Introduction to Frontiers of Physics

This galaxy is ejecting huge jets of matter, powered by an immensely massive black hole at its center. (credit: X-ray: NASA/CXC/CfA/R. Kraft et al.)

Frontiers are exciting. There is mystery, surprise, adventure, and discovery. The satisfaction of finding the answer to a question is made keener by the fact that the answer always leads to a new question. The picture of nature becomes more complete, yet nature retains its sense of mystery and never loses its ability to awe us. The view of physics is beautiful looking both backward and forward in time. What marvelous patterns we have discovered. How clever nature seems in its rules and connections. How awesome. And we continue looking ever deeper and ever further, probing the basic structure of matter, energy, space, and time and wondering about the scope of the universe, its beginnings and future.

You are now in a wonderful position to explore the forefronts of physics, both the new discoveries and the unanswered questions. With the concepts, qualitative and quantitative, the problem-solving skills, the feeling for connections among topics, and all the rest you have mastered, you can more deeply appreciate and enjoy the brief treatments that follow. Years from now you will still enjoy the quest with an insight all the greater for your efforts.

Cosmology and Particle Physics

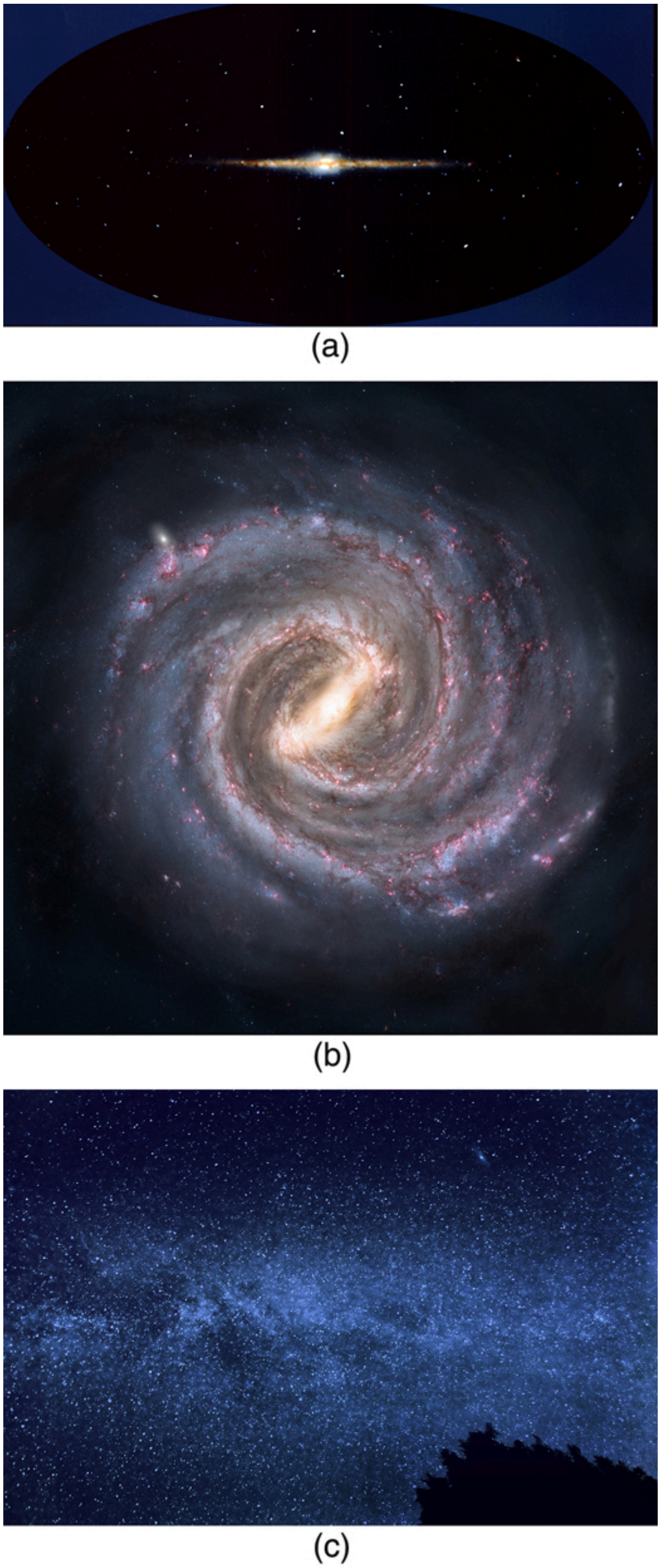
- Discuss the expansion of the universe.
- Explain the Big Bang.

Look at the sky on some clear night when you are away from city lights. There you will see thousands of individual stars and a faint glowing background of millions more. The Milky Way, as it has been called since ancient times, is an arm of our galaxy of stars—the word *galaxy* coming from the Greek word _ galaxias_, meaning milky. We know a great deal about our Milky Way galaxy and of the billions of other galaxies beyond its fringes. But they still provoke wonder and awe (see [Figure 1]). And there are still many questions to be answered. Most remarkable when we view the universe on the large scale is that once again explanations of its character and evolution are tied to the very small scale. Particle physics and the questions being asked about the very small scales may also have their answers in the very large scales.

Take a moment to contemplate these clusters of galaxies, photographed by the Hubble Space Telescope. Trillions of stars linked by gravity in fantastic forms, glowing with light and showing evidence of undiscovered matter. What are they like, these myriad stars? How did they evolve? What can they tell us of matter, energy, space, and time? (credit: NASA, ESA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech))

As has been noted in numerous Things Great and Small vignettes, this is not the first time the large has been explained by the small and vice versa. Newton realized that the nature of gravity on Earth that pulls an apple to the ground could explain the motion of the moon and planets so much farther away. Minute atoms and molecules explain the chemistry of substances on a much larger scale. Decays of tiny nuclei explain the hot interior of the Earth. Fusion of nuclei likewise explains the energy of stars. Today, the patterns in particle physics seem to be explaining the evolution and character of the universe. And the nature of the universe has implications for unexplored regions of particle physics.

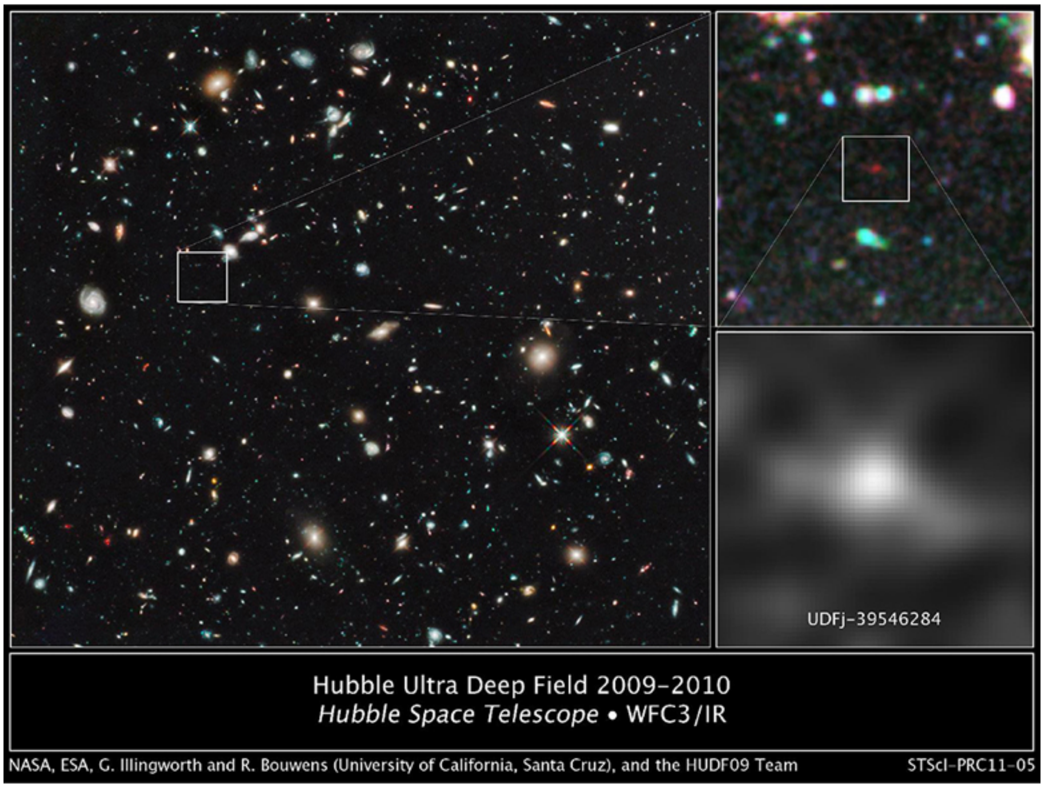
Cosmology is the study of the character and evolution of the universe. What are the major characteristics of the universe as we know them today? First, there are approximately 10^{11} galaxies in the observable part of the universe. An average galaxy contains more than 10^{11} stars, with our Milky Way galaxy being larger than average, both in its number of stars and its dimensions. Ours is a spiral-shaped galaxy with a diameter of about 100 000 light years and a thickness of about 2000 light years in the arms with a central bulge about 10 000 light years across. The Sun lies about 30 000 light years from the center near the galactic plane. There are significant clouds of gas, and there is a halo of less-dense regions of stars surrounding the main body. (See [Figure 2].) Evidence strongly suggests the existence of a large amount of additional matter in galaxies that does not produce light—the mysterious dark matter we shall later discuss.



The Milky Way galaxy is typical of large spiral galaxies in its size, its shape, and the presence of gas and dust. We are fortunate to be in a location where we can see out of the galaxy and observe the vastly larger and fascinating universe around us. (a) Side view. (b) View from above. (c) The Milky Way as seen from Earth. (credits: (a) NASA, (b) Nick Risinger, (c) Andy)

Distances are great even within our galaxy and are measured in light years (the distance traveled by light in one year). The average distance between galaxies is on the order of a million light years, but it varies greatly with galaxies forming clusters such as shown in [Figure 1]. The Magellanic Clouds, for example, are small galaxies close to our own, some 160 000 light years from Earth. The Andromeda galaxy is a large spiral galaxy like ours and lies 2 million light years away. It is just visible to the naked eye as an extended glow in the Andromeda constellation. Andromeda is the closest large galaxy in our local group, and we can see some individual stars in it with our larger telescopes. The most distant known galaxy is 14 billion light years from Earth—a truly incredible distance. (See [Figure 3].)

(a)



(b)

(a) Andromeda is the closest large galaxy, at 2 million light years distance, and is very similar to our Milky Way. The blue regions harbor young and emerging stars, while dark streaks are vast clouds of gas and dust. A smaller satellite galaxy is clearly visible. (b) The box indicates what may be the most distant known galaxy, estimated to be 13 billion light years from us. It exists in a much older part of the universe. (credit: NASA, ESA, G. Illingworth (University of California, Santa Cruz), R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team)

Consider the fact that the light we receive from these vast distances has been on its way to us for a long time. In fact, the time in years is the same as the distance in light years. For example, the Andromeda galaxy is 2 million light years away, so that the light now reaching us left it 2 million years ago. If we could be there now, Andromeda would be different. Similarly, light from the most distant galaxy left it 14 billion years ago. We have an incredible view of the past when looking great distances. We can try to see if the universe was different then—if distant galaxies are more tightly packed or have younger-looking stars, for example, than closer galaxies, in which case there has been an evolution in time. But the problem is that the uncertainties in our data are great. Cosmology is almost typified by these large uncertainties, so that we must be especially cautious in drawing conclusions. One consequence is that there are more questions than answers, and so there are many competing theories. Another consequence is that any hard data produce a major result. Discoveries of some importance are being made on a regular basis, the hallmark of a field in its golden age.

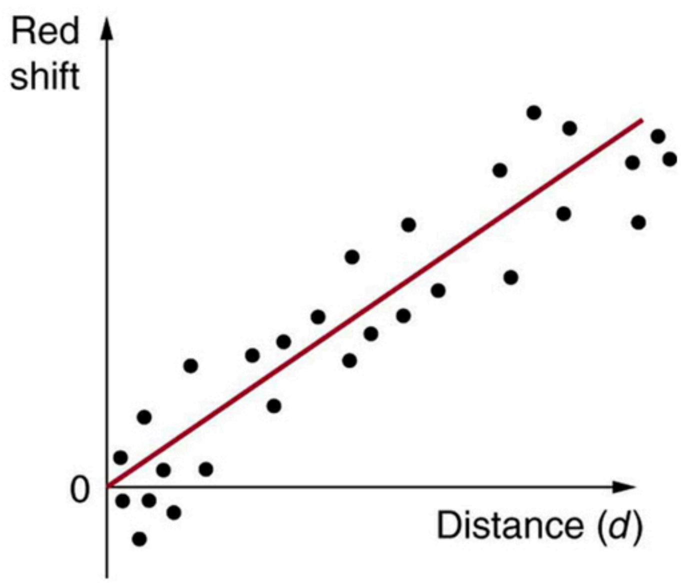
Perhaps the most important characteristic of the universe is that all galaxies except those in our local cluster seem to be moving away from us at speeds proportional to their distance from our galaxy. It looks as if a gigantic explosion, universally called the **Big Bang**, threw matter out some billions of years ago. This amazing conclusion is based on the pioneering work of Edwin Hubble (1889–1953), the American astronomer. In the 1920s, Hubble first demonstrated conclusively that other galaxies, many previously called nebulae or clouds of stars, were outside our own. He then found that all but the closest galaxies have a red shift in their hydrogen spectra that is proportional to their distance. The explanation is that there is a **cosmological red shift** due to the expansion of space itself. The photon wavelength is stretched in transit from the source to the observer. Double the distance, and the red shift is doubled. While this cosmological red shift is often called a Doppler shift, it is not—space itself is expanding. There is no center of expansion in the universe. All observers see themselves as stationary; the other objects in space appear to be moving away from them. Hubble was directly responsible for discovering that the universe was much larger than had previously been imagined and that it had this amazing characteristic of rapid expansion.

Universal expansion on the scale of galactic clusters (that is, galaxies at smaller distances are not uniformly receding from one another) is an integral part of modern cosmology. For galaxies farther away than about 50 Mly (50 million light years), the expansion is uniform with variations due to local motions of galaxies within clusters. A representative recession velocity v can be obtained from the simple formula

$$\mathrm{v}=H_0 d,$$

where d is the distance to the galaxy and H_0 is the **Hubble constant**. The Hubble constant is a central concept in cosmology. Its value is determined by taking the slope of a graph of velocity versus distance, obtained from red shift measurements, such as shown in [Figure 4]. We shall use an approximate value of $H_0 = 20\text{km/s}\cdot\text{Mly}$. Thus, $v = H\_0 d$ is an average behavior for all but the closest galaxies. For example, a galaxy 100 Mly away (as determined by its size and brightness) typically moves away from us at a speed of $v = (20\text{km/s}\cdot\text{Mly})(100\text{Mly}) = 2000\text{km/s}$. There can be variations in this speed due to so-called local motions or interactions with neighboring galaxies. Conversely, if a galaxy is found to be moving away from us at speed of 100 000 km/s based on its red shift, it is at a distance

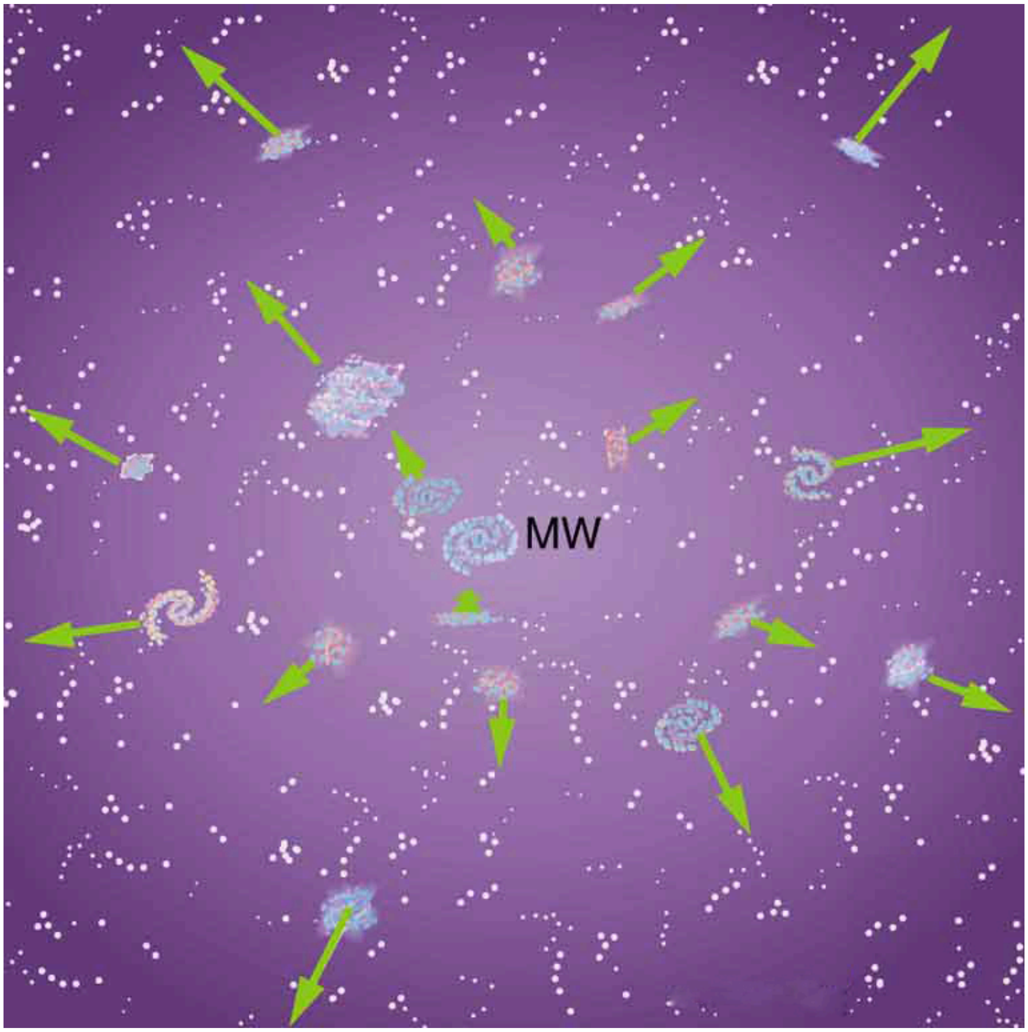
$d = v/H_0 = (10000\text{km/s})/(20\text{km/s}\cdot\text{Mly}) = 5000\text{Mly} = 5\text{Gly}$ or $5 \times 10^9\text{ly}$. This last calculation is approximate, because it assumes the expansion rate was the same 5 billion years ago as now. A similar calculation in Hubble's measurement changed the notion that the universe is in a steady state.



This graph of red shift versus distance for galaxies shows a linear relationship, with larger red shifts at greater distances, implying an expanding universe. The slope gives an approximate value for the expansion rate. (credit: John Cub).

One of the most intriguing developments recently has been the discovery that the expansion of the universe may be *faster now* than in the past, rather than slowing due to gravity as expected. Various groups have been looking, in particular, at supernovas in moderately distant galaxies (less than 1 Gly) to get improved distance measurements. Those distances are larger than expected for the observed galactic red shifts, implying the expansion was slower when that light was emitted. This has cosmological consequences that are discussed in Dark Matter and Closure. The first results, published in 1999, are only the beginning of emerging data, with astronomy now entering a data-rich era.

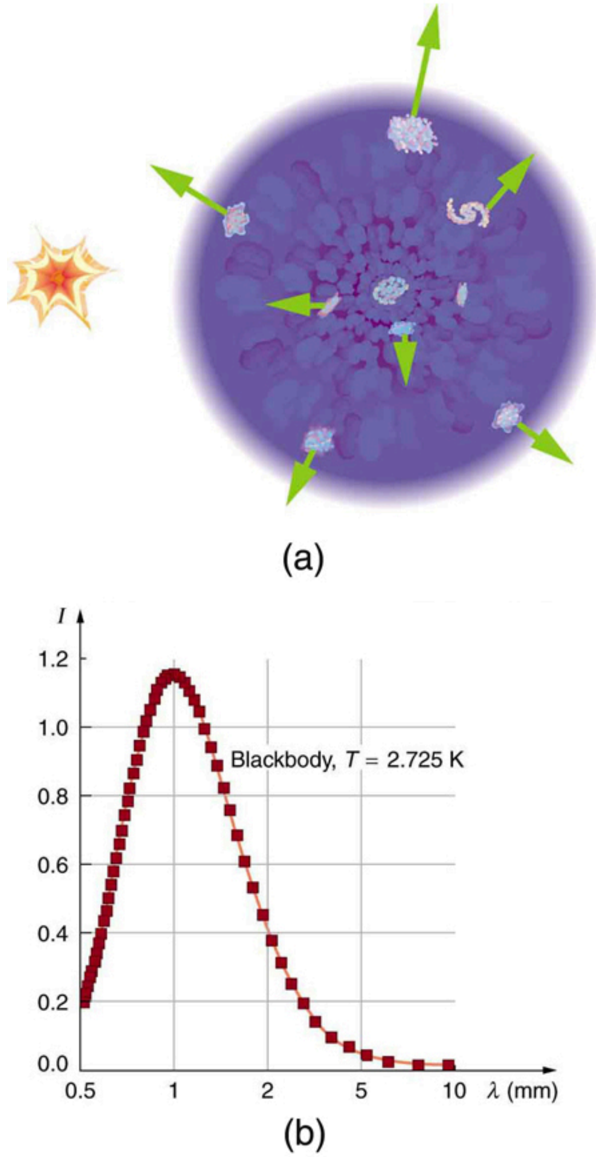
[Figure 5] shows how the recession of galaxies looks like the remnants of a gigantic explosion, the famous Big Bang. Extrapolating backward in time, the Big Bang would have occurred between 13 and 15 billion years ago when all matter would have been at a point. Questions instantly arise. What caused the explosion? What happened before the Big Bang? Was there a before, or did time start then? Will the universe expand forever, or will gravity reverse it into a Big Crunch? And is there other evidence of the Big Bang besides the well-documented red shifts?



