly formed stars, observed with the Hubble Space Telescope, are shown below. The disks are dark because they contain dust in addition to gas. [Source of images: nasa.gov]



[2] Any component of the motion that is perpendicular to the plane of the rotation (*i.e.*, the equator) does not contribute to the angular momentum.

The contraction of the cloud therefore forms a protostar at the center with a disk of dust and gas revolving around it. The system is enshrouded by the dust and gas from the outer parts of the original cloud that have not yet reached the central region.[3] Initially, the protostar can be detected at infrared wavelengths, which penetrate through the surrounding dust (see Fig. 12-14 for an example of a region where stars have formed relatively recently). The disk — at least for some stars — contains the material out of which planets eventually form (see Ch. 14).

Figure 12-14. The Trifid Nebula, a cloud with active star formation. *Left:* Viewed in visible light. The pink color is from hot hydrogen gas, the blue color is from reflection off dust, and the dark lanes are where dust in front blocks out the light from the cloud. *Right:* Viewed in infrared light. The red, yellow, and green areas are blackbody emission from hot dust. The white, yellow, and blue points are young stars that glow in infrared light. [Source: nasa.gov]

Summary

The universe now consists of a "cosmic web" of galaxies congregating in clusters and superclusters that form a network of filaments of high concentrations of galaxies surrounding huge voids where the density of galaxies is low. Computer simulations can reproduce this structure if most of the matter in the universe is in a non-luminous form. The evidence for this dark matter includes speeds of galaxies that are greater than the escape speeds would be with only luminous matter in clusters of galaxies, yet the clusters have not broken up. In addition, the orbits of stars around the centers of their galaxies are faster in the outer parts of the galaxies than would be the case if the only matter were in the form of stars. The data indicate that the dark matter is in the form of particles not yet discovered in laboratories on Earth that interact with "normal" matter only through gravity and the weak force.

Although the universe is expanding, galaxies have been able to form from clumps of higher than average density. This is because the force of gravity in the clumps was strong enough to counter the tendency of the matter to separate from the expansion. The largest clumps formed superclusters of galaxies. This broke into fragments that formed clusters of galaxies, single galaxies, and stars. The first of the most massive galaxies tended to be smaller and more irregularly shaped than the spiral and elliptical galaxies that we see today. After formation, merging of galaxies by gravity increased the sizes and masses of galaxies, including the giant elliptical galaxies that now reside near the centers of clusters.

The galaxy formation process created super-massive black holes in the centers of the galaxies. Black holes have collapsed to such a compact state (with a radius given by eq. 12-1) that even light cannot escape from them. A black hole bends space-time so much that it forms a hole in space-time. The presence of a black hole can be detected by (1) its gravitational influence on nearby stars, (2) the emission of visible, UV, and X-ray light by matter in the process of falling into it (and heated by compression), or

[3] There are other phenomena that are observed as well, such as jets of gas that shoot out the poles, probably for reasons similar to those discussed in the case of quasars but with speeds much less than the speed of light. In addition, magnetic fields are thought to play a role in the processes by which the gas and dust in the cloud eventually loses angular momentum, but this is rather complex and not completely understood.

(3) other high-energy phenomena such as jets of high-energy particles flowing away from the region surrounding the black hole at speeds close to that of light. These jets are highly luminous at essentially all wavelengths across the electromagnetic spectrum, and propagate through the galaxy out to inter-galactic space. The nuclei of galaxies that display such exotic behavior, called quasars, contain black holes with masses as high as billions of solar masses. Their luminosities are enormous — thousands of times higher than the total luminosity of all the stars in the galaxy — and depend directly on the mass of the black hole and on the amount of matter falling into it. The jets may have interfered with the growth of the galaxy by preventing gas from falling in freely. Perhaps as a consequence of this, we find that the mass of the black hole at the center of a galaxy is now proportional to the total mass of stars in the bulge of the galaxy. Quasars are now much less common than in the distant past, since the supply of gas is more scarce. Because of this, there are dormant super-massive black holes at the centers of many galaxies.

Stars form from clouds of gas and dust that collapse because of gravity, eventually condensing into one or more stars at the center. The dust keeps the cloud cool by blocking ultraviolet light from hot stars in the galaxy from entering and heating the cloud. The newly formed stars are surrounded by a disk of dust and gas. The disk forms as a consequence of conservation of angular momentum. This inhibits matter from falling in directly along the equatorial plane, but allows it to fall vertically (parallel to the rotation pole) to form the disk. At first, and for a relatively short time, the source of energy is heat from the compression of the gravitational collapse during the protostar stage. However, after the protostar contracts further to form a normal star, the energy source is nuclear fusion reactions in the star's core. The protostar shines brightly at infrared wavelengths, while normal stars are brightest at visible or UV wavelengths.