Galaxies are flying apart from one another, with the more distant moving faster as if a primordial explosion expelled the matter from which they formed. The most distant known galaxies move nearly at the speed of light relative to us.

The Russian-born American physicist George Gamow (1904–1968) was among the first to note that, if there was a Big Bang, the remnants of the primordial fireball should still be evident and should be blackbody radiation. Since the radiation from this fireball has been traveling to us since shortly after the Big Bang, its wavelengths should be greatly stretched. It will look as if the fireball has cooled in the billions of years since the Big Bang. Gamow and collaborators predicted in the late 1940s that there should be blackbody radiation from the explosion filling space with a characteristic temperature of about 7 K. Such blackbody radiation would have its peak intensity in the microwave part of the spectrum. (See [Figure 6].) In 1964, Arno Penzias and Robert Wilson, two American scientists working with Bell Telephone Laboratories on a low-noise radio antenna, detected the radiation and eventually recognized it for what it is.

[Figure 6](b) shows the spectrum of this microwave radiation that permeates space and is of cosmic origin. It is the most perfect blackbody spectrum known, and the temperature of the fireball remnant is determined from it to be $2.725 \pm 0.002\text{K}$. The detection of what is now called the **cosmic microwave background** (CMBR) was so important (generally considered as important as Hubble's detection that the galactic red shift is proportional to distance) that virtually every scientist has accepted the expansion of the universe as fact. Penzias and Wilson shared the 1978 Nobel Prize in Physics for their discovery.



(a) The Big Bang is used to explain the present observed expansion of the universe. It was an incredibly energetic explosion some 10 to 20 billion years ago. After expanding and cooling, galaxies form inside the now-cold remnants of the primordial fireball. (b) The spectrum of cosmic microwave radiation is the most perfect blackbody spectrum ever detected. It is characteristic of a temperature of 2.725 K, the expansion-cooled temperature of the Big Bang's remnant. This radiation can be measured coming from any direction in space not obscured by some other source. It is compelling evidence of the creation of the universe in a gigantic explosion, already indicated by galactic red shifts.

Making Connections: Cosmology and Particle Physics

There are many connections of cosmology—by definition involving physics on the largest scale—with particle physics—by definition physics on the smallest scale. Among these are the dominance of matter over antimatter, the nearly perfect uniformity of the cosmic microwave background, and the mere existence of galaxies.

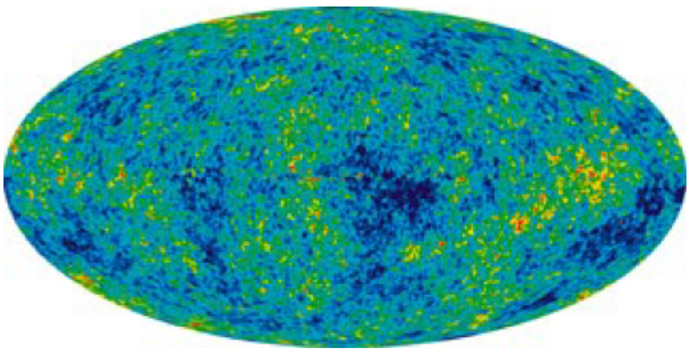
Matter versus antimatter We know from direct observation that antimatter is rare. The Earth and the solar system are nearly pure matter. Space probes and cosmic rays give direct evidence—the landing of the Viking probes on Mars would have been spectacular explosions of mutual annihilation energy if Mars were antimatter. We also know that most of the universe is dominated by matter. This is proven by the lack of annihilation radiation coming to us from space, particularly the relative absence of 0.511-MeV γ rays created by the mutual annihilation of electrons and positrons. It seemed possible that there could be entire solar systems or galaxies made of antimatter in perfect symmetry with our matter-dominated systems. But the interactions between stars and galaxies would sometimes bring matter and antimatter together in large amounts. The annihilation radiation they would produce is simply not observed. Antimatter in nature is created in particle collisions and in β^+ decays, but only in small amounts that quickly annihilate, leaving almost pure matter surviving.

Particle physics seems symmetric in matter and antimatter. Why isn't the cosmos? The answer is that particle physics is not quite perfectly symmetric in this regard. The decay of one of the neutral K -mesons, for example, preferentially creates more matter than antimatter. This is caused by a fundamental small asymmetry in the basic forces. This small asymmetry produced slightly more matter than antimatter in the early universe. If there was only one part in 10^9 more matter (a small asymmetry), the rest would annihilate pair for pair, leaving nearly pure matter to form the stars and galaxies we see today. So the vast number of stars we observe may be only a tiny remnant of the original matter created in the Big Bang. Here at last we see a very real and important asymmetry in nature. Rather than be disturbed by an asymmetry, most physicists are impressed by how small it is. Furthermore, if the universe were completely symmetric, the mutual annihilation would be more complete, leaving far less matter to form us and the universe we know.

How can something so old have so few wrinkles?A troubling aspect of cosmic microwave background radiation (CMBR) was soon recognized. True, the CMBR verified the Big Bang, had the correct temperature, and had a blackbody spectrum as expected. But the CMBR was *too* smooth—it looked identical in every direction. Galaxies and other similar entities could not be formed without the existence of fluctuations in the primordial stages of the universe and so there should be hot and cool spots in the CMBR, nicknamed wrinkles, corresponding to dense and sparse regions of gas caused by turbulence or early fluctuations. Over time, dense regions would contract under gravity and form stars and galaxies. Why aren't the fluctuations there? (This is a good example of an answer producing more questions.) Furthermore, galaxies are observed very far from us, so that they formed very long ago. The problem was to explain how galaxies could form so early and so quickly after the Big Bang if its remnant fingerprint is perfectly smooth. The answer is that if you look very closely, the CMBR is not perfectly smooth, only extremely smooth.

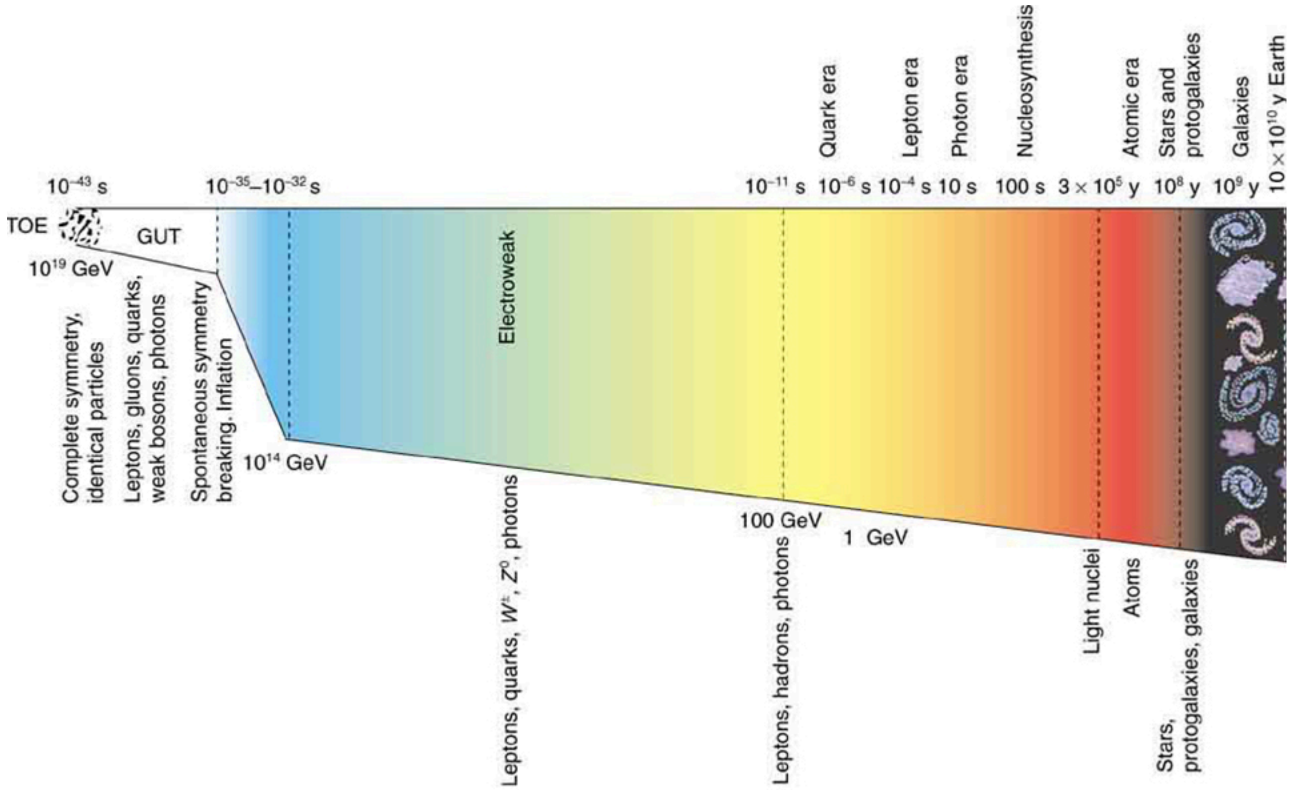
A satellite called the Cosmic Background Explorer (COBE) carried an instrument that made very sensitive and accurate measurements of the CMBR. In April of 1992, there was extraordinary publicity of COBE's first results—there were small fluctuations in the CMBR. Further measurements were carried out by experiments including NASA's Wilkinson Microwave Anisotropy Probe (WMAP), which launched in

1. Data from WMAP provided a much more detailed picture of the CMBR fluctuations. (See [Figure 7].) These amount to temperature fluctuations of only $200 \mu \mathrm{k}$ out of 2.7 K, better than one part in 1000.
2. The WMAP experiment will be followed up by the European Space Agency's Planck Surveyor, which launched in 2009.



This map of the sky uses color to show fluctuations, or wrinkles, in the cosmic microwave background observed with the WMAP spacecraft. The Milky Way has been removed for clarity. Red represents higher temperature and higher density, while blue is lower temperature and density. The fluctuations are small, less than one part in 1000, but these are still thought to be the cause of the eventual formation of galaxies. (credit: NASA/WMAP Science Team)

Let us now examine the various stages of the overall evolution of the universe from the Big Bang to the present, illustrated in [Figure 8]. Note that scientific notation is used to encompass the many orders of magnitude in time, energy, temperature, and size of the universe. Going back in time, the two lines approach but do not cross (there is no zero on an exponential scale). Rather, they extend indefinitely in ever-smaller time intervals to some infinitesimal point.



The evolution of the universe from the Big Bang onward is intimately tied to the laws of physics, especially those of particle physics at the earliest stages. The universe is relativistic throughout its history. Theories of the unification of forces at high energies may be verified by their shaping of the universe and its evolution.

Going back in time is equivalent to what would happen if expansion stopped and gravity pulled all the galaxies together, compressing and heating all matter. At a time long ago, the temperature and density were too high for stars and galaxies to exist. Before then, there was a time when the temperature was too great for atoms to exist. And farther back yet, there was a time when the temperature and density were so great that nuclei could not exist. Even farther back in time, the temperature was so high that average kinetic energy was great enough to create short-lived particles, and the density was high enough to make this likely. When we extrapolate back to the point of $W^{\pm}$ and Z^{0} production (thermal energies reaching 1 TeV, or a temperature of about 10^{15}K), we reach the limits of what we know directly about particle physics. This is at a time about 10^{-12}s after the Big Bang. While 10^{-12}s may seem to be negligibly close to the instant of creation, it is not. There are important stages before this time that are tied to the unification of forces. At those stages, the universe was at extremely high energies and average particle separations were smaller than we can achieve with accelerators. What happened in the early stages before

10^{-12} \text{s} $$ is crucial to all later stages and is possibly discerned by observing present conditions in the universe. One of these is the smoothness of the CMBR.

Names are given to early stages representing key conditions. The stage before 10^{-11}s back to 10^{-34}s is called the **electroweak epoch**, because the electromagnetic and weak forces become identical for energies above about 100 GeV. As discussed earlier, theorists expect that the strong force becomes identical to and thus unified with the electroweak force at energies of about 10^{14}GeV . The average particle energy would be this great at 10^{-34}s after the Big Bang, if there are no surprises in the unknown physics at energies above about 1 TeV. At the immense energy of 10^{14}GeV (corresponding to a temperature of about 10^{26}K), the $W^{\pm}$ and Z^{0} carrier particles would be transformed into massless gauge bosons to accomplish the unification. Before 10^{-34}s back to about 10^{-43}s , we have Grand Unification in the **GUT epoch**, in which all forces except gravity are identical. At 10^{-43}s , the average energy reaches the immense 10^{19}GeV needed to unify gravity with the other forces in TOE, the Theory of Everything. Before that time is the **TOE epoch**, but we have almost no idea as to the nature of the universe then, since we have no workable theory of quantum gravity. We call the hypothetical unified force **superforce**.

Now let us imagine starting at TOE and moving forward in time to see what type of universe is created from various events along the way. As temperatures and average energies decrease with expansion, the universe reaches the stage where average particle separations are large enough to see differences between the strong and electroweak forces (at about 10^{-35}s). After this time, the forces become distinct in almost all interactions—they are no longer unified or symmetric. This transition from GUT to electroweak is an example of **spontaneous symmetry breaking**, in which conditions spontaneously evolved to a point where the forces were no longer unified, breaking that symmetry. This is analogous to a phase transition in the universe, and a clever proposal by American physicist Alan Guth in the early 1980s ties it to the smoothness of the CMBR. Guth proposed that spontaneous symmetry breaking (like a phase transition during cooling of normal matter) released an immense amount of energy that caused the universe to expand extremely rapidly for the brief time from 10^{-35}s to about 10^{-32}s . This expansion may have been by an incredible factor of 10^{50} or more in the size of the universe and is thus called the **inflationary scenario**. One result of this inflation is that it would stretch the wrinkles in the universe nearly flat, leaving an extremely smooth CMBR. While speculative, there is as yet no other plausible explanation for the smoothness of the CMBR. Unless the CMBR is not really cosmic but local in origin, the distances between regions of similar temperatures are too great for any coordination to have caused them, since any coordination mechanism must travel at the speed of light. Again, particle physics and cosmology are intimately entwined. There is little hope that we may be able to test the inflationary scenario directly, since it occurs at energies near 10^{14}GeV , vastly greater than the limits of modern accelerators. But the idea is so attractive that it is incorporated into most cosmological theories.

Characteristics of the present universe may help us determine the validity of this intriguing idea. Additionally, the recent indications that the universe's expansion rate may be *increasing* (see Dark Matter and Closure) could even imply that we are *in* another inflationary epoch.

It is important to note that, if conditions such as those found in the early universe could be created in the laboratory, we would see the unification of forces directly today. The forces have not changed in time, but the average energy and separation of particles in the universe have. As discussed in The Four Basic Forces, the four basic forces in nature are distinct under most circumstances found today. The early universe and its remnants provide evidence from times when they were unified under most circumstances.

Section Summary

- Cosmology is the study of the character and evolution of the universe.
- The two most important features of the universe are the cosmological red shifts of its galaxies being proportional to distance and its cosmic microwave background (CMBR). Both support the notion that there was a gigantic explosion, known as the Big Bang that created the universe.
- Galaxies farther away than our local group have, on an average, a recessional velocity given by

  $$v = H_0 d,$$

  where d is the distance to the galaxy and H_0 is the Hubble constant, taken to have the average value $H_0 = 20\text{km/s}\cdot\text{Mly}$.
- Explanations of the large-scale characteristics of the universe are intimately tied to particle physics.
- The dominance of matter over antimatter and the smoothness of the CMBR are two characteristics that are tied to particle physics.
- The epochs of the universe are known back to very shortly after the Big Bang, based on known laws of physics.
- The earliest epochs are tied to the unification of forces, with the electroweak epoch being partially understood, the GUT epoch being speculative, and the TOE epoch being highly speculative since it involves an unknown single superforce.
- The transition from GUT to electroweak is called spontaneous symmetry breaking. It released energy that caused the inflationary scenario, which in turn explains the smoothness of the CMBR.

Conceptual Questions

Explain why it only *appears* that we are at the center of expansion of the universe and why an observer in another galaxy would see the same relative motion of all but the closest galaxies away from her.

If there is no observable edge to the universe, can we determine where its center of expansion is? Explain.

If the universe is infinite, does it have a center? Discuss.

Another known cause of red shift in light is the source being in a high gravitational field. Discuss how this can be eliminated as the source of galactic red shifts, given that the shifts are proportional to distance and not to the size of the galaxy.

If some unknown cause of red shift—such as light becoming "tired" from traveling long distances through empty space—is discovered, what effect would there be on cosmology?

Olbers's paradox poses an interesting question: If the universe is infinite, then any line of sight should eventually fall on a star's surface. Why then is the sky dark at night? Discuss the commonly accepted evolution of the universe as a solution to this paradox.

If the cosmic microwave background radiation (CMBR) is the remnant of the Big Bang's fireball, we expect to see hot and cold regions in it. What are two causes of these wrinkles in the CMBR? Are the observed temperature variations greater or less than originally expected?

The decay of one type of K -meson is cited as evidence that nature favors matter over antimatter. Since mesons are composed of a quark and an antiquark, is it surprising that they would preferentially decay to one type over another? Is this an asymmetry in nature? Is the predominance of matter over antimatter an asymmetry?

Distances to local galaxies are determined by measuring the brightness of stars, called Cepheid variables, that can be observed individually and that have absolute brightnesses at a standard distance that are well known. Explain how the measured brightness would vary with distance as compared with the absolute brightness.

Distances to very remote galaxies are estimated based on their apparent type, which indicate the number of stars in the galaxy, and their measured brightness. Explain how the measured brightness would vary with distance. Would there be any correction necessary to compensate for the red shift of the galaxy (all distant galaxies have significant red shifts)? Discuss possible causes of uncertainties in these measurements.

If the smallest meaningful time interval is greater than zero, will the lines in [Figure 9] ever meet?

Problems & Exercises

Find the approximate mass of the luminous matter in the Milky Way galaxy, given it has approximately 10^{11} stars of average mass 1.5 times that of our Sun.

Show Solution

3×10^{41}kg

Find the approximate mass of the dark and luminous matter in the Milky Way galaxy. Assume the luminous matter is due to approximately 10^{11} stars of average mass 1.5 times that of our Sun, and take the dark matter to be 10 times as massive as the luminous matter.

Show Solution

Strategy

We need to find the total mass of both luminous and dark matter in the Milky Way galaxy. From the previous problem, we know the mass of luminous matter is 3×10^{41} kg. The problem states that dark matter is 10 times as massive as the luminous matter, so we can calculate the dark matter mass and then add both components to get the total mass.

Solution

From the previous problem, the mass of luminous matter in the Milky Way is:

$$m_{\text{luminous}}=3\times10^{41}\text{ kg}$$

The mass of dark matter is 10 times the luminous matter:

$$m_{\text{dark}}=10\times m_{\text{luminous}}=10\times3\times10^{41}\text{ kg}=3\times10^{42}\text{ kg}$$

The total mass is the sum of luminous and dark matter:

$$m_{\text{total}}=m_{\text{luminous}}+m_{\text{dark}}=3\times10^{41}\text{ kg}+3\times10^{42}\text{ kg}$$
$$m_{\text{total}}=3\times10^{41}\text{ kg}+30\times10^{41}\text{ kg}=33\times10^{41}\text{ kg}=3.3\times10^{42}\text{ kg}$$

Discussion

The total mass of the Milky Way galaxy, including both dark and luminous matter, is approximately **3.3×10^{42} kg**. This result reveals a profound truth about our galaxy: the vast majority (about 91%) of its mass is in the form of dark matter, which does not emit light and can only be detected through its gravitational effects. The luminous matter—all the stars, gas, and dust we can observe—represents only about 9% of the total mass. This is consistent with observations of galactic rotation curves, which show that stars far from the galactic center orbit faster than would be expected based on the visible matter alone. The presence of this massive dark matter halo is necessary to explain the observed dynamics of our galaxy and prevent the outer stars from flying off into intergalactic space. This dark matter problem is one of the most significant unsolved mysteries in modern physics, and understanding its nature is crucial for our comprehension of galaxy formation, structure, and evolution throughout the universe.

(a) Estimate the mass of the luminous matter in the known universe, given there are 10^{11} galaxies, each containing 10^{11} stars of average mass 1.5 times that of our Sun. (b) How many protons (the most abundant nuclide) are there in this mass? (c) Estimate the total number of particles in the observable universe by multiplying the answer to (b) by two, since there is an electron for each proton, and then by 10^{9} , since there are far more particles (such as photons and neutrinos) in space than in luminous matter.

Show Solution

(a) 3×10^{52}kg (b) 2×10^{79} (c) 4×10^{88}

If a galaxy is 500 Mly away from us, how fast do we expect it to be moving and in what direction?

Show Solution

Strategy

We can use Hubble's law to determine the recession velocity of a galaxy at a given distance. Hubble's law states that $v = H_0 d$, where v is the recession velocity, H_0 is the Hubble constant, and d is the distance to the galaxy. From the chapter, we know that $H_0 = 20\text{ km/s}\cdot\text{Mly}$. The direction of motion for distant galaxies is always away from us due to the expansion of the universe.

Solution

Using Hubble's law:

$$v=H_0 d$$

Substituting the given values:

$$v=(20\text{ km/s}\cdot\text{Mly})\times500\text{ Mly}$$

$$v = 10{,}000\ \text{km/s} = 1.0 \times 10^4\ \text{km/s}$$

The galaxy is moving **away from us** at a speed of approximately **10,000 km/s** (or **1.0 × 10^4 km/s**).

Discussion

This velocity of 10,000 km/s is quite substantial—about 3.3% of the speed of light. The fact that the galaxy is moving away from us is not because we are at the center of the universe, but rather because space itself is expanding uniformly in all directions. Every observer in the universe would see distant galaxies receding from them, with velocities proportional to distance. This is a fundamental characteristic of the expanding universe first discovered by Edwin Hubble. The recession velocity we calculated represents the rate at which the space between us and the galaxy is expanding. It's important to note that this is not motion through space in the conventional sense, but rather the expansion of space itself. For a galaxy at 500 Mly, this velocity is well within the regime where Hubble's law gives accurate predictions. For much more distant galaxies (several billion light years away), relativistic corrections become necessary, and the simple linear relationship between distance and velocity begins to break down.

On average, how far away are galaxies that are moving away from us at 2.0% of the speed of light?

Show Solution

0.30 Gly

Our solar system orbits the center of the Milky Way galaxy. Assuming a circular orbit 30 000 ly in radius and an orbital speed of 250 km/s, how many years does it take for one revolution? Note that this is approximate, assuming constant speed and circular orbit, but it is representative of the time for our system and local stars to make one revolution around the galaxy.

Show Solution

Strategy

To find the orbital period, we need to calculate the circumference of the circular orbit and divide by the orbital speed. The orbital radius is given in light years (ly), so we'll need to work with consistent units. We can either convert the speed to ly/year or convert the circumference to kilometers. The former approach is more elegant for this problem since it allows us to directly calculate the period in years.

Solution

First, let's find the orbital circumference:

$$C = 2\pi r = 2\pi \times 30{,}000\ \text{ly} = 188{,}496\ \text{ly}$$

Next, we need to convert the orbital speed from km/s to ly/year.

The speed of light is $c = 3.00 \times 10^8$ m/s, and one light year is the distance light travels in one year. Therefore:

$$\frac{v}{c} = \frac{250\ \text{km/s}}{3.00 \times 10^5\ \text{km/s}} = 8.33 \times 10^{-4}$$

This means the orbital speed is 8.33×10^{-4} light years per year.

The orbital period is:

$$T = \frac{C}{v} = \frac{188{,}496\ \text{ly}}{8.33 \times 10^{-4}\ \text{ly/year}}$$
$$T = 2.26 \times 10^8\ \text{years} = 226\ \text{million years}$$

Discussion

Our solar system takes approximately **226 million years** to complete one orbit around the center of the Milky Way galaxy. This immense period is often called a "galactic year" or "cosmic year." Since the Sun formed about 4.6 billion years ago, it has completed roughly 20 orbits around the galactic center during its lifetime. This long orbital period reflects the enormous size of our galaxy and the relatively modest orbital speed of the Sun. During one complete orbit, the solar system travels a distance of nearly 190,000 light years—a truly astronomical journey! This orbital motion has important implications for Earth's long-term evolution: as we move through different regions of the galaxy, we may encounter varying densities of interstellar material, different radiation environments, and even spiral arm crossings that could affect the rate of star formation and supernova frequency in our cosmic neighborhood. The last time the Sun was in its current position in the galaxy, dinosaurs had not yet evolved on Earth, illustrating the vast timescales involved in galactic dynamics.

(a) What is the approximate speed relative to us of a galaxy near the edge of the known universe, some 10 Gly away? (b) What fraction of the speed of light is this? Note that we have observed galaxies moving away from us at greater than $0.9c$.

Show Solution

(a) $2.0 \times 10^5 \text{km/s}$ (b) $0.67c$

(a) Calculate the approximate age of the universe from the average value of the Hubble constant, $H_0 = 20 \text{km/s} \cdot \text{Mly}$. To do this, calculate the time it would take to travel 1 Mly at a constant expansion rate of 20 km/s. (b) If deceleration is taken into account, would the actual age of the universe be greater or less than that found here? Explain.

Show Solution

Strategy

(a) The age of the universe can be estimated by calculating the Hubble time, which is the time it would take for two galaxies separated by 1 Mly to reach that separation if they have been moving apart at a constant rate of 20 km/s. This requires converting 1 Mly to kilometers and then calculating the time as distance divided by speed.

(b) We need to consider how the expansion rate has changed over time. If the universe has been decelerating (slowing down), this means it was expanding faster in the past, which would affect our age estimate.

Solution

(a) The time to travel 1 Mly at 20 km/s is:

$$t = \frac{d}{v} = \frac{1\ \text{Mly}}{20\ \text{km/s}}$$

First, convert 1 Mly to kilometers:

$$1\ \text{Mly} = 10^6\ \text{ly} \times 9.46 \times 10^{12}\ \text{km/ly} = 9.46 \times 10^{18}\ \text{km}$$

Now calculate the time:

$$t = \frac{9.46 \times 10^{18}\ \text{km}}{20\ \text{km/s}} = 4.73 \times 10^{17}\ \text{s}$$

Converting to years (using $1\ \text{year} = 3.156 \times 10^7\ \text{s}$):

$$t = \frac{4.73 \times 10^{17}\ \text{s}}{3.156 \times 10^7\ \text{s/year}} = 1.5 \times 10^{10}\ \text{years} = 15\ \text{billion years}$$

(b) If deceleration is taken into account, the actual age of the universe would be **less** than the value calculated above.

Discussion

(a) Our calculation gives an approximate age of the universe of **15 billion years** (or 1.5×10^{10} years). This is reasonably close to the currently accepted age of approximately 13.8 billion years, demonstrating that the Hubble constant provides a useful way to estimate the universe's age. This calculation assumes the expansion rate has been constant throughout the universe's history, which is why we call it the "Hubble time."

(b) The reasoning for part (b) is crucial: If the universe has been decelerating (as was long believed due to gravitational attraction between galaxies), this means the expansion was faster in the past. If galaxies were moving apart faster in the earlier universe, they would have reached their current separations in less time than our constant-rate calculation suggests. Think of it this way: if you're currently traveling at 20 km/s but you used to be traveling at 30 km/s and have been slowing down, you would have covered the same distance in less time than if you had been traveling at a constant 20 km/s the entire time. Therefore, accounting for deceleration would give a younger universe than our Hubble time estimate. Interestingly, recent observations suggest the universe's expansion may actually be accelerating (not decelerating), which is attributed to dark energy. If acceleration is occurring, the actual age would be greater than our estimate, since the universe was expanding more slowly in the past. This shows how the dynamics of cosmic expansion directly affect our understanding of the universe's age and evolution.

Assuming a circular orbit for the Sun about the center of the Milky Way galaxy, calculate its orbital speed using the following information: The mass of the galaxy is equivalent to a single mass 1.5×10^{11} times that of the Sun (or $3 \times 10^{41}\ \text{kg}$), located 30 000 ly away.

Show Solution

$2.7 \times 10^5\ \text{m/s}$

(a) What is the approximate force of gravity on a 70-kg person due to the Andromeda galaxy, assuming its total mass is 10^{13} that of our Sun and acts like a single mass 2 Mly away? (b) What is the ratio of this force to the person's weight? Note that Andromeda is the closest large galaxy.

Show Solution

Strategy

(a) We can use Newton's law of universal gravitation to calculate the gravitational force between the person and the Andromeda galaxy. We'll need to convert the galaxy's mass (given in solar masses) to kilograms and the distance (given in Mly) to meters.

(b) To find the ratio, we'll divide the gravitational force from Andromeda by the person's weight on Earth (which is the gravitational force due to Earth).

Solution

(a) Newton's law of universal gravitation is:

$$F = \frac{GMm}{r^2}$$

where $G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$, M is the mass of Andromeda, $m = 70\ \text{kg}$ is the person's mass, and r is the distance.

The mass of Andromeda:

$$M=10^{13}\times M_{\text{Sun}}=10^{13}\times 2.0\times 10^{30}\text{ kg}=2.0\times 10^{43}\text{ kg}$$

The distance in meters:

$$r=2\text{ Mly}=2\times 10^{6}\text{ ly}\times 9.46\times 10^{15}\text{ m/ly}=1.892\times 10^{22}\text{ m}$$

Substituting into Newton's law:

$$F=\frac{(6.67\times 10^{-11})(2.0\times 10^{43})(70)}{(1.892\times 10^{22})^{2}}$$
$$F=\frac{9.34\times 10^{34}}{3.58\times 10^{44}}=2.6\times 10^{-10}\text{ N}$$

(b) The person's weight on Earth is:

$$W=mg=70\text{ kg}\times 9.8\text{ m/s}^{2}=686\text{ N}$$

The ratio is:

$$\frac{F}{W}=\frac{2.6\times 10^{-10}\text{ N}}{686\text{ N}}=3.8\times 10^{-13}$$

Discussion

The gravitational force exerted by the entire Andromeda galaxy on a person is extraordinarily small: only **2.6×10^{-10} N**. To put this in perspective, this is about the weight of a single bacterium! The ratio of this force to the person's weight is **3.8×10^{-13}**, meaning Andromeda's gravitational pull is less than a trillionth of Earth's pull on the same person. This demonstrates a fundamental principle: while gravity has infinite range and never goes to zero, it becomes vanishingly weak over astronomical distances due to the inverse square law. Even though Andromeda contains hundreds of billions of stars and has a total mass 10 trillion times that of our Sun, its enormous distance (2 million light years) makes its gravitational effect on us utterly negligible. This is why we don't feel the gravitational pull of distant galaxies in our daily lives, and why the universe's expansion can overcome gravity on the largest scales. The calculation also shows that local gravitational effects (from Earth, the Sun, and even our own galaxy) completely dominate over the pull from external galaxies. This is reassuring—if Andromeda's gravity were significant, we'd be in serious trouble, as it's on a collision course with the Milky Way (though that collision won't happen for about 4 billion years)!

Andromeda galaxy is the closest large galaxy and is visible to the naked eye. Estimate its brightness relative to the Sun, assuming it has luminosity 10^{12} times that of the Sun and lies 2 Mly away.

Show Solution

6×10^{-11} (an overestimate, since some of the light from Andromeda is blocked by gas and dust within that galaxy)

(a) A particle and its antiparticle are at rest relative to an observer and annihilate (completely destroying both masses), creating two γ rays of equal energy. What is the characteristic γ -ray energy you would look for if searching for evidence of proton-antiproton annihilation? (The fact that such radiation is rarely observed is evidence that there is very little antimatter in the universe.) (b) How does this compare with the 0.511-MeV energy associated with electron-positron annihilation?

Show Solution

Strategy

(a) When a particle and antiparticle at rest annihilate, conservation of energy and momentum requires that two photons of equal energy be produced (moving in opposite directions to conserve momentum). The total energy available is the sum of the rest mass energies of both particles. For a proton-antiproton pair, each has a rest mass energy of approximately 938 MeV, so the total is divided equally between the two photons.

(b) We'll compare the proton-antiproton annihilation energy per photon with the electron-positron annihilation energy per photon (0.511 MeV).

Solution

(a) The rest mass energy of a proton is:

$$E_p=m_pc^{2}=938.3\text{ MeV}$$

When a proton and antiproton annihilate at rest, the total energy is:

$$E_{\text{total}}=2m_pc^{2}=2\times 938.3\text{ MeV}=1877\text{ MeV}$$

This energy is shared equally between two photons, so each photon has energy:

$$E_\gamma=\frac{E_{\text{total}}}{2}=\frac{1877\text{ MeV}}{2}=938\text{ MeV}$$

(b) The ratio of the proton-antiproton annihilation photon energy to the electron-positron annihilation photon energy is:

$\frac{E_{\gamma}(p\text{-}\bar{p})}{E_{\gamma}(e^{+}-e^{-})}=\frac{938\text{ MeV}}{0.511\text{ MeV}}=1836$

The proton-antiproton annihilation produces photons with **1836 times** more energy than electron-positron annihilation.

Discussion

We would look for **938-MeV gamma rays** as evidence of proton-antiproton annihilation. This is a very specific signature—gamma rays of this energy would be a clear indicator of matter-antimatter annihilation involving baryons. The fact that we don't observe significant amounts of 938-MeV gamma radiation from space provides strong evidence that the universe is dominated by matter, not antimatter. If there were substantial amounts of antimatter in the form of anti-galaxies or anti-stars, we would expect to see annihilation radiation at the boundaries where matter and antimatter regions meet.

The comparison with electron-positron annihilation is revealing: the energy ratio of 1836 is exactly the mass ratio of the proton to the electron. This makes perfect sense from Einstein's mass-energy relation $E = mc^2$—the annihilation energy is directly proportional to the particle mass. The 0.511-MeV photons from electron-positron annihilation are relatively common in certain astrophysical environments and can be detected by gamma-ray telescopes. The 938-MeV photons from proton-antiproton annihilation would be even more energetic and equally detectable if they existed in significant quantities. The rarity of such observations confirms that the matter-antimatter asymmetry in the universe is profound: essentially all of the universe we can observe is made of ordinary matter, with antimatter being produced only briefly in high-energy collisions or certain radioactive decays before quickly annihilating with the abundant matter around it.

The average particle energy needed to observe unification of forces is estimated to be 10^{19}GeV . (a) What is the rest mass in kilograms of a particle that has a rest mass of $10^{19}\text{GeV}/c^2$? (b) How many times the mass of a hydrogen atom is this?

Show Solution

(a) $2 \times 10^{-8}\text{kg}$ (b) 1×10^{19}

The peak intensity of the CMBR occurs at a wavelength of 1.1 mm. (a) What is the energy in eV of a 1.1-mm photon? (b) There are approximately 10^9 photons for each massive particle in deep space. Calculate the energy of 10^9 such photons. (c) If the average massive particle in space has a mass half that of a proton, what energy would be created by converting its mass to energy? (d) Does this imply that space is "matter dominated"? Explain briefly.

Show Solution

Strategy

(a) We'll use the photon energy formula $E = hf = hc/\lambda$ to find the energy of a 1.1-mm photon, then convert from joules to electron volts.

(b) We'll multiply the single-photon energy by 10^9 to find the total photon energy per massive particle.

(c) We'll use Einstein's mass-energy relation $E = mc^2$ with half the proton mass.

(d) We'll compare the energy densities from parts (b) and (c) to determine which dominates.

Solution

(a) The energy of a photon is:

$$E=\frac{hc}{\lambda}$$

where $h = 6.626 \times 10^{-34}$ J·s, $c = 3.00 \times 10^8$ m/s, and $\lambda = 1.1\text{ mm} = 1.1 \times 10^{-3}$ m.

$$E=\frac{(6.626\times10^{-34})(3.00\times10^{8})}{1.1\times10^{-3}}=1.81\times10^{-22}\text{ J}$$

Converting to eV (using $1\text{ eV} = 1.60 \times 10^{-19}$ J):

$$E=\frac{1.81\times10^{-22}\text{ J}}{1.60\times10^{-19}\text{ J/eV}}=1.13\times10^{-3}\text{ eV}=0.00113\text{ eV}$$

(b) The energy of 10^9 such photons:

$$E_{\text{photons}}=10^{9}\times1.13\times10^{-3}\text{ eV}=1.13\times10^{6}\text{ eV}=1.13\text{ MeV}$$

(c) The rest mass energy of a particle with half the proton mass:

$$E=mc^2=\frac{1}{2}m_pc^2=\frac{1}{2}\times938.3\text{ MeV}=469\text{ MeV}$$

(d) Comparing the energies:

$$\frac{E_{\text{matter}}}{E_{\text{radiation}}} = \frac{469\ \text{MeV}}{1.13\ \text{MeV}} \approx 415$$

Yes, this implies that space is **“matter dominated”** because the energy density in matter is about 415 times greater than the energy density in radiation.

Discussion

(a) The CMBR photons are very low energy: only **0.00113 eV** (or 1.13 meV). This is characteristic of microwave radiation from a blackbody at 2.7 K, confirming that the primordial fireball has cooled dramatically since the Big Bang.

(b) Even though there are a billion photons for each massive particle, their combined energy is only **1.13 MeV** due to their individual low energies. This demonstrates that while photons vastly outnumber massive particles in the universe, their total energy contribution is limited by their low individual energies.

(c) A single particle with half the proton’s mass has a rest energy of **469 MeV**, which is much larger than the combined energy of a billion CMBR photons.

(d) The universe today is indeed **matter-dominated**: the energy density in matter exceeds that in radiation by a factor of about 400. However, this wasn’t always the case! In the early universe, when temperatures were much higher, photons had much more energy, and radiation dominated. The transition from radiation-dominated to matter-dominated occurred about 50,000 years after the Big Bang, when the universe had cooled sufficiently that the energy density in matter began to exceed that in radiation. This transition is a crucial epoch in cosmology because it affects how structure formation proceeded. The fact that we live in a matter-dominated era means that gravity acting on matter (both ordinary and dark) is the primary driver of cosmic structure, allowing galaxies, stars, and planets to form. Interestingly, even though matter dominates over radiation today, recent evidence suggests that dark energy now dominates over matter, making our current era “dark energy dominated.”

(a) What Hubble constant corresponds to an approximate age of the universe of 10^{10} y? To get an approximate value, assume the expansion rate is constant and calculate the speed at which two galaxies must move apart to be separated by 1 Mly (present average galactic separation) in a time of 10^{10} y. (b) Similarly, what Hubble constant corresponds to a universe approximately 2×10^{10} -y old?

Show Solution

(a) $30\text{km/s}\cdot\text{Mly}$ (b) $15\text{km/s}\cdot\text{Mly}$

Show that the velocity of a star orbiting its galaxy in a circular orbit is inversely proportional to the square root of its orbital radius, assuming the mass of the stars inside its orbit acts like a single mass at the center of the galaxy. You may use an equation from a previous chapter to support your conclusion, but you must justify its use and define all terms used.

Show Solution

Strategy

For a star in a circular orbit around the galactic center, the gravitational force provides the centripetal force needed to maintain the circular motion. We’ll equate these two forces and solve for the orbital velocity. By examining how velocity depends on radius, we can demonstrate the inverse square root relationship.

Solution

Consider a star of mass m orbiting at radius r from the galactic center with orbital speed v. Let M be the total mass of all stars within the orbit, which we treat as concentrated at the galactic center.

The gravitational force on the star is given by Newton’s law of universal gravitation:

$$F_{\text{grav}} = \frac{GMm}{r^2}$$

where $G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$ is the gravitational constant.

For circular motion, the required centripetal force is:

$$F_{\text{cent}} = \frac{mv^2}{r}$$

This equation comes from Newton’s second law applied to circular motion, where the centripetal acceleration is $a_c = v^2/r$.

Setting the gravitational force equal to the centripetal force:

$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

Canceling m from both sides and multiplying both sides by r:

$$\frac{GM}{r} = v^2$$

Solving for v:

$$v=\sqrt{\frac{GM}{r}}=\sqrt{GM}\cdot\frac{1}{\sqrt{r}}$$

This can be written as:

$$v=\frac{k}{\sqrt{r}}$$

where $k=\sqrt{GM}$ is a constant (assuming M is constant).

Therefore, **the orbital velocity is inversely proportional to the square root of the orbital radius**: $v \propto r^{-1/2}$ or $v \propto 1/\sqrt{r}$.

Discussion

This derivation shows that for a star orbiting a galaxy, if all the mass interior to the orbit can be treated as concentrated at the center, then the orbital velocity should decrease as we move farther from the galactic center, following a $1/\sqrt{r}$ relationship. This is exactly analogous to planetary motion in our solar system, where planets farther from the Sun orbit more slowly according to Kepler's laws.

However, this prediction is **not** what astronomers observe when they measure galactic rotation curves! Actual observations show that the orbital velocities of stars remain roughly constant (or even slightly increase) at large radii, rather than decreasing as $1/\sqrt{r}$. This discrepancy is one of the strongest pieces of evidence for dark matter. The flat rotation curves can be explained if there is a massive dark matter halo surrounding the galaxy, such that the mass M enclosed within radius r continues to increase with radius, rather than remaining constant. If $M \propto r$, then $v=\sqrt{GM/r} \propto \sqrt{r/r}=\text{constant}$, which matches observations. The study of galactic rotation curves has therefore revealed that galaxies contain far more mass than can be accounted for by visible stars, gas, and dust—this additional mass is the mysterious dark matter that makes up about 85% of the total matter in the universe.