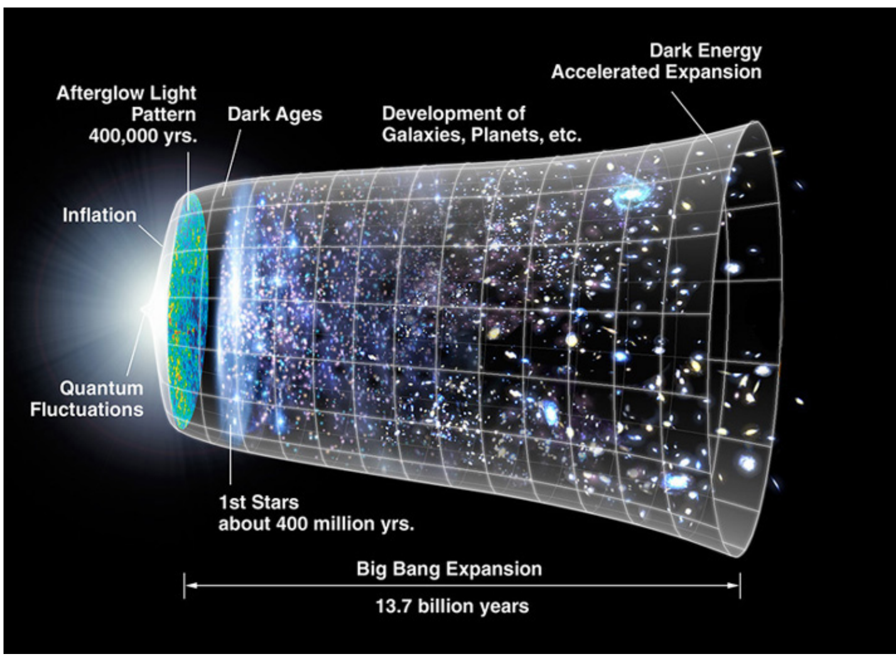


Figure 12-15. Diagram describing the development of the universe at different cosmic epochs. [Source: http://aether.lbl.gov]

The development of the universe (Fig. 12-15) proceeded from an extraordinarily hot mixture of fundamental particles and force fields to nuclei of light atoms and electrons to atoms and then to galaxies and stars. The photons progressed from γ-ray to X-ray to UV to visible to infrared to microwave wavelengths. Visible, UV, and X-ray photons made a comeback after the "dark ages" when quasars started to produce light at enormous luminosities. The universe is now a mixture of massive, luminous objects (stars and the galaxies they reside in); gas; photons (mostly from the Cosmic Microwave Background); and dark matter particles. The next two chapters examine the development of the more familiar inhabitants of the universe: stars and planets.

Glossary

Galaxy: A gravitationally bound system of millions, billions, or even trillions of stars.

Spiral galaxy: Flattened system of billions of stars that displays a general spiral pattern.

Elliptical galaxy: System of millions, billions, or trillions of stars with a circular or elliptical shape as viewed in the sky.

Milky Way Galaxy: The spiral galaxy to which our solar system belongs.

Cluster of galaxies: A gravitationally bound system of hundreds or thousands of galaxies.

Supercluster of galaxies: A collection of clusters of galaxies grouped together. Superclusters are thought to be the largest non-random structures in the universe.

Cosmic web: Nickname given to the pattern of superclusters in the universe consisting of interwoven filaments.

Void: A large region containing a low density of galaxies.

Hubble's constant (symbol: H_0): Slope of the Hubble Law (Fig. 10-2 and eqs. 10-1 and 10-4). Its value at the current epoch of the universe is about 70 km/s/Mpc.

Redshift (symbol: z, no units): A measurement of the increase in wavelength of photons caused by the expansion of the universe; see eqs. 10-2 and 10-3. One plus the redshift ($1+z$) equals by how many times the universe has spread out since the light we now receive left the object being observed. Galaxies and quasars with high redshifts are so distant that the light we now see from them left billions of years ago, so that we view these objects as they existed during early stages in the universe's development.

Dark matter: Material (probably particles that we have not yet discovered in laboratories on the Earth) that does not emit light but whose gravitational influence is apparent in galaxies and clusters of galaxies.

Space-time: The framework of the 4-dimensional macroscopic universe, consisting of three dimensions in space and one in time.

Black hole: Object that has shrunk to a radius smaller than the Schwarzschild radius corresponding to its mass (see eq. 12-1). Matter or energy that falls into a black hole cannot escape. A black hole causes a hole in space-time.

Schwarzschild radius (symbol: R_s): The radius of a black hole. See eq. 12-1.