The core of a star collapses during a supernova, forming a neutron star. Angular momentum of the core is conserved, and so the neutron star spins rapidly. If the initial core radius is $5.0\times10^5\,\text{km}$ and it collapses to 10.0 km, find the neutron star's angular velocity in revolutions per second, given the core's angular velocity was originally 1 revolution per 30.0 days.

Show Solution

960 rev/s

Using data from the previous problem, find the increase in rotational kinetic energy, given the core's mass is 1.3 times that of our Sun. Where does this increase in kinetic energy come from?

Show Solution

Strategy

We need to calculate the rotational kinetic energy before and after the collapse using $KE_{\text{rot}}=\frac{1}{2}I\omega^2$, where the moment of inertia for a sphere is $I=\frac{2}{5}MR^2$. From the previous problem, we know the initial and final radii and angular velocities. The increase in kinetic energy comes from gravitational potential energy released during the collapse.

Solution

From the previous problem:

- Initial radius: $R_i=5.0\times10^5$ km $=5.0\times10^8$ m
- Final radius: $R_f=10.0$ km $=1.0\times10^4$ m
- Initial angular velocity: $\omega_i=\frac{1\text{ rev}}{30.0\text{ days}}=\frac{2\pi}{30.0\times24\times3600}=2.42\times10^{-6}$ rad/s
- Final angular velocity: $\omega_f=960$ rev/s $=960\times2\pi=6030$ rad/s
- Mass: $M=1.3M_{\text{Sun}}=1.3\times2.0\times10^{30}$ kg $=2.6\times10^{30}$ kg

Initial moment of inertia:

$$I_i=\frac{2}{5}MR_i^2=\frac{2}{5}(2.6\times10^{30})(5.0\times10^8)^2=2.6\times10^{47}\ \text{kg}\cdot\text{m}^2$$

Initial rotational kinetic energy:

$$KE_i=\frac{1}{2}I_i\omega_i^2=\frac{1}{2}(2.6\times10^{47})(2.42\times10^{-6})^2=7.6\times10^{35}\ \text{J}$$

Final moment of inertia:

$$I_f=\frac{2}{5}MR_f^2=\frac{2}{5}(2.6\times10^{30})(1.0\times10^4)^2=1.04\times10^{38}\ \text{kg}\cdot\text{m}^2$$

Final rotational kinetic energy:

$$KE_f = \frac{1}{2} I_f \omega_f^2 = \frac{1}{2}(1.04\times10^{38})(6030)^2 = 1.9\times10^{45}\ \text{J}$$

Increase in rotational kinetic energy:

$$\Delta KE = KE_f - KE_i = 1.9\times10^{45} - 7.6\times10^{35} \approx 1.9\times10^{45}\ \text{J}$$

(Note that KE_i is negligible compared to KE_f.)

Where does this energy come from? This enormous increase in rotational kinetic energy comes from **gravitational potential energy** released during the collapse of the core.

Discussion

The increase in rotational kinetic energy is approximately **1.9×10^{45} J**, which is an absolutely staggering amount of energy. To put this in perspective, this is about 100,000 times the energy our Sun will radiate over its entire 10-billion-year lifetime! The initial rotational kinetic energy (7.6×10^{35} J) is completely negligible compared to the final value, demonstrating the dramatic acceleration that occurs during collapse.

This energy comes from gravitational potential energy released as the core contracts. When a star's core collapses during a supernova, it falls inward under its own gravity, releasing enormous amounts of gravitational potential energy. Most of this energy (about 99%) is actually carried away by neutrinos, but some goes into the kinetic energy of the explosion, heating the surrounding material, and—as we see here—into rotational kinetic energy. Because angular momentum is conserved during the collapse ($L = I\omega = \text{constant}$), as the moment of inertia decreases by a factor of about 10^9 (due to the radius shrinking by a factor of 50,000), the angular velocity must increase by the same factor. This results in the spectacular increase in rotational kinetic energy we calculated.

Neutron stars are among the fastest-rotating objects in the universe, and pulsars (rotating neutron stars that emit beams of radiation) can spin hundreds of times per second, as in this problem. The regular pulses we detect from pulsars are like cosmic lighthouses, and they are among the most precise clocks in nature. Some millisecond pulsars are even more stable than atomic clocks over certain time scales!

Distances to the nearest stars (up to 500 ly away) can be measured by a technique called parallax, as shown in [Figure 2]. What are the angles θ_1 and θ_2 relative to the plane of the Earth's orbit for a star 4.0 ly directly above the Sun?

Show Solution

89.999773° (many digits are used to show the difference between 90°)

(a) Use the Heisenberg uncertainty principle to calculate the uncertainty in energy for a corresponding time interval of 10^{-43}s . (b) Compare this energy with the 10^{19}GeV unification-of-forces energy and discuss why they are similar.

Show Solution

Strategy

(a) The Heisenberg uncertainty principle relating energy and time states that $\Delta E \Delta t \geq \hbar/2$, where $\hbar = h/(2\pi)$ is the reduced Planck constant. We can rearrange this to find the minimum energy uncertainty for a given time interval.

(b) We'll compare our calculated energy with the unification energy and explain the physical significance of the time interval 10^{-43} s, which is the Planck time.

Solution

(a) The Heisenberg uncertainty principle for energy and time is:

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

where $\hbar = \frac{h}{2\pi} = \frac{6.626\times10^{-34}}{2\pi} = 1.055\times10^{-34}$ J·s.

For the minimum uncertainty:

$$\Delta E = \frac{\hbar}{2\Delta t} = \frac{1.055\times10^{-34}\ \text{J·s}}{2\times10^{-43}\ \text{s}} = 5.28\times10^{8}\ \text{J}$$

Converting to GeV (using $1\ \text{GeV} = 1.60\times10^{-10}$ J):

$$\Delta E = \frac{5.28\times10^{8}\ \text{J}}{1.60\times10^{-10}\ \text{J/GeV}} = 3.3\times10^{18}\ \text{GeV}$$

(b) Comparing with the unification energy:

$$\frac{\Delta E}{E_{\text{unification}}} = \frac{3.3\times10^{18}\ \text{GeV}}{10^{19}\ \text{GeV}} \approx 0.3$$

The calculated energy uncertainty is **of the same order of magnitude** as the unification-of-forces energy (within a factor of 3).

Discussion

The remarkable similarity between these two energies is not a coincidence—it reveals a profound connection between quantum mechanics, gravity, and the fundamental structure of spacetime. The time interval 10^{-43} s is known as the **Planck time**, the fundamental quantum timescale below which our current understanding of physics breaks down. It is defined as:

$$t_{\text{Planck}}=\sqrt{\hbar G c^5}\approx 5.4\times 10^{-44}\ \text{s}$$

At this timescale, quantum fluctuations in spacetime itself become significant, and a complete theory of quantum gravity (Theory of Everything) would be needed to describe physics. The corresponding energy scale, called the **Planck energy**, is:

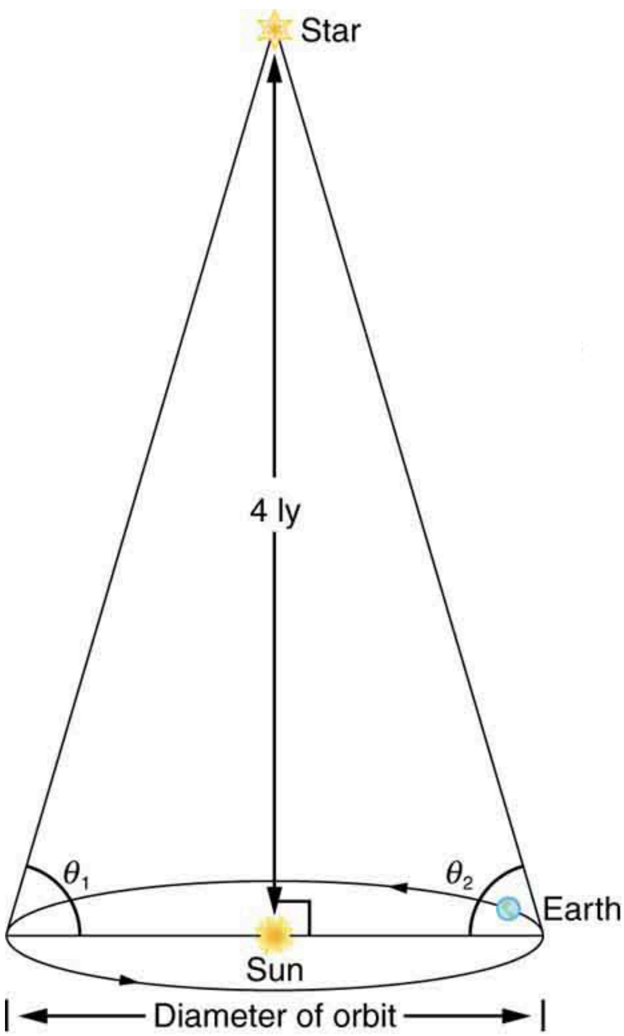
$$E_{\text{Planck}}=\sqrt{\hbar c^5 G}\approx 1.2\times 10^{19}\ \text{GeV}$$

This is exactly the energy scale at which all four fundamental forces (electromagnetic, weak, strong, and gravitational) are expected to unify into a single superforce! The Heisenberg uncertainty principle provides the bridge: for processes occurring on the Planck timescale, the energy uncertainty is necessarily on the order of the Planck energy.

This connection tells us that the TOE epoch immediately after the Big Bang (before 10^{-43} s) was governed by physics at the Planck scale, where spacetime itself was subject to violent quantum fluctuations. At these energies and timescales, the distinctions between forces disappear, and the universe was truly unified. The fact that these fundamental scales emerge from combining the constants of quantum mechanics ($\hbar$), gravity (G), and relativity (c) suggests that a complete theory of nature must incorporate all three domains—which is exactly what physicists are striving to achieve with theories like string theory and loop quantum gravity.

Construct Your Own Problem

Consider a star moving in a circular orbit at the edge of a galaxy. Construct a problem in which you calculate the mass of that galaxy in kg and in multiples of the solar mass based on the velocity of the star and its distance from the center of the galaxy.



Distances to nearby stars are measured using triangulation, also called the parallax method. The angle of line of sight to the star is measured at intervals six months apart, and the distance is calculated by using the known diameter of the Earth's orbit. This can be done for stars up to about 500 ly away.

Show Solution

Sample Problem

Astronomers observe a star in a circular orbit at the outer edge of a spiral galaxy. Spectroscopic measurements reveal that the star is moving at a velocity of 220 km/s, and its distance from the galactic center is measured to be 50,000 light years. Calculate the mass of the galaxy (a) in kilograms, and (b) in multiples of the solar mass. Assume all the galaxy’s mass is contained within the star’s orbit and acts as if concentrated at the galactic center.

Strategy

For a star in circular orbit, the gravitational force provides the centripetal force. Setting these equal gives us $GMm/r^2 = mv^2/r$, which simplifies to $M = v^2 r/G$. We need to convert the distance to meters, calculate the mass in kilograms, then convert to solar masses.

Solution

Given information:

- Orbital velocity: $v = 220 \text{ km/s} = 2.20 \times 10^5 \text{ m/s}$
- Orbital radius: $r = 50{,}000 \text{ ly}$

Convert the radius to meters:

$$r = 50{,}000 \text{ ly} \times 9.46 \times 10^{15} \text{ m/ly} = 4.73 \times 10^{20} \text{ m}$$

From the condition that gravitational force equals centripetal force:

$$GMmr^2 = mv^2r$$

Solving for the galactic mass M:

$$M = v^2rG$$

(a) Substituting values (with $G = 6.67 \times 10^{-11} \text{ N·m}^2/\text{kg}^2$):

$$M = (2.20 \times 10^5)^2 \times 4.73 \times 10^{20} 6.67 \times 10^{-11}$$
$$M = 4.84 \times 10^{10} \times 4.73 \times 10^{20} 6.67 \times 10^{-11} = 2.29 \times 10^{31} 6.67 \times 10^{-11} = 3.4 \times 10^{41} \text{ kg}$$

(b) Converting to solar masses (using $M_{\text{Sun}} = 2.0 \times 10^{30}$ kg):

$$M = 3.4 \times 10^{41} \text{ kg} 2.0 \times 10^{30} \text{ kg} = 1.7 \times 10^{11} M_{\text{Sun}}$$

Answer: The mass of the galaxy is **(a) 3.4 × 10^{41} kg** and **(b) 1.7 × 10^{11} solar masses** (or 170 billion solar masses).

Discussion

This problem demonstrates how astronomers determine galactic masses using orbital dynamics. The calculated mass of 170 billion solar masses is typical for a large spiral galaxy like the Milky Way. This method, based on Newtonian mechanics, is remarkably powerful—it allows us to “weigh” entire galaxies from Earth by observing the motion of stars or gas clouds at their edges.

However, this calculation reveals only the mass within the star’s orbit. Additional mass may exist beyond this radius, which is why astronomers study rotation curves at various distances to build up a complete picture of a galaxy’s mass distribution. When this analysis is performed for most galaxies, a surprising result emerges: the orbital velocities of stars remain nearly constant (or even increase slightly) at large radii, rather than decreasing as expected from the visible matter distribution. This observation, first made by astronomer Vera Rubin in the 1970s, provided some of the strongest evidence for dark matter—invisible matter that extends far beyond the visible edges of galaxies in massive halos.

Students constructing their own version of this problem should choose reasonable values: orbital velocities typically range from 150-300 km/s for spiral galaxies, and orbital radii from 10,000 to 100,000 light years. The resulting masses should be on the order of 10^{10} to 10^{12} solar masses for typical galaxies. This exercise reinforces the connection between observable kinematics and invisible mass—a fundamental technique in modern astrophysics.

Glossary

Big Bang
: a gigantic explosion that threw out matter a few billion years ago

cosmic microwave background
: the spectrum of microwave radiation of cosmic origin

cosmological red shift

the photon wavelength is stretched in transit from the source to the observer because of the expansion of space itself

cosmology
: the study of the character and evolution of the universe

electroweak epoch
: the stage before 10^{-11} back to 10^{-34} after the Big Bang

GUT epoch
: the time period from 10^{-43} to 10^{-34} after the Big Bang, when Grand Unification Theory, in which all forces except gravity are identical, governed the universe

Hubble constant
: a central concept in cosmology whose value is determined by taking the slope of a graph of velocity versus distance, obtained from red shift measurements

inflationary scenario
: the rapid expansion of the universe by an incredible factor of 10^{-50} for the brief time from 10^{-35} to about 10^{-32}s

spontaneous symmetry breaking
: the transition from GUT to electroweak where the forces were no longer unified

superforce
: hypothetical unified force in TOE epoch

TOE epoch
: before 10^{-43} after the Big Bang

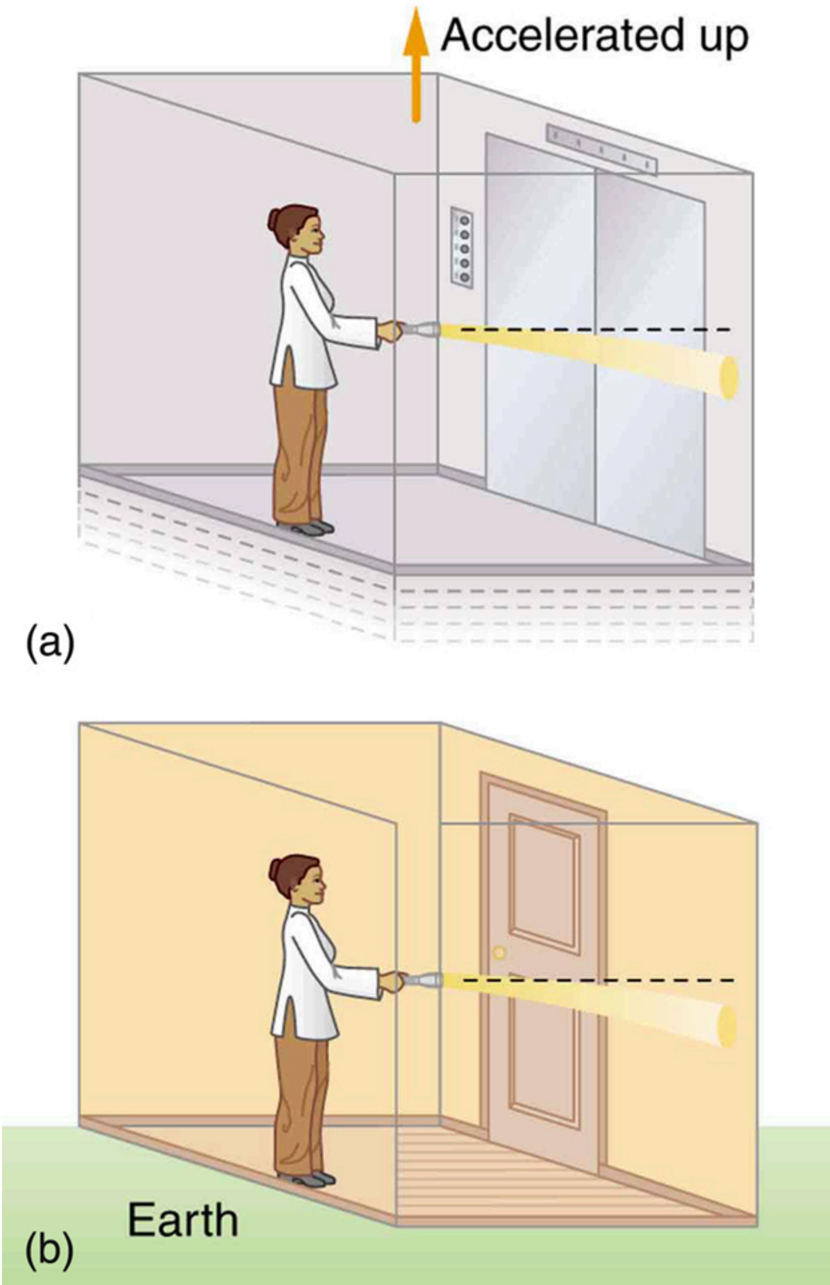
General Relativity and Quantum Gravity

- Explain the effect of gravity on light.
- Discuss black hole.
- Explain quantum gravity.

When we talk of black holes or the unification of forces, we are actually discussing aspects of general relativity and quantum gravity. We know from Special Relativity that relativity is the study of how different observers measure the same event, particularly if they move relative to one another. Einstein's theory of **general relativity** describes all types of relative motion including accelerated motion and the effects of gravity. General relativity encompasses special relativity and classical relativity in situations where acceleration is zero and relative velocity is small compared with the speed of light. Many aspects of general relativity have been verified experimentally, some of which are better than science fiction in that they are bizarre but true. **Quantum gravity** is the theory that deals with particle exchange of gravitons as the mechanism for the force, and with extreme conditions where quantum mechanics and general relativity must both be used. A good theory of quantum gravity does not yet exist, but one will be needed to understand how all four forces may be unified. If we are successful, the theory of quantum gravity will encompass all others, from classical physics to relativity to quantum mechanics—truly a Theory of Everything (TOE).

General Relativity

Einstein first considered the case of no observer acceleration when he developed the revolutionary special theory of relativity, publishing his first work on it in 1905. By 1916, he had laid the foundation of general relativity, again almost on his own. Much of what Einstein did to develop his ideas was to mentally analyze certain carefully and clearly defined situations—doing this is to perform a **thought experiment**. [Figure 1] illustrates a thought experiment like the ones that convinced Einstein that light must fall in a gravitational field. Think about what a person feels in an elevator that is accelerated upward. It is identical to being in a stationary elevator in a gravitational field. The feet of a person are pressed against the floor, and objects released from hand fall with identical accelerations. In fact, it is not possible, without looking outside, to know what is happening—acceleration upward or gravity. This led Einstein to correctly postulate that acceleration and gravity will produce identical effects in all situations. So, if acceleration affects light, then gravity will, too. [Figure 1] shows the effect of acceleration on a beam of light shone horizontally at one wall. Since the accelerated elevator moves up during the time light travels across the elevator, the beam of light strikes low, seeming to the person to bend down. (Normally a tiny effect, since the speed of light is so great.) The same effect must occur due to gravity, Einstein reasoned, since there is no way to tell the effects of gravity acting downward from acceleration of the elevator upward. Thus gravity affects the path of light, even though we think of gravity as acting between masses and photons are massless.

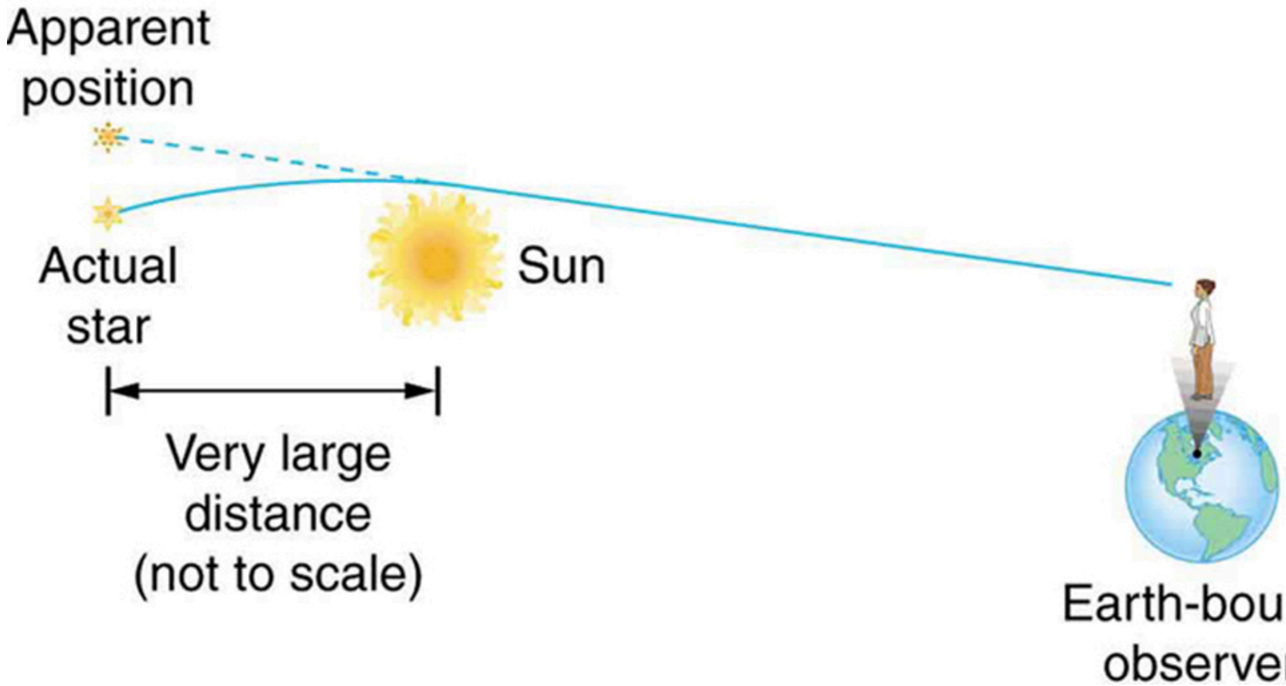


(a) A beam of light emerges from a flashlight in an upward-accelerating elevator. Since the elevator moves up during the time the light takes to reach the wall, the beam strikes lower than it would if the elevator were not accelerated. (b) Gravity has the same effect on light, since it is not possible to tell whether the elevator is accelerating upward or acted upon by gravity.

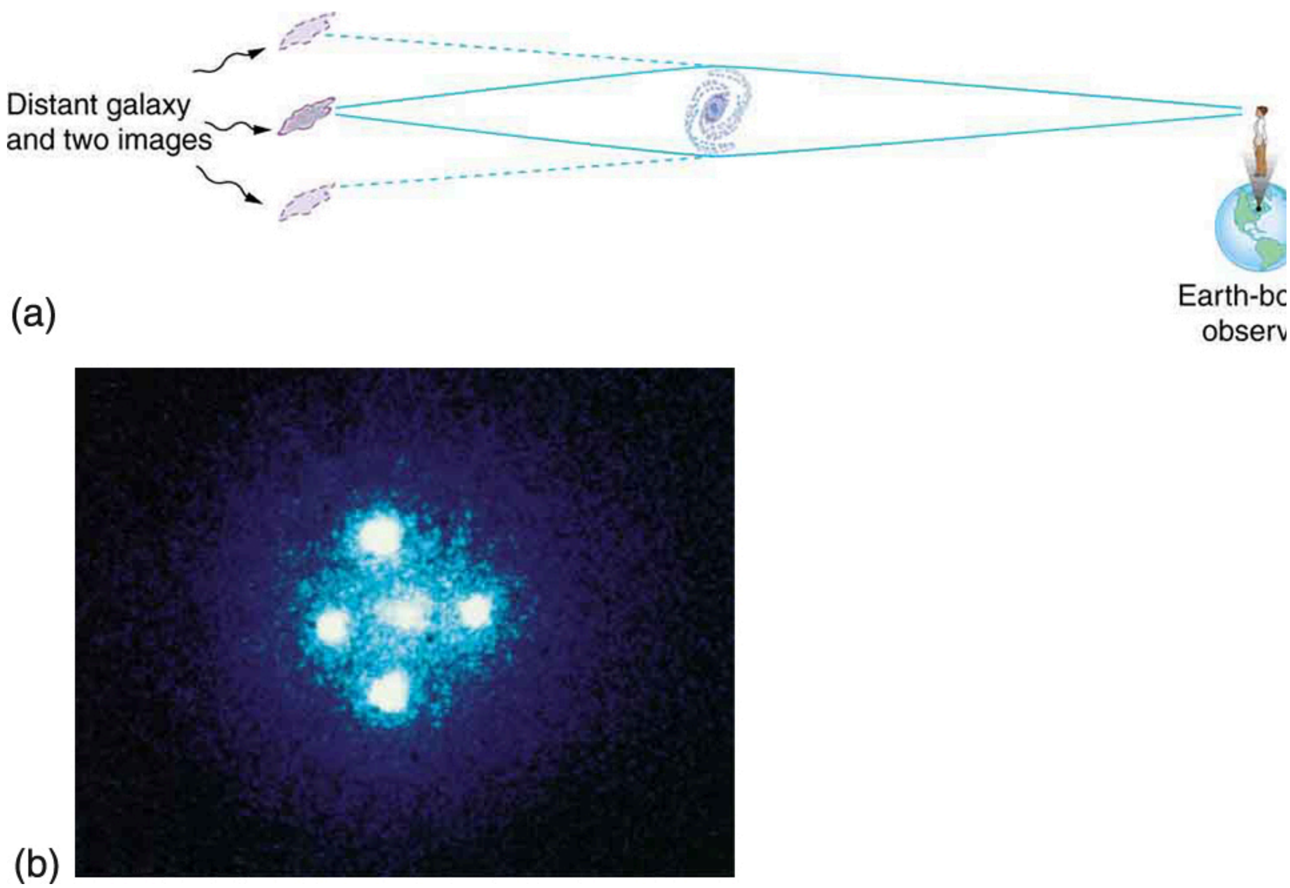
Einstein's theory of general relativity got its first verification in 1919 when starlight passing near the Sun was observed during a solar eclipse. (See [Figure 2].) During an eclipse, the sky is darkened and we can briefly see stars. Those in a line of sight nearest the Sun should have a shift in their apparent positions. Not only was this shift observed, but it agreed with Einstein's predictions well within experimental uncertainties. This discovery created a scientific and public sensation. Einstein was now a folk hero as well as a very great scientist. The bending of light by matter is equivalent to a bending of space itself, with light following the curve. This is another radical change in our concept of space and time. It is also another connection that any particle with mass or energy (massless photons) is affected by gravity.

There are several current forefront efforts related to general relativity. One is the observation and analysis of gravitational lensing of light. Another is analysis of the definitive proof of the existence of black holes. Direct observation of gravitational waves or moving wrinkles in space is being searched for. Theoretical efforts are also being aimed at the possibility of time travel and wormholes into other parts of space due to black holes.

Gravitational lensing As you can see in [Figure 2], light is bent toward a mass, producing an effect much like a converging lens (large masses are needed to produce observable effects). On a galactic scale, the light from a distant galaxy could be "lensed" into several images when passing close by another galaxy on its way to Earth. Einstein predicted this effect, but he considered it unlikely that we would ever observe it. A number of cases of this effect have now been observed; one is shown in [Figure 3]. This effect is a much larger scale verification of general relativity. But such gravitational lensing is also useful in verifying that the red shift is proportional to distance. The red shift of the intervening galaxy is always less than that of the one being lensed, and each image of the lensed galaxy has the same red shift. This verification supplies more evidence that red shift is proportional to distance. Confidence that the multiple images are not different objects is bolstered by the observations that if one image varies in brightness over time, the others also vary in the same manner.



This schematic shows how light passing near a massive body like the Sun is curved toward it. The light that reaches the Earth then seems to be coming from different locations than the known positions of the originating stars. Not only was this effect observed, the amount of bending was precisely what Einstein predicted in his general theory of relativity.



(a) Light from a distant galaxy can travel different paths to the Earth because it is bent around an intermediary galaxy by gravity. This produces several images of the more distant galaxy. (b) The images around the central galaxy are produced by gravitational lensing. Each image has the same spectrum and a larger red shift than the intermediary. (credit: NASA, ESA, and STScI)

Black holesBlack holes are objects having such large gravitational fields that things can fall in, but nothing, not even light, can escape. Bodies, like the Earth or the Sun, have what is called an **escape velocity**. If an object moves straight up from the body, starting at the escape velocity, it will just be able to escape the gravity of the body. The greater the acceleration of gravity on the body, the greater is the escape velocity. As long ago as the late 1700s, it was proposed that if the escape velocity is greater than the speed of light, then light cannot escape. Simon Laplace (1749–1827), the French astronomer and mathematician, even incorporated this idea of a dark star into his writings. But the idea was dropped after Young's double slit experiment showed light to be a wave. For some time, light was thought not to have particle characteristics and, thus, could not be acted upon by gravity. The idea of a black hole was very quickly reincarnated in 1916 after Einstein's theory of general relativity was published. It is now thought that black holes can form in the supernova collapse of a massive star, forming an object perhaps 10 km across and having a mass greater than that of our Sun. It is interesting that several prominent physicists who worked on the concept, including Einstein, firmly believed that nature would find a way to prohibit such objects.

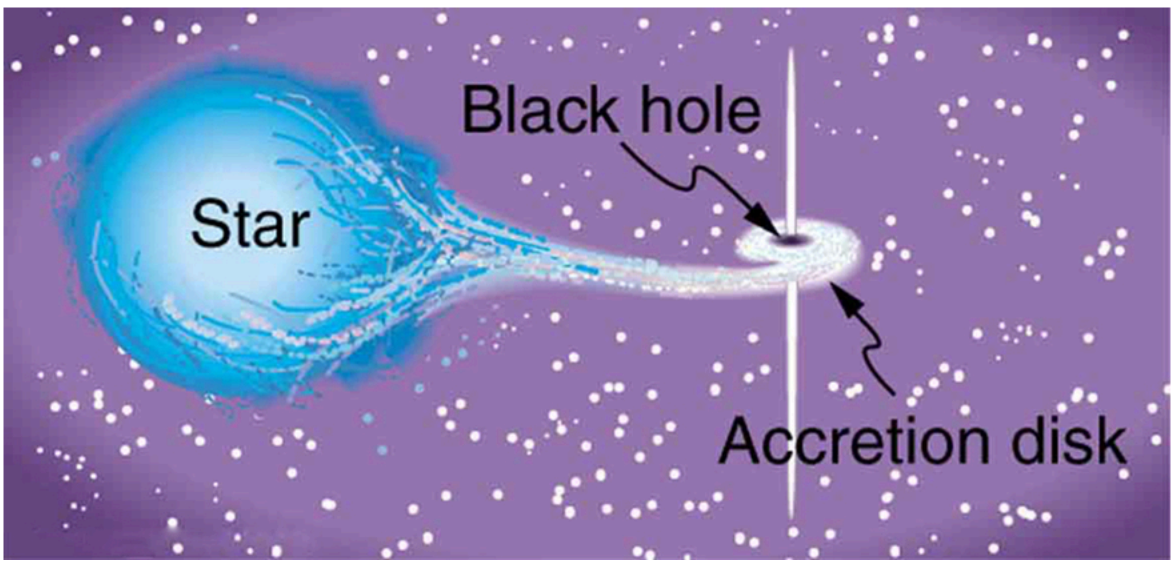
Black holes are difficult to observe directly, because they are small and no light comes directly from them. In fact, no light comes from inside the **event horizon**, which is defined to be at a distance from the object at which the escape velocity is exactly the speed of light. The radius of the event horizon is known as the **Schwarzschild radius** R_S and is given by

$$R_S = 2GMc^2,$$

where G is the universal gravitational constant, M ** is the mass of the body, and c is the speed of light. The event horizon is the edge of the black hole and R_S is its radius (that is, the size of a black hole is twice R_S). Since G is small and c^2 is large, you can see that black holes are extremely small, only a few kilometers for masses a little greater than the Sun's. The object itself is inside the event horizon.

Physics near a black hole is fascinating. Gravity increases so rapidly that, as you approach a black hole, the tidal effects tear matter apart, with matter closer to the hole being pulled in with much more force than that only slightly farther away. This can pull a companion star apart and heat inflowing gases to the point of producing X-rays. (See [Figure 4].) We have observed X rays from certain binary star systems that are consistent with such a picture. This is not quite proof of black holes, because the X-rays could also be caused by matter falling onto a neutron star. These objects were first discovered in 1967 by the British astrophysicists, Jocelyn Bell and Anthony Hewish. **Neutron stars** are literally a star composed of neutrons. They are formed by the collapse of a star's core in a supernova, during which electrons and protons are forced together to form neutrons (the reverse of neutron β decay). Neutron stars are slightly larger than a black hole of the same mass and will not collapse further because of resistance by the strong force. However, neutron stars cannot have a mass greater than about eight solar masses or they must collapse to a black hole. With recent improvements in our ability to resolve small details, such as with the orbiting Chandra X-ray Observatory, it has become possible to measure the masses of X-ray-emitting objects by observing the motion of companion stars and other matter in their vicinity. What has emerged is a plethora of X-ray-emitting objects too massive to be neutron stars. This evidence is considered conclusive and the existence of black holes is widely accepted. These black holes are concentrated near galactic centers.

We also have evidence that supermassive black holes may exist at the cores of many galaxies, including the Milky Way. Such a black hole might have a mass millions or even billions of times that of the Sun, and it would probably have formed when matter first coalesced into a galaxy billions of years ago. Supporting this is the fact that very distant galaxies are more likely to have abnormally energetic cores. Some of the moderately distant galaxies, and hence among the younger, are known as **quasars** and emit as much or more energy than a normal galaxy but from a region less than a light year across. Quasar energy outputs may vary in times less than a year, so that the energy-emitting region must be less than a light year across. The best explanation of quasars is that they are young galaxies with a supermassive black hole forming at their core, and that they become less energetic over billions of years. In closer superactive galaxies, we observe tremendous amounts of energy being emitted from very small regions of space, consistent with stars falling into a black hole at the rate of one or more a month. The Hubble Space Telescope (1994) observed an accretion disk in the galaxy M87 rotating rapidly around a region of extreme energy emission. (See [Figure 4].) A jet of material being ejected perpendicular to the plane of rotation gives further evidence of a supermassive black hole as the engine.



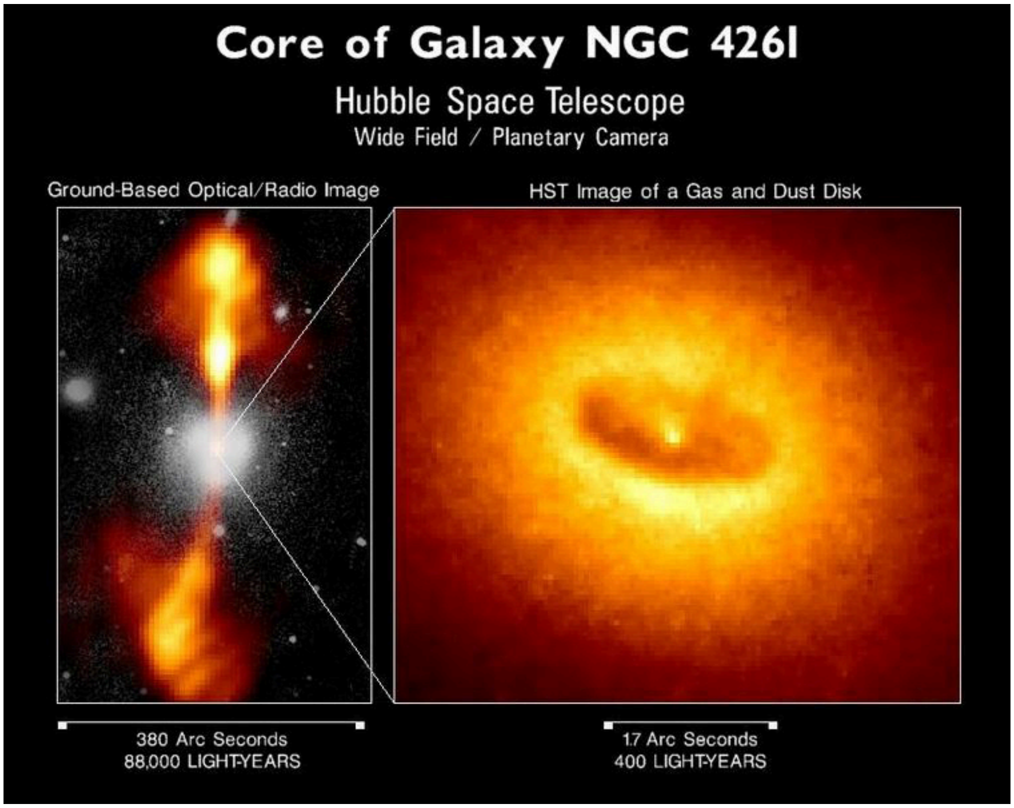
A black hole is shown pulling matter away from a companion star, forming a superheated accretion disk where X-rays are emitted before the matter disappears forever into the hole. The in-fall energy also ejects some material, forming the two vertical spikes. (See also the photograph in Introduction to Frontiers of Physics.) There are several X-ray-emitting objects in space that are consistent with this picture and are likely to be black holes.

Gravitational waves If a massive object distorts the space around it, like the foot of a water bug on the surface of a pond, then movement of the massive object should create waves in space like those on a pond. **Gravitational waves** are mass-created distortions in space that propagate at the speed of light and are predicted by general relativity. Since gravity is by far the weakest force, extreme conditions are needed to generate significant gravitational waves.

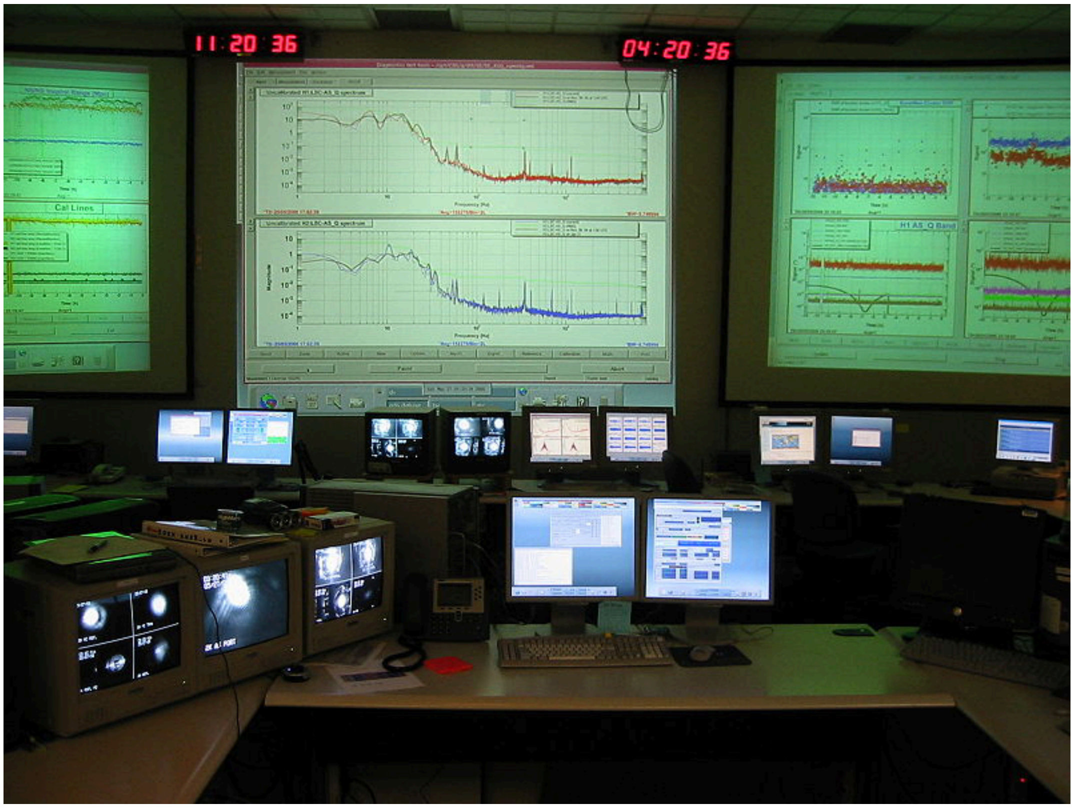
Gravity near binary neutron star systems is so great that significant gravitational wave energy is radiated as the two neutron stars orbit one another. American astronomers, Joseph Taylor and Russell Hulse, measured changes in the orbit of such a binary neutron star system. They found its orbit to change precisely as predicted by general relativity, a strong indication of gravitational waves, and were awarded the 1993 Nobel Prize. But direct detection of gravitational waves on Earth would be conclusive. For many years, various attempts have been made to detect gravitational waves by observing vibrations induced in matter distorted by these waves. American physicist Joseph Weber pioneered this field in the 1960s. Gravitational wave signals were first observed directly on September 14, 2015 by the LIGO system. On February 11, 2016, LIGO and the VIRGO facility announced the first confirmed observation of gravitational waves from colliding black holes. There are now several ambitious systems of gravitational wave detectors in use around the world. These include the LIGO (Laser Interferometer Gravitational Wave Observatory) system with two laser interferometer detectors, one in the state of Washington and another in Louisiana (See [Figure 6]) and the VIRGO (Variability of Irradiance and Gravitational Oscillations) facility in Italy with a single detector. Since then, LIGO has discovered additional merger events and neutron star collisions.