Event horizon: Boundary that defines the outer edge of a black hole. For a non-rotating black hole, the event horizon is a distance from the center equal to the Schwarzschild radius.

Nucleus of a galaxy: The central region of a galaxy.

Bulge of a galaxy: A structure in the shape of a sphere or flattened sphere that surrounds the nucleus of a galaxy. The structure contains a substantial fraction of the stars of the galaxy. See Figure 12-6.

Active galactic nucleus: The center of a galaxy that produces a very high luminosity

Quasar: The active nucleus of a galaxy that produces extremely high luminosities of electromagnetic radiation and displays highly energetic phenomena. Thought to be powered by matter falling into a super-massive black hole, which converts gravitational potential energy to thermal and kinetic energy.

Jet: A high-speed beam of particles and magnetic field. Many quasars and less luminous active galactic nuclei produce jets that flow from the nucleus at speeds that are near the speed of light in the most extreme cases. Such jets can extend beyond the boundary of the galaxy into inter-galactic space.

"Dark ages": Period in the development of the universe between when atoms formed and when galaxies formed. There was very little visible light in the universe during this time.

Merging ("cannabalism") of galaxies: Process by which the mutual gravitational attraction of galaxies passing close to each other causes them to combine into a single, larger galaxy.

Blackbody: An opaque object. Its luminosity depends strongly on its temperature and size, and its spectrum (intensity vs. wavelength) has a characteristic shape.

Gravitional collapse: Process by which the attraction of the mass of different regions causes them all to fall toward the center of the mass distribution.

Gas pressure: Force per unit area, directed outward, exerted by a gas. Depends directly on the density and temperature of the gas.

Dust: Cosmic dust consists of tiny grains, each containing many molecules. It absorbs and reflects visible and ultraviolet light.

Nuclear fusion: Process by which light atomic nuclei combine to form more complex nuclei. (See also Chapter 10.) Mass is converted to energy. Main source of energy in a normal star.

Supernova: The explosion of a star. Most or all of the star is ejected into space. The luminosity of the expanding remnant is extremely high during the first several weeks after the explosion.

Angular Momentum: The equivalent of momentum for objects or particles that are spinning or moving along curved trajectories. For an object of mass m in a circular orbit of radius r at a speed v, the angular momentum is equal to mvr. Angular momentum is a conserved quantity.

Axis of rotation: Imaginary line about which an object revolves or rotates. It is perpendicular to the equatorial plane.

Protostar: A newly formed star that obtains its energy mainly from the heat of the gravitational contraction that formed it. This is a stage prior to when nuclear fusion at the core of the object produces the energy, at which point the object is a normal star.

Star: A massive object composed of gas that radiates light. Its energy source is nuclear fusion in its core.

Questions for Discussion

A. Many students have difficulty with the concept that gravity can pull together enough material to form galaxies while space is expanding. Imagine that you are running with a friend and you are each holding one end of a rope. If you start running at an angle so that you drift farther apart, would it be possible to exert enough force on the rope to pull you and your friend together? What determines how much force is necessary?

B. Dark matter has been hypothesized to explain why galaxies and clusters of galaxies remain intact while their internal speeds are higher than the escape velocities calculated from the mass of the luminous material (stars). There is an alternative explanation — that gravity declines as $1/r^b$, where b is a bit less than Newton's value of 2 or that Newton's 2nd Law $a = F/m$ is not exactly correct. Do you consider this to be more or less plausible than the dark matter hypothesis? What should decide the issue?

C. Falling into or orbiting close to a black hole can be dangerous. Consider the difference in gravitational attraction between your head and your feet if your feet were pointing toward the black hole. If the black hole had a mass similar to that of a star, you would be torn apart by this difference, since your feet would be pulled in with a much greater acceleration than your head. But the super-massive black holes at the centers of galaxies — *e.g.,* the one with a mass 4 million times the Sun's mass at the center of the Milky Way — are so much larger than your height that your feet and head would be pulled in at almost the same acceleration. If you could do it safely, would you like to take a vacation orbiting close to the Schwarzschild radius given the difference in passage of time relative to the outside world?

D. Imagine that you are in a spaceship that falls into a super-massive black hole. What do you expect would happen to you after you fall past the event horizon?

E. What might be the consequences to life on Earth if the center of the Milky Way Galaxy were to become a quasar with a jet of particles shooting along the rotational pole of the black hole and radiating X-rays and γ-rays with a huge luminosity (1000 times the luminosity of all the stars in the Galaxy combined)?

F. The formation of a new star recycles material from earlier stars that exploded, making more elements heavier than helium. How does this relate to the formation of solid objects like planets?