Quantum Gravity

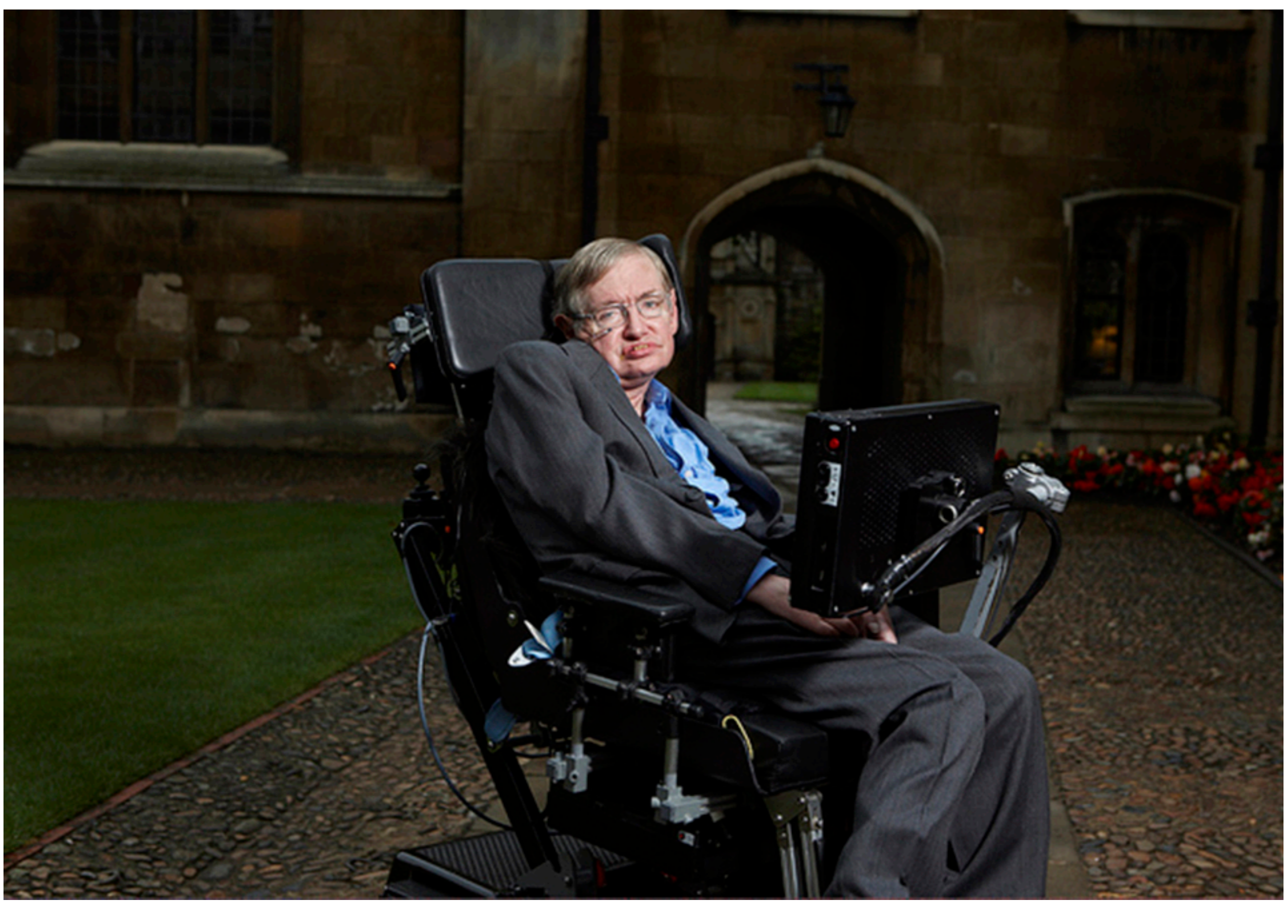
Black holes radiate Quantum gravity is important in those situations where gravity is so extremely strong that it has effects on the quantum scale, where the other forces are ordinarily much stronger. The early universe was such a place, but black holes are another. The first significant connection between gravity and quantum effects was made by the Russian physicist Yakov Zel'dovich in 1971, and other significant advances followed from the British physicist Stephen Hawking. (See [Figure 7] .) These two showed that black holes could radiate away energy by quantum effects just outside the event horizon (nothing can escape from inside the event horizon). Black holes are, thus, expected to radiate energy and shrink to nothing, although extremely slowly for most black holes. The mechanism is the creation of a particle-antiparticle pair from energy in the extremely strong gravitational field near the event horizon. One member of the pair falls into the hole and the other escapes, conserving momentum. (See [Figure 8] .) When a black hole loses energy and, hence, rest mass, its event horizon shrinks, creating an even greater gravitational field. This increases the rate of pair production so that the process grows exponentially until the black hole is nuclear in size. A final burst of particles and γ rays ensues. This is an extremely slow process for black holes about the mass of the Sun (produced by supernovas) or larger ones (like those thought to be at galactic centers), taking on the order of 10^{67} years or longer! Smaller black holes would evaporate faster, but they are only speculated to exist as remnants of the Big Bang. Searches for characteristic γ -ray bursts have produced events attributable to more mundane objects like neutron stars accreting matter.



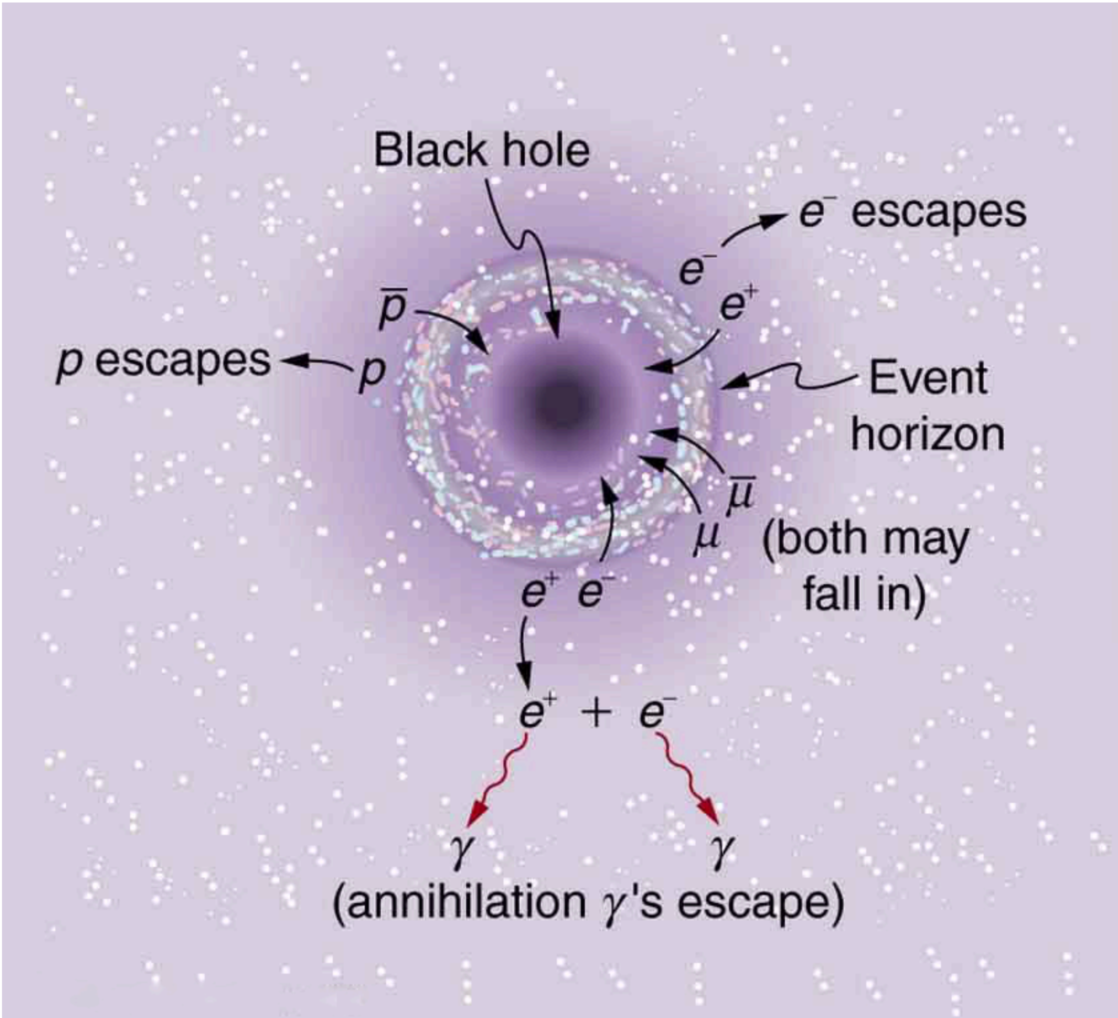
This Hubble Space Telescope photograph shows the extremely energetic core of the NGC 4261 galaxy. With the superior resolution of the orbiting telescope, it has been possible to observe the rotation of an accretion disk around the energy-producing object as well as to map jets of material being ejected from the object. A supermassive black hole is consistent with these observations, but other possibilities are not quite eliminated. (credit: NASA and ESA)



The control room of the LIGO gravitational wave detector. Gravitational waves will cause extremely small vibrations in a mass in this detector, which will be detected by laser interferometer techniques. Such detection in coincidence with other detectors and with astronomical events, such as supernovas, would provide direct evidence of gravitational waves. (credit: Tobin Fricke)



Stephen Hawking (b. 1942) has made many contributions to the theory of quantum gravity. Hawking is a long-time survivor of ALS and has produced popular books on general relativity, cosmology, and quantum gravity. (credit: Lwp Kommunikáció)



Gravity and quantum mechanics come into play when a black hole creates a particle-antiparticle pair from the energy in its gravitational field. One member of the pair falls into the hole while the other escapes, removing energy and shrinking the black hole. The search is on for the characteristic energy.

Wormholes and time travel The subject of time travel captures the imagination. Theoretical physicists, such as the American Kip Thorne, have treated the subject seriously, looking into the possibility that falling into a black hole could result in popping up in another time and place—a trip through a so-called wormhole. Time travel and wormholes appear in innumerable science fiction dramatizations, but the consensus is that time travel is not possible in theory. While still debated, it appears that quantum gravity effects inside a black hole prevent time travel due to the creation of particle pairs. Direct evidence is elusive.

The shortest time Theoretical studies indicate that, at extremely high energies and correspondingly early in the universe, quantum fluctuations may make time intervals meaningful only down to some finite time limit. Early work indicated that this might be the case for times as long as 10^{-43}s , the time at which all forces were unified. If so, then it would be meaningless to consider the universe at times earlier than this. Subsequent studies indicate that the crucial time may be as short as 10^{-95}s . But the point remains—quantum gravity seems to imply that there is no such thing as a vanishingly short time. Time may, in fact, be grainy with no meaning to time intervals shorter than some tiny but finite size.

The future of quantum gravity Not only is quantum gravity in its infancy, no one knows how to get started on a theory of gravitons and unification of forces. The energies at which TOE should be valid may be so high (at least 10^{19}GeV) and the necessary particle separation so small (less than $10^{-35}m$) that only indirect evidence can provide clues. For some time, the common lament of theoretical physicists was one so familiar to struggling students—how do you even get started? But Hawking and others have made a start, and the approach many theorists have taken is called Superstring theory, the topic of the Superstrings.

Section Summary

- Einstein’s theory of general relativity includes accelerated frames and, thus, encompasses special relativity and gravity. Created by use of careful thought experiments, it has been repeatedly verified by real experiments.

- One direct result of this behavior of nature is the gravitational lensing** of light by massive objects, such as galaxies, also seen in the microlensing ** of light by smaller bodies in our galaxy.
- Another prediction is the existence of black holes, objects for which the escape velocity is greater than the speed of light and from which nothing can escape.
- The event horizon is the distance from the object at which the escape velocity equals the speed of light c . It is called the Schwarzschild radius R_S and is given by

  $$R_S=2GMc^2,$$

  where G is the universal gravitational constant, and M is the mass of the body.

- Physics is unknown inside the event horizon, and the possibility of wormholes and time travel are being studied.
- Candidates for black holes may power the extremely energetic emissions of quasars, distant objects that seem to be early stages of galactic evolution.
- Neutron stars are stellar remnants, having the density of a nucleus, that hint that black holes could form from supernovas, too.
- Gravitational waves are wrinkles in space, predicted by general relativity but not yet observed, caused by changes in very massive objects.
- Quantum gravity is an incompletely developed theory that strives to include general relativity, quantum mechanics, and unification of forces (thus, a TOE) .
- One unconfirmed connection between general relativity and quantum mechanics is the prediction of characteristic radiation from just outside black holes.

Conceptual Questions

Quantum gravity, if developed, would be an improvement on both general relativity and quantum mechanics, but more mathematically difficult. Under what circumstances would it be necessary to use quantum gravity? Similarly, under what circumstances could general relativity be used? When could special relativity, quantum mechanics, or classical physics be used?

Does observed gravitational lensing correspond to a converging or diverging lens? Explain briefly.

Suppose you measure the red shifts of all the images produced by gravitational lensing, such as in [Figure 3]. You find that the central image has a red shift less than the outer images, and those all have the same red shift. Discuss how this not only shows that the images are of the same object, but also implies that the red shift is not affected by taking different paths through space. Does it imply that cosmological red shifts are not caused by traveling through space (light getting tired, perhaps)?

What are gravitational waves, and have they yet been observed either directly or indirectly?

Is the event horizon of a black hole the actual physical surface of the object?

Suppose black holes radiate their mass away and the lifetime of a black hole created by a supernova is about 10^{67} years. How does this lifetime compare with the accepted age of the universe? Is it surprising that we do not observe the predicted characteristic radiation?

Problems & Exercises

What is the Schwarzschild radius of a black hole that has a mass eight times that of our Sun? Note that stars must be more massive than the Sun to form black holes as a result of a supernova.

Show Solution

23.6 km

Black holes with masses smaller than those formed in supernovas may have been created in the Big Bang. Calculate the radius of one that has a mass equal to the Earth’s.

Show Solution

Strategy

The Schwarzschild radius (event horizon radius) of a black hole is given by $R_S = 2GMc^2$, where G is the gravitational constant, M is the mass of the black hole, and c is the speed of light. We’ll substitute Earth’s mass and calculate the radius.

Solution

Given:

- Mass of Earth: $M_{\text{Earth}} = 5.97 \times 10^{24}$ kg
- Gravitational constant: $G = 6.67 \times 10^{-11}$ $\text{N}\cdot\text{m}^2/\text{kg}^2$
- Speed of light: $c = 3.00 \times 10^8$ m/s

The Schwarzschild radius is:

$$R_S=2GMc^2$$

Substituting values:

$$R_S=2\times(6.67\times10^{-11})\times(5.97\times10^{24})(3.00\times10^{8})^2$$
$$R_S=7.96\times10^{14}9.00\times10^{16}=8.84\times10^{-3}\text{ m}=8.84\text{ mm}$$

The Schwarzschild radius of an Earth-mass black hole is approximately **8.8 mm** (or about **0.9 cm**).

Discussion

If the entire Earth were compressed into a black hole, its event horizon would have a radius of less than **1 centimeter**—about the size of a marble! This astonishingly small size illustrates just how dense a black hole must be. The Earth's actual radius is about 6,371 km, so compressing it to a black hole would require reducing its radius by a factor of about 700 million while keeping all its mass.

This calculation reveals the extreme nature of black holes. For an object to become a black hole, it must be compressed to incredibly high densities. The average density required for Earth to become a black hole would be approximately $2\times10^{30}\text{ kg/m}^3$—far denser than any known material, even nuclear matter. For comparison, nuclear matter has a density of about 10^{17} kg/m^3, so a black hole's core would be trillions of times denser still.

Small primordial black holes like this (if they exist) would have formed in the extremely dense conditions of the early Big Bang, not through stellar collapse. A black hole with Earth's mass would be too small to form from normal astrophysical processes. According to Hawking radiation theory, such a small black hole would also evaporate relatively quickly (on cosmic timescales)—in roughly 10^{50} years. While this is still an enormous amount of time (far longer than the current age of the universe), it's much shorter than the lifetime of solar-mass black holes, which would take 10^{67} years or more to evaporate. The existence of primordial black holes remains hypothetical, but they are actively searched for as potential dark matter candidates.

Supermassive black holes are thought to exist at the center of many galaxies.

(a) What is the radius of such an object if it has a mass of 10^9 Suns?

(b) What is this radius in light years?

Show Solution

(a) $2.95\times10^{12}\text{m}$ (b) $3.12\times10^{-4}\text{ly}$

Construct Your Own Problem

Consider a supermassive black hole near the center of a galaxy. Calculate the radius of such an object based on its mass. You must consider how much mass is reasonable for these large objects, and which is now nearly directly observed. (Information on black holes posted on the Web by NASA and other agencies is reliable, for example.)

Show Solution

Sample Problem

Astronomers have observed the supermassive black hole Sagittarius A* (Sgr A*) at the center of our Milky Way galaxy. Based on observations of stellar orbits around this object, its mass has been determined to be approximately 4 million solar masses. Calculate (a) the Schwarzschild radius of this supermassive black hole in meters, (b) express this radius in kilometers, and (c) compare this radius to the Earth-Sun distance (1 AU = 1.50×10^{11} m).

Strategy

We'll use the Schwarzschild radius formula $R_S=2GMc^2$ with the mass of Sgr A*. We need to convert the mass from solar masses to kilograms, then calculate the radius and make the requested comparisons.

Solution

Given information:

- Mass of Sgr A*: $M=4.0\times10^6 M_\odot$
- Solar mass: $M_\odot=2.0\times10^{30}\text{ kg}$
- Gravitational constant: $G=6.67\times10^{-11}\text{ N}\cdot\text{m}^2/\text{kg}^2$
- Speed of light: $c=3.00\times10^8\text{ m/s}$

(a) Convert the mass to kilograms:

$$M=4.0\times10^6\times2.0\times10^{30}\text{ kg}=8.0\times10^{36}\text{ kg}$$

Calculate the Schwarzschild radius:

$$R_S = \frac{2GM}{c^2} = \frac{2 \times (6.67 \times 10^{-11}) \times (8.0 \times 10^{36})}{(3.00 \times 10^8)^2}$$

$$R_S = \frac{1.067 \times 10^{27}}{9.00 \times 10^{16}} = 1.19 \times 10^{10} \text{ m}$$

(b) Converting to kilometers:

$$R_S = 1.19 \times 10^{10} \text{ m} = 1.19 \times 10^{7} \text{ km} = 11{,}900{,}000 \text{ km} \approx 12 \text{ million km}$$

(c) Comparing to the Earth-Sun distance:

$$\frac{R_S}{1 \text{ AU}} = \frac{1.19 \times 10^{10} \text{ m}}{1.50 \times 10^{11} \text{ m}} = 0.079 \approx 0.08$$

The Schwarzschild radius is approximately **8%** of the Earth-Sun distance, or about **1/12 AU**.

Answer: The Schwarzschild radius of Sagittarius A* is **(a) 1.19 × 10^{10} m**, **(b) 12 million km**, and **(c) 0.08 AU or about 8% of the Earth-Sun distance**.

Discussion

This calculation shows that the supermassive black hole at the center of our galaxy, despite having a mass 4 million times that of the Sun, has an event horizon with a radius of only about 12 million kilometers. While this sounds large (it's about 17 times the radius of the Sun), it's remarkably small compared to astronomical distances—less than 1/10 the distance from Earth to the Sun. If Sgr A* were placed at the center of our solar system, its event horizon wouldn't even reach Mercury's orbit (0.39 AU).

What makes supermassive black holes particularly fascinating is their relatively low average density compared to stellar-mass black holes. The average density within the event horizon goes as $\rho \propto 1/M^2$, so more massive black holes are actually less dense on average. For Sgr A*, the average density is about $5 \times 10^3 \text{ kg/m}^3$—only about 5 times the density of water! Of course, the actual density increases dramatically as you approach the singularity at the center.

Students constructing their own version should choose masses in the realistic range for supermassive black holes:

- **Small supermassive:** $10^5 - 10^6$ solar masses (found in smaller galaxies)
- **Moderate:** $10^6 - 10^8$ solar masses (like Sgr A* in the Milky Way)
- **Giant:** $10^9 - 10^{10}$ solar masses (found in quasars and giant elliptical galaxies)

The corresponding Schwarzschild radii range from about 300,000 km (smaller than the Sun-Mercury distance) to 30 billion km (about 200 AU, or 5 times Neptune's orbit) for the largest. These calculations have been confirmed by direct observations, including the Event Horizon Telescope's imaging of the supermassive black hole in M87 (mass $\sim 6.5 \times 10^9 M_\odot$) in 2019, providing stunning visual confirmation of Einstein's predictions.

Glossary

black holes
: objects having such large gravitational fields that things can fall in, but nothing, not even light, can escape

general relativity
: Einstein's theory that describes all types of relative motion including accelerated motion and the effects of gravity

gravitational waves
: mass-created distortions in space that propagate at the speed of light and that are predicted by general relativity

escape velocity
: takeoff velocity when kinetic energy just cancels gravitational potential energy

event horizon
: the distance from the object at which the escape velocity is exactly the speed of light

neutron stars
: literally a star composed of neutrons

Schwarzschild radius
: the radius of the event horizon

thought experiment
: mental analysis of certain carefully and clearly defined situations to develop an idea

quasars
: the moderately distant galaxies that emit as much or more energy than a normal galaxy

Quantum gravity
: the theory that deals with particle exchange of gravitons as the mechanism for the force

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Superstrings

- Define Superstring theory.
- Explain the relationship between Superstring theory and the Big Bang.

Introduced earlier in GUTS: The Unification of Forces **Superstring theory** is an attempt to unify gravity with the other three forces and, thus, must contain quantum gravity. The main tenet of Superstring theory is that fundamental particles, including the graviton that carries the gravitational force, act like one-dimensional vibrating strings. Since gravity affects the time and space in which all else exists, Superstring theory is an attempt at a Theory of Everything (TOE). Each independent quantum number is thought of as a separate dimension in some super space (analogous to the fact that the familiar dimensions of space are independent of one another) and is represented by a different type of Superstring. As the universe evolved after the Big Bang and forces became distinct (spontaneous symmetry breaking), some of the dimensions of superspace are imagined to have curled up and become unnoticed.

Forces are expected to be unified only at extremely high energies and at particle separations on the order of $10^{-35}\mathrm{m}$. This could mean that Superstrings must have dimensions or wavelengths of this size or smaller. Just as quantum gravity may imply that there are no time intervals shorter than some finite value, it also implies that there may be no sizes smaller than some tiny but finite value. That may be about $10^{-35}\mathrm{m}$. If so, and if Superstring theory can explain all it strives to, then the structures of Superstrings are at the lower limit of the smallest possible size and can have no further substructure. This would be the ultimate answer to the question the ancient Greeks considered. There is a finite lower limit to space.

Not only is Superstring theory in its infancy, it deals with dimensions about 17 orders of magnitude smaller than the $10^{-18}\mathrm{m}$ details that we have been able to observe directly. It is thus relatively unconstrained by experiment, and there are a host of theoretical possibilities to choose from. This has led theorists to make choices subjectively (as always) on what is the most elegant theory, with less hope than usual that experiment will guide them. It has also led to speculation of alternate universes, with their Big Bangs creating each new universe with a random set of rules. These speculations may not be tested even in principle, since an alternate universe is by definition unattainable. It is something like exploring a self-consistent field of mathematics, with its axioms and rules of logic that are not consistent with nature. Such endeavors have often given insight to mathematicians and scientists alike and occasionally have been directly related to the description of new discoveries.

Section Summary

- Superstring theory holds that fundamental particles are one-dimensional vibrations analogous to those on strings and is an attempt at a theory of quantum gravity.

Problems & Exercises

The characteristic length of entities in Superstring theory is approximately $10^{-35}\mathrm{m}$.

(a) Find the energy in GeV of a photon of this wavelength.

(b) Compare this with the average particle energy of $10^{19}\mathrm{GeV}$ needed for unification of forces.

Show Solution

(a) $1\ \times 10^{20}$ (b) 10 times greater

Glossary

Superstring theory
: a theory to unify gravity with the other three forces in which the fundamental particles are considered to act like one-dimensional vibrating strings

Dark Matter and Closure

- Discuss the existence of dark matter.
- Explain neutrino oscillations and their consequences.

One of the most exciting problems in physics today is the fact that there is far more matter in the universe than we can see. The motion of stars in galaxies and the motion of galaxies in clusters imply that there is about 10 times as much mass as in the luminous objects we can see. The indirectly observed non-luminous matter is called **dark matter**. Why is dark matter a problem? For one thing, we do not know what it is. It may well be 90% of all matter in the universe, yet there is a possibility that it is of a completely unknown form—a stunning discovery if verified. Dark matter has implications for particle physics. It may be possible that neutrinos actually have small masses or that there are completely unknown types of particles. Dark matter also has implications for cosmology, since there may be enough dark matter to stop the expansion of the universe. That is another problem related to dark matter—we do not know how much there is. We keep finding evidence for more matter in the universe, and we have an idea of how much it would take to eventually stop the expansion of the universe, but whether there is enough is still unknown.

Evidence

The first clues that there is more matter than meets the eye came from the Swiss-born American astronomer Fritz Zwicky in the 1930s; major work was also done by the American astronomer Vera Rubin. Zwicky measured the velocities of stars orbiting the galaxy, using the relativistic Doppler shift of their spectra (see [Figure 1](a)). He found that velocity varied with distance from the center of the galaxy, as graphed in [Figure 1](b). If the mass of the galaxy was concentrated in its center, as are its luminous stars, the velocities should decrease as the square root of the distance from the center. Instead, the velocity curve is almost flat, implying that there is a tremendous amount of matter in the galactic halo. Using instruments and methods that offered a greater degree of precision, Rubin investigated the movement of spiral galaxies and observed that their outermost reaches were rotating as quickly as their centers. She also calculated that the rotational velocity of galaxies should have been enough to cause them to fly apart, unless there was a significant discrepancy between their observable matter and their actual matter. This became known as the galaxy rotation problem, which can be “solved” by the presence of unobserved or dark matter. Although not immediately recognized for its significance, such measurements have now been made for many galaxies, with similar results. Further, studies of galactic clusters have also indicated that galaxies have a mass distribution greater than that obtained from their brightness (proportional to the number of stars), which also extends into large halos surrounding the luminous parts of galaxies. Observations of other EM wavelengths, such as radio waves and X-rays, have similarly confirmed the existence of dark matter. Take, for example, X-rays in the relatively dark space between galaxies, which indicates the presence of previously unobserved hot, ionized gas (see [Figure 1](c)).

Theoretical Yearnings for Closure

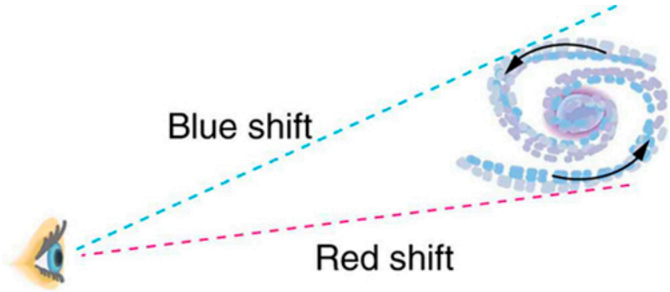
Is the universe open or closed? That is, will the universe expand forever or will it stop, perhaps to contract? This, until recently, was a question of whether there is enough gravitation to stop the expansion of the universe. In the past few years, it has become a question of the combination of gravitation and what is called the **cosmological constant**. The cosmological constant was invented by Einstein to prohibit the expansion or contraction of the universe. At the time he developed general relativity, Einstein considered that an illogical possibility. The cosmological constant was discarded after Hubble discovered the expansion, but has been re-invoked in recent years.

Gravitational attraction between galaxies is slowing the expansion of the universe, but the amount of slowing down is not known directly. In fact, the cosmological constant can counteract gravity’s effect. As recent measurements indicate, the universe is expanding *faster* now than in the past—perhaps a “modern inflationary era” in which the dark energy is thought to be causing the expansion of the present-day universe to accelerate. If the expansion rate were affected by gravity alone, we should be able to see that the expansion rate between distant galaxies was once greater than it is now. However, measurements show it was *less* than now. We can, however, calculate the amount of slowing based on the average density of matter we observe directly. Here we have a definite answer—there is far less visible matter than needed to stop expansion. The **critical density** ρ_c is defined to be the density needed to just halt universal expansion in a universe with no cosmological constant. It is estimated to be about

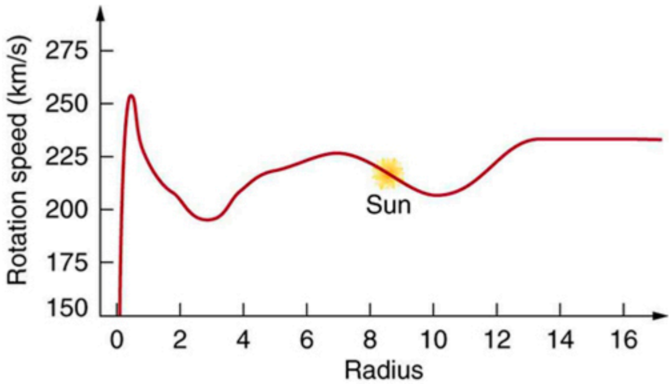
$$\rho_c \approx 10^{-26} \text{kg/m}^3.$$

However, this estimate of ρ_c is only good to about a factor of two, due to uncertainties in the expansion rate of the universe. The critical density is equivalent to an average of only a few nucleons per cubic meter, remarkably small and indicative of how truly empty intergalactic space is. Luminous matter seems to account for roughly 0.5% to 2% of the critical density, far less than that needed for closure. Taking into account the amount of dark matter we detect indirectly and all other types of indirectly observed normal matter, there is only 10% to 40% of what is needed for closure. If we are able to refine the measurements of expansion rates now and in the past, we will have our answer regarding the curvature of space and we will determine a value for the cosmological constant to justify this observation. Finally, the most recent measurements of the CMBR have implications for the cosmological constant, so it is not simply a device concocted for a single purpose.

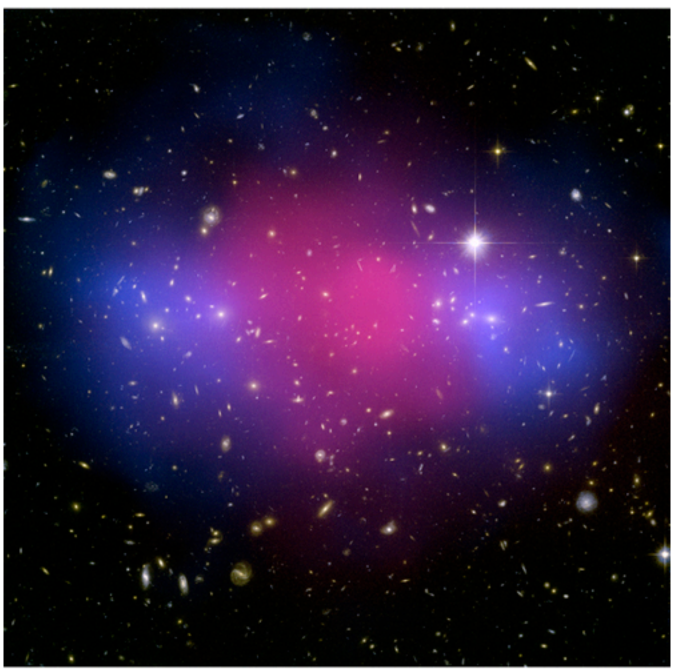
After the recent experimental discovery of the cosmological constant, most researchers feel that the universe should be just barely open. Since matter can be thought to curve the space around it, we call an open universe **negatively curved**. This means that you can in principle travel an unlimited distance in any direction. A universe that is closed is called **positively curved**. This means that if you travel far enough in any direction, you will return to your starting point, analogous to circumnavigating the Earth. In between these two is a **flat (zero curvature) universe**. The recent discovery of the cosmological constant has shown the universe is very close to flat, and will expand forever. Why do theorists feel the universe is flat? Flatness is a part of the inflationary scenario that helps explain the flatness of the microwave background. In fact, since general relativity implies that matter creates the space in which it exists, there is a special symmetry to a flat universe.



(a)



(b)



(c)

Evidence for dark matter: (a) We can measure the velocities of stars relative to their galaxies by observing the Doppler shift in emitted light, usually using the hydrogen spectrum. These measurements indicate the rotation of a spiral galaxy. (b) A graph of velocity versus distance from the galactic center shows that the velocity does not decrease as it would if the matter were concentrated in luminous stars. The flatness of the curve implies a massive galactic halo of dark matter extending beyond the visible stars. (c) This is a computer-generated image of X-rays from a galactic cluster. The X-rays indicate the presence of otherwise unseen hot clouds of ionized gas in the regions of space previously considered more empty. (credit: NASA, ESA, CXC, M. Bradac (University of California, Santa Barbara), and S. Allen (Stanford University))

What Is the Dark Matter We See Indirectly?

There is no doubt that dark matter exists, but its form and the amount in existence are two facts that are still being studied vigorously. As always, we seek to explain new observations in terms of known principles. However, as more discoveries are made, it is becoming more and more difficult to explain dark matter as a known type of matter.

One of the possibilities for normal matter is being explored using the Hubble Space Telescope and employing the lensing effect of gravity on light (see [Figure 2]). Stars glow because of nuclear fusion in them, but planets are visible primarily by reflected light. Jupiter, for example, is too small to ignite fusion in its core and become a star, but we can see sunlight reflected from it, since we are relatively close. If Jupiter orbited another star, we would not be able to see it directly. The question is open as to how many planets or other bodies smaller than about 1/1000 the mass of the Sun are there. If such bodies pass between us and a star, they will not block the star's light, being too small, but they will form a gravitational lens, as discussed in General Relativity and Quantum Gravity.

In a process called **microlensing**, light from the star is focused and the star appears to brighten in a characteristic manner. Searches for dark matter in this form are particularly interested in galactic halos because of the huge amount of mass that seems to be there. Such microlensing objects are thus called **massive compact halo objects**, or **MACHOs**. To date, a few MACHOs have been observed, but not predominantly in galactic halos, nor in the numbers needed to explain dark matter.

MACHOs are among the most conventional of unseen objects proposed to explain dark matter. Others being actively pursued are red dwarfs, which are small dim stars, but too few have been seen so far, even with the Hubble Telescope, to be of significance. Old remnants of stars called white dwarfs are also under consideration, since they contain about a solar mass, but are small as the Earth and may dim to the point that we ordinarily do not observe them. While white dwarfs are known, old dim ones are not. Yet another possibility is the existence of large numbers of smaller than stellar mass black holes left from the Big Bang—here evidence is entirely absent.

There is a very real possibility that dark matter is composed of the known neutrinos, which may have small, but finite, masses. As discussed earlier, neutrinos are thought to be massless, but we only have upper limits on their masses, rather than knowing they are exactly zero. So far, these upper limits come from difficult measurements of total energy emitted in the decays and reactions in which neutrinos are involved. There is an amusing possibility of proving that neutrinos have mass in a completely different way.

We have noted in Particles, Patterns, and Conservation Laws that there are three flavors of neutrinos (ν_e , ν_μ , and ν_τ) and that the weak interaction could change quark flavor. It should also change neutrino flavor—that is, any type of neutrino could change spontaneously into any other, a process called **neutrino oscillations**. However, this can occur only if neutrinos have a mass. Why? Crudely, because if neutrinos are massless, they must travel at the speed of light and time will not pass for them, so that they cannot change without an interaction. In 1999, results began to be published containing convincing evidence that neutrino oscillations do occur. Using the Super-Kamiokande detector in Japan, the oscillations have been observed and are being verified and further explored at present at the same facility and others.

Neutrino oscillations may also explain the low number of observed solar neutrinos. Detectors for observing solar neutrinos are specifically designed to detect electron neutrinos ν_e produced in huge numbers by fusion in the Sun. A large fraction of electron neutrinos ν_e may be changing flavor to muon neutrinos ν_μ on their way out of the Sun, possibly enhanced by specific interactions, reducing the flux of electron neutrinos to observed levels. There is also a discrepancy in observations of neutrinos produced in cosmic ray showers. While these showers of radiation produced by extremely energetic cosmic rays should contain twice as many ν_μ s as ν_e s, their numbers are nearly equal. This may be explained by neutrino oscillations from muon flavor to electron flavor. Massive neutrinos are a particularly appealing possibility for explaining dark matter, since their existence is consistent with a large body of known information and explains more than dark matter. The question is not settled at this writing.

The most radical proposal to explain dark matter is that it consists of previously unknown leptons (sometimes obtusely referred to as non-baryonic matter). These are called **weakly interacting massive particles**, or **WIMPs**, and would also be chargeless, thus interacting negligibly with normal matter, except through gravitation. One proposed group of WIMPs would have masses several orders of magnitude greater than nucleons and are sometimes called **neutralinos**. Others are called **axions** and would have masses about 10^{-10} that of an electron mass. Both neutralinos and axions would be gravitationally attached to galaxies, but because they are chargeless and only feel the weak force, they would be in a halo rather than interact and coalesce into spirals, and so on, like normal matter (see [Figure 3]).

The Hubble Space Telescope is producing exciting data with its corrected optics and with the absence of atmospheric distortion. It has observed some MACHOs, disks of material around stars thought to precede planet formation, black hole candidates, and collisions of comets with Jupiter. (credit: NASA (crew of STS-125))

Dark matter may shepherd normal matter gravitationally in space, as this stream moves the leaves. Dark matter may be invisible and even move through the normal matter, as neutrinos penetrate us without small-scale effect. (credit: Shinichi Sugiyama)

Some particle theorists have built WIMPs into their unified force theories and into the inflationary scenario of the evolution of the universe so popular today. These particles would have been produced in just the correct numbers to make the universe flat, shortly after the Big Bang. The proposal is radical in the sense that it invokes entirely new forms of matter, in fact *two* entirely new forms, in order to explain dark matter and other phenomena. WIMPs have the extra burden of automatically being very difficult to observe directly. This is somewhat analogous to quark confinement, which guarantees that quarks are there, but they can never be seen directly. One of the primary goals of the LHC at CERN, however, is to produce and detect WIMPs. At any rate, before WIMPs are accepted as the best explanation, all other possibilities utilizing known phenomena will have to be shown inferior. Should that occur, we will be in the unanticipated position of admitting that, to date, all we know is only 10% of what exists. A far cry from the days when people firmly believed themselves to be not only the center of the universe, but also the reason for its existence.

Section Summary

- Dark matter is non-luminous matter detected in and around galaxies and galactic clusters.
- It may be 10 times the mass of the luminous matter in the universe, and its amount may determine whether the universe is open or closed (expands forever or eventually stops).
- The determining factor is the critical density of the universe and the cosmological constant, a theoretical construct intimately related to the expansion and closure of the universe.
- The critical density ρ_c is the density needed to just halt universal expansion. It is estimated to be approximately 10^{-26} kg/m^3.
- An open universe is negatively curved, a closed universe is positively curved, whereas a universe with exactly the critical density is flat.
- Dark matter's composition is a major mystery, but it may be due to the suspected mass of neutrinos or a completely unknown type of leptonic matter.
- If neutrinos have mass, they will change families, a process known as neutrino oscillations, for which there is growing evidence.

Conceptual Questions

Discuss the possibility that star velocities at the edges of galaxies being greater than expected is due to unknown properties of gravity rather than to the existence of dark matter. Would this mean, for example, that gravity is greater or smaller than expected at large distances? Are there other tests that could be made of gravity at large distances, such as observing the motions of neighboring galaxies?

How does relativistic time dilation prohibit neutrino oscillations if they are massless?

If neutrino oscillations do occur, will they violate conservation of the various lepton family numbers (L_e , L_μ , and L_τ) ? Will neutrino oscillations violate conservation of the total number of leptons?

Lacking direct evidence of WIMPs as dark matter, why must we eliminate all other possible explanations based on the known forms of matter before we invoke their existence?

Problems Exercises

If the dark matter in the Milky Way were composed entirely of MACHOs (evidence shows it is not), approximately how many would there have to be? Assume the average mass of a MACHO is 1/1000 that of the Sun, and that dark matter has a mass 10 times that of the luminous Milky Way galaxy with its 10^{11} stars of average mass 1.5 times the Sun's mass.

Show Solution

1.5×10^{15}

The critical mass density needed to just halt the expansion of the universe is approximately 10^{-26}kg/m^3.

(a) Convert this to $\text{eV}/c^2\cdot\text{m}^3$.

(b) Find the number of neutrinos per cubic meter needed to close the universe if their average mass is $7\text{eV}/c^2$ and they have negligible kinetic energies.

Show Solution

Strategy

(a) To convert mass density from kg/m³ to eV/c²·m³, we use the mass-energy equivalence relation $E = mc^2$. We need to convert kg to eV/c² using the conversion factor between joules and electron volts.

(b) If neutrinos with mass $m_\nu = 7\ \text{eV}/c^2$ make up the critical density, we can find the number density by dividing the critical density (in eV/c²·m³) by the mass of a single neutrino.

Solution

(a) First, we need to convert 1 kg to eV/c².