Sample Problems Related to the Material in this Chapter

1. What is the Schwarzschild radius in km of the black hole at the center of the Milky Way, which has a mass of about $4\times10^6\ M_{sun}$?

Answer: Eq. 12-1 gives $R_s = 3.0\ M/M_{sun}$ km. So, we have

$R_s = 3(4\times10^6)$ km = $\underline{1.2\times10^7\text{ km}}$. This is 17 times the radius of the Sun ($R_{sun} = 7.0\times10^5$ km).

2. If a quasar is powered by matter falling onto a black hole of mass 1.0×10^9 times the mass of the Sun, what is the maximum steady luminosity that the quasar can have?

Answer: This is the Eddington luminosity, given by eq. (12-2):

$L_{edd} = 1.3\times10^{31}\ (M/M_{sun})$ W $= 1.3\times10^{31}\ (1.0\times10^9)$ W $= 1.3\times10^{40}$ W.
This is about 10,000 times higher than the luminosity of a massive galaxy.

3. If a protostar of radius $R_p = 2.1\times10^{10}$ m with a rotational velocity $v_{p,rot} = 1.0\times10^4$ m/s contracts to a radius $R_s = 7.0\times10^8$ m to become a star, how fast will it rotate if angular momentum is conserved?

<u>Answer</u>: Eq. 12-2 states that angular momentum $p_{ang} = mvr$. Since it is conserved, we can write $p_{ang} = p_{ang,i}$, where the subscript "i" means the initial value. So, we have

$mv_{p,rot}R_p = mv_{s,rot}R_s$; m does not change, so we can divide it out to get $v_{p,rot}R_p = v_{s,rot}R_s$.

We can solve for $v_{s,rot}$:

$v_{s,rot} = v_{p,rot}R_p \,/\, R_s = (1.0\times10^4 \text{ m/s})(2.1\times10^{10} \text{ m}) \,/\, (7.0\times10^8 \text{ m}) = \underline{3.0\times10^5 \text{ m/s}}$.

Homework Questions

1. Briefly describe <u>two</u> differences between the observed properties of galaxies (including clusters and superclusters, if you wish) and the properties they would have if dark matter did not exist. [*Hint:* look at the evidence for dark matter discussed in this chapter.]

2. A black hole with a mass equal to 6.6 billion solar masses ($6.6\times10^9\ M_{sun}$) lies at the center of the galaxy M87.

a. Calculate the Schwarzschild radius of this supermassive black hole. Express your answer in kilometers (km).

b. Compare this Schwarzshild radius with the semi-major axis of Neptune's orbit, 4.5×10^9 km. (That is, divide one by the other to determine the ratio.) Is the black hole, as defined by its Schwarzschild radius, larger or smaller than our planetary system (in which Neptune's orbit is the largest)?

c. Calculate the maximum luminosity that the matter falling onto the black hole could produce. (1 point)

d. Compare (using a ratio) this maximum luminosity to the total luminosity of all the stars in the galaxy, about 4×10^{38} W. (That is, divide one luminosity by the other to determine the ratio.) (1 point)

e. The luminosity of the nucleus of M87 is much less than the maximum luminosity. Propose a hypothesis for why this is the case. Also propose an observational test for this hypothesis. [2 points of extra credit for this part]

3. a. Calculate the Schwarzschild radius of a black hole with mass similar to that of a human, 80 kg. Use the first half of equation (12-1), in which case your answer will be in meters (m).

b. Compare this Schwarzshild radius with the size of an atomic nucleus, about 2×10^{-15} m. (That is, divide one by the other to determine the ratio.) Is the black hole (as defined by its event horizon) larger or smaller than an atomic nucleus?

4. The black hole at the center of the Milky Way Galaxy has a mass of 4×10^6 times the mass of the Sun.

a. Calculate the maximum luminosity that the matter falling onto the black hole could produce.

b. Compare (using a ratio) this maximum luminosity to the total luminosity of all the stars in the Milky Way, about 1.0×10^{36} W.

c. The luminosity of the nucleus of the Milky Way is much less than the maximum luminosity. Propose a hypothesis for why this is the case. Also propose an observational test for this hypothesis. [extra credit for this part]

5. A cloud of gas and dust has a radius of 3×10^{16} m and rotates with a speed of 15 m/s. It then collapses from gravity to form a star of radius 1.0×10^{9} m.

a. Calculate the final rotational velocity of the star under the assumption that angular momentum is conserved.

b. Compare your answer to (a) with the cosmic speed limit, the speed of light (3.0×10^{8} m/s). (*I.e.*, determine the ratio of the rotational speed to the speed of light.) Is the speed less than or greater than the speed of light?

c. Given your answer to part (b), comment on whether it was possible for all of the matter in the cloud to collapse to become part of the star while conserving angular momentum.