The energy equivalent of 1 kg is:

$$E = mc^2 = 1\ \text{kg} \times (3.00 \times 10^8\ \text{m/s})^2 = 9.00 \times 10^{16}\ \text{J}$$

Converting to eV (using $1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$):

$$E = \frac{9.00 \times 10^{16}\ \text{J}}{1.60 \times 10^{-19}\ \text{J/eV}} = 5.625 \times 10^{35}\ \text{eV}$$

Therefore: $1\ \text{kg} = 5.625 \times 10^{35}\ \text{eV}/c^2$

Now converting the critical density:

$$\rho_c = 10^{-26}\ \text{kg/m}^3 \times 5.625 \times 10^{35} \frac{\text{eV}/c^2}{\text{kg}} = 5.6 \times 10^9\ \text{eV}/(c^2 \cdot \text{m}^3)$$

(b) The number density of neutrinos needed is:

$$n = \frac{\rho_c}{m_\nu} = \frac{5.6 \times 10^9\ \text{eV}/(c^2 \cdot \text{m}^3)}{7\ \text{eV}/c^2} = 8.0 \times 10^8\ \text{neutrinos/m}^3$$

Discussion

(a) The critical density in particle physics units is approximately **5.6 × 10^9 eV/(c²·m³)** or about **6 × 10^9 eV/(c²·m³)**. This conversion is useful in particle physics and cosmology because masses of elementary particles are typically expressed in eV/c² rather than kilograms. For reference, an electron has a mass of about 511,000 eV/c², so the critical density corresponds to a tiny fraction of an electron mass per cubic meter.

(b) To close the universe with neutrinos having an average mass of **7 eV/c²**, we would need approximately **8 × 10^8 neutrinos per cubic meter**. This is an enormous number density—800 million neutrinos in every cubic meter of space! However, this is actually plausible. The cosmic neutrino background, a relic from the Big Bang similar to the cosmic microwave background, is predicted to have a number density of about 3 × 10^8 neutrinos/m³ for each neutrino flavor. With three flavors, the total is about 10^9 neutrinos/m³, which is remarkably close to what we calculated. This coincidence is one reason why massive neutrinos were long considered a promising dark matter candidate.

However, modern measurements suggest that neutrino masses are too small (probably less than 1 eV/c² for the heaviest flavor) to account for all dark matter, though they contribute a small fraction. The neutrino oscillation experiments that confirmed neutrinos have mass represent one of the most important discoveries in particle physics, showing physics beyond the Standard Model. While neutrinos don't solve the dark matter mystery completely, they remain an important component of the universe's mass-energy budget.

Assume the average density of the universe is 0.1 of the critical density needed for closure. What is the average number of protons per cubic meter, assuming the universe is composed mostly of hydrogen?

Show Solution

$0.6 m^{-3}$

To get an idea of how empty deep space is on the average, perform the following calculations:

(a) Find the volume our Sun would occupy if it had an average density equal to the critical density of 10^{-26}kg/m^3 thought necessary to halt the expansion of the universe.

(b) Find the radius of a sphere of this volume in light years.

(c) What would this radius be if the density were that of luminous matter, which is approximately 5% that of the critical density?

(d) Compare the radius found in part (c) with the 4-ly average separation of stars in the arms of the Milky Way.

Show Solution

Strategy

(a) We'll use the relationship $V = M/\rho$ with the Sun's mass and the critical density to find the volume.

(b) For a sphere, $V = \frac{4}{3}\pi r^3$, so we can solve for r and convert to light years.

(c) We'll repeat part (b) with 5% of the critical density.

(d) We'll calculate the ratio of the radius from part (c) to the 4-ly stellar separation.

Solution

(a) The volume the Sun's mass would occupy at critical density:

$$V = \frac{M_{\text{Sun}}}{\rho_c} = \frac{2.0\times10^{30}\text{ kg}}{10^{-26}\text{ kg/m}^3} = 2.0\times10^{56}\text{ m}^3$$

(b) For a sphere, $V = \frac{4}{3}\pi r^3$, so:

$$r^3 = \frac{3V}{4\pi} = \frac{3\times2.0\times10^{56}}{4\pi} = \frac{6.0\times10^{56}}{12.566} = 4.77\times10^{55}\text{ m}^3$$
$$r = (4.77\times10^{55})^{1/3} = 3.63\times10^{18}\text{ m}$$

Converting to light years (using $1\text{ ly} = 9.46\times10^{15}\text{ m}$):

$$r = \frac{3.63\times10^{18}\text{ m}}{9.46\times10^{15}\text{ m/ly}} = 384\text{ ly}$$

(c) If the density is 5% of critical density:

$$\rho = 0.05\times10^{-26}\text{ kg/m}^3 = 5\times10^{-28}\text{ kg/m}^3$$
$$V = \frac{2.0\times10^{30}\text{ kg}}{5\times10^{-28}\text{ kg/m}^3} = 4.0\times10^{57}\text{ m}^3$$
$$r^3 = \frac{3\times4.0\times10^{57}}{4\pi} = 9.55\times10^{56}\text{ m}^3$$
$$r = (9.55\times10^{56})^{1/3} = 2.12\times10^{19}\text{ m}$$

Converting to light years:

$$r = \frac{2.12\times10^{19}\text{ m}}{9.46\times10^{15}\text{ m/ly}} = 2240\text{ ly} \approx 2200\text{ ly}$$

(d) Comparing with the 4-ly stellar separation:

$$\frac{r}{d_{\text{stars}}} = \frac{2200\text{ ly}}{4\text{ ly}} = 550$$

The radius is approximately **550 times** larger than the average stellar separation.

Discussion

These calculations dramatically illustrate just how empty the universe is on average:

(a-b) If the Sun's mass were spread out at the critical density of the universe, it would occupy a sphere with a radius of **384 light years**—roughly 100 times the distance to the nearest star! This shows that even the "critical density" required to close the universe is astonishingly low. Space is incredibly empty.

(c) When we use the density of luminous matter (only 5% of critical density), the required radius increases to **2200 light years**. This is about the thickness of the disk of our Milky Way galaxy. Imagine spreading the Sun's mass uniformly throughout a sphere this large—that gives you an idea of how sparse luminous matter is in the universe.

(d) The fact that this radius is **550 times** the typical 4-ly separation between stars in our galactic neighborhood demonstrates a profound truth: stars and galaxies are like tiny islands of dense matter in an overwhelmingly empty universe. The average density of the universe is incomprehensibly lower than even the sparse density of interstellar space within our galaxy.

This exercise helps us appreciate why cosmologists say the universe is "matter dominated" even though space is nearly empty. The critical density—the density needed to eventually halt cosmic expansion through gravity—is so low that it corresponds to only about 6 protons per cubic meter of space. By comparison, the air you're breathing contains about 10^{25} molecules per cubic meter! Yet even this incredibly low critical density is higher than the density of luminous matter we actually observe, which is why dark matter is necessary to explain the universe's dynamics. The emptiness of space on cosmic scales is truly difficult for our everyday intuition to grasp.

Glossary

axions
: a type of WIMPs having masses about 10^{-10} of an electron mass

cosmological constant
: a theoretical construct intimately related to the expansion and closure of the universe

critical density
: the density of matter needed to just halt universal expansion

dark matter
: indirectly observed non-luminous matter

flat (zero curvature) universe
: a universe that is infinite but not curved

microlensing
: a process in which light from a distant star is focused and the star appears to brighten in a characteristic manner, when a small body (smaller than about 1/1000 the mass of the Sun) passes between us and the star

MACHOs
: massive compact halo objects; microlensing objects of huge mass

neutrino oscillations
: a process in which any type of neutrino could change spontaneously into any other

neutralinos
: a type of WIMPs having masses several orders of magnitude greater than nucleon masses

negatively curved
: an open universe that expands forever

positively curved
: a universe that is closed and eventually contracts

WIMPs
: weakly interacting massive particles; chargeless leptons (non-baryonic matter) interacting negligibly with normal matter

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Complexity and Chaos

- Explain complex systems.
- Discuss chaotic behavior of different systems.

Much of what impresses us about physics is related to the underlying connections and basic simplicity of the laws we have discovered. The language of physics is precise and well defined because many basic systems we study are simple enough that we can perform controlled experiments and discover unambiguous relationships. Our most spectacular successes, such as the prediction of previously unobserved particles, come from the simple underlying patterns we have been able to recognize. But there are systems of interest to physicists that are inherently complex. The simple laws of physics apply, of course, but complex systems may reveal patterns that simple systems do not. The emerging field of **complexity** is devoted to the study of complex systems, including those outside the traditional bounds of physics. Of particular interest is the ability of complex systems to adapt and evolve.

What are some examples of complex adaptive systems? One is the primordial ocean. When the oceans first formed, they were a random mix of elements and compounds that obeyed the laws of physics and chemistry. In a relatively short geological time (about 500 million years), life had emerged. Laboratory simulations indicate that the emergence of life was far too fast to have come from random combinations of compounds, even if driven by lightning and heat. There must be an underlying ability of the complex system to organize itself, resulting in the self-replication we recognize as life. Living entities, even at the unicellular level, are highly organized and systematic. Systems of living organisms are themselves complex adaptive systems. The grandest of these evolved into the biological system we have today, leaving traces in the geological record of steps taken along the way.

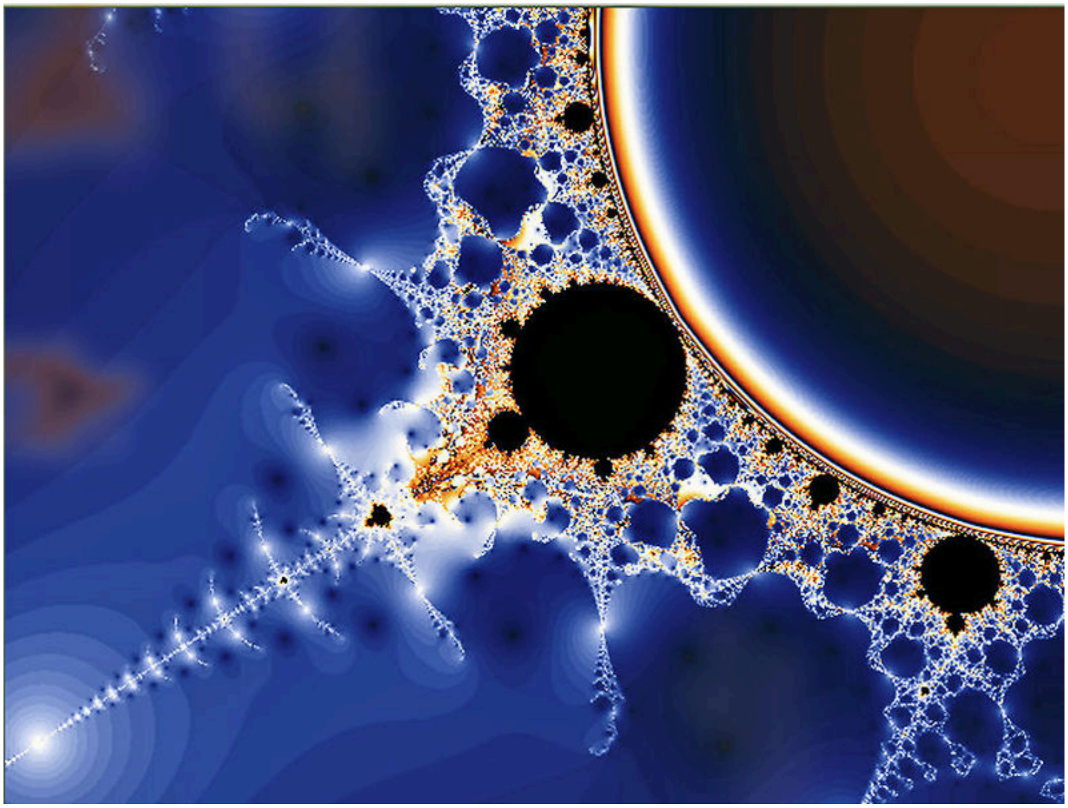
Complexity as a discipline examines complex systems, how they adapt and evolve, looking for similarities with other complex adaptive systems. Can, for example, parallels be drawn between biological evolution and the evolution of *economic systems*? Economic systems do emerge quickly, they show tendencies for self-organization, they are complex (in the number and types of transactions), and they adapt and evolve. Biological systems do all the same types of things. There are other examples of complex adaptive systems being studied for fundamental similarities. *Cultures* show signs of adaptation and evolution. The comparison of different cultural evolutions may bear fruit as well as comparisons to biological evolution. *Science* also is a complex system of human interactions, like culture and economics, that adapts to new information and political pressure, and evolves, usually becoming more organized rather than less. Those who study *creative thinking* also see parallels with complex systems. Humans sometimes organize almost random pieces of information, often subconsciously while doing other things, and come up with brilliant creative insights. The development of *language* is another complex adaptive system that may show similar tendencies. *Artificial intelligence* is an overt attempt to devise an adaptive system that will self-organize and evolve in the same manner as an intelligent living being learns. These are a few of the broad range of topics being studied by those who investigate complexity. There are now institutes, journals, and meetings, as well as popularizations of the emerging topic of complexity.

In traditional physics, the discipline of complexity may yield insights in certain areas. Thermodynamics treats systems on the average, while statistical mechanics deals in some detail with complex systems of atoms and molecules in random thermal motion. Yet there is organization, adaptation, and evolution in those complex systems. Non-equilibrium phenomena, such as heat transfer and phase changes, are characteristically complex in detail, and new approaches to them may evolve from complexity as a discipline. Crystal growth is another example of self-organization spontaneously emerging in a complex system. Alloys are also inherently complex mixtures that show certain simple characteristics implying some self-organization. The organization of iron atoms into magnetic domains as they cool is another. Perhaps insights into these difficult areas will emerge from complexity. But at the minimum, the discipline of complexity is another example of human effort to understand and organize the universe around us, partly rooted in the discipline of physics.

A predecessor to complexity is the topic of chaos, which has been widely publicized and has become a discipline of its own. It is also based partly in physics and treats broad classes of phenomena from many disciplines. **Chaos** is a word used to describe systems whose outcomes are extremely sensitive to initial conditions. The orbit of the planet Pluto, for example, may be chaotic in that it can change tremendously due to small interactions with other planets. This makes its long-term behavior impossible to predict with precision, just as we cannot tell precisely where a decaying Earth satellite will land or how many pieces it will break into. But the discipline of chaos has found ways to deal with such systems and has been applied to apparently unrelated systems. For example, the heartbeat of people with certain types of potentially lethal arrhythmias seems to be chaotic, and this knowledge may allow more sophisticated monitoring and recognition of the need for intervention.

Chaos is related to complexity. Some chaotic systems are also inherently complex; for example, vortices in a fluid as opposed to a double pendulum. Both are chaotic and not predictable in the same sense as other systems. But there can be organization in chaos and it can also be quantified. Examples of chaotic systems are beautiful fractal patterns such as in [Figure 1]. Some chaotic systems exhibit self-organization, a type of stable chaos. The orbits of the planets in our solar system, for example, may be chaotic (we are not certain yet). But they are definitely organized and systematic, with a simple formula describing the orbital radii of the first eight planets *and* the asteroid belt. Large-scale vortices in Jupiter’s atmosphere are chaotic, but the Great Red Spot is a stable self-organization of rotational energy. (See [Figure 2] .) The Great Red Spot has been in existence for at least 400 years and is a complex self-adaptive system.

The emerging field of complexity, like the now almost traditional field of chaos, is partly rooted in physics. Both attempt to see similar systematics in a very broad range of phenomena and, hence, generate a better understanding of them. Time will tell what impact these fields have on more traditional areas of physics as well as on the other disciplines they relate to.



This image is related to the Mandelbrot set, a complex mathematical form that is chaotic. The patterns are infinitely fine as you look closer and closer, and they indicate order in the presence of chaos. (credit: Gilberto Santa Rosa)

The Great Red Spot on Jupiter is an example of self-organization in a complex and chaotic system. Smaller vortices in Jupiter's atmosphere behave chaotically, but the triple-Earth-size spot is self-organized and stable for at least hundreds of years. (credit: NASA)

Section Summary

- Complexity is an emerging field, rooted primarily in physics, that considers complex adaptive systems and their evolution, including self-organization.
- Complexity has applications in physics and many other disciplines, such as biological evolution.
- Chaos is a field that studies systems whose properties depend extremely sensitively on some variables and whose evolution is impossible to predict.
- Chaotic systems may be simple or complex.
- Studies of chaos have led to methods for understanding and predicting certain chaotic behaviors.

Conceptual Questions

Must a complex system be adaptive to be of interest in the field of complexity? Give an example to support your answer.

State a necessary condition for a system to be chaotic.

Glossary

complexity
: an emerging field devoted to the study of complex systems

chaos
: word used to describe systems the outcomes of which are extremely sensitive to initial conditions

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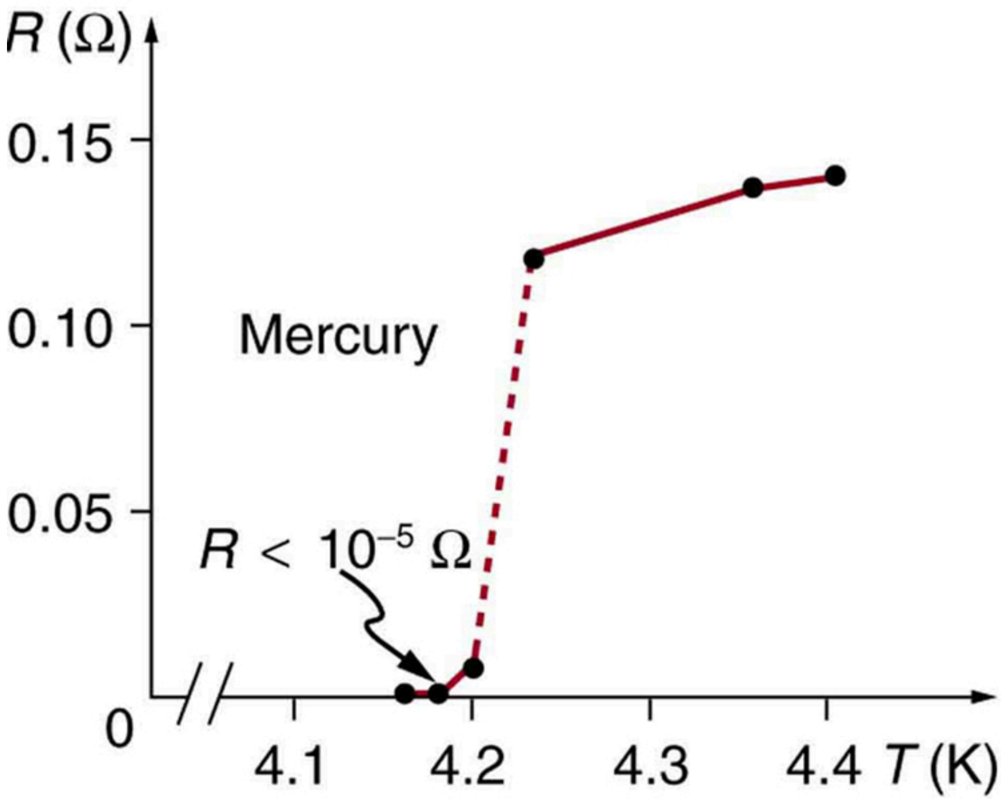
High-temperature Superconductors

- Identify superconductors and their uses.
- Discuss the need for a high-T_c superconductor.

Superconductors are materials with a resistivity of zero. They are familiar to the general public because of their practical applications and have been mentioned at a number of points in the text. Because the resistance of a piece of superconductor is zero, there are no heat losses for currents through them; they are used in magnets needing high currents, such as in MRI machines, and could cut energy losses in power transmission. But most superconductors must be cooled to temperatures only a few kelvin above absolute zero, a costly procedure limiting their practical applications. In the past decade, tremendous advances have been made in producing materials that become superconductors at relatively high temperatures. There is hope that room temperature superconductors may someday be manufactured.

Superconductivity was discovered accidentally in 1911 by the Dutch physicist H. Kamerlingh Onnes (1853–1926) when he used liquid helium to cool mercury. Onnes had been the first person to liquefy helium a few years earlier and was surprised to observe the resistivity of a mediocre conductor like mercury drop to zero at a temperature of 4.2 K. We define the temperature at which and below which a material becomes a superconductor to be its **critical temperature**, denoted by T_C . (See [Figure 1].) Progress in understanding how and why a material became a superconductor was relatively slow, with the first workable theory coming in 1957. Certain other elements were also found to become superconductors, but all had T_C s less than 10 K, which are expensive to maintain. Although Onnes received a Nobel prize in 1913, it was primarily for his work with liquid helium.

In 1986, a breakthrough was announced—a ceramic compound was found to have an unprecedented T_C of 35 K. It looked as if much higher critical temperatures could be possible, and by early 1988 another ceramic (this of thallium, calcium, barium, copper, and oxygen) had been found to have T_C =125K (see [Figure 2].) The economic potential of perfect conductors saving electric energy is immense for T_C s above 77 K, since that is the temperature of liquid nitrogen. Although liquid helium has a boiling point of 4 K and can be used to make materials superconducting, it costs about 5$perliter.Liquidnitrogenboilsat77K,butonlycostsabout$0.30 per liter. There was general euphoria at the discovery of these complex ceramic superconductors, but this soon subsided with the sobering difficulty of forming them into usable wires. The first commercial use of a high temperature superconductor is in an electronic filter for cellular phones. High-temperature superconductors are used in experimental apparatus, and they are actively being researched, particularly in thin film applications.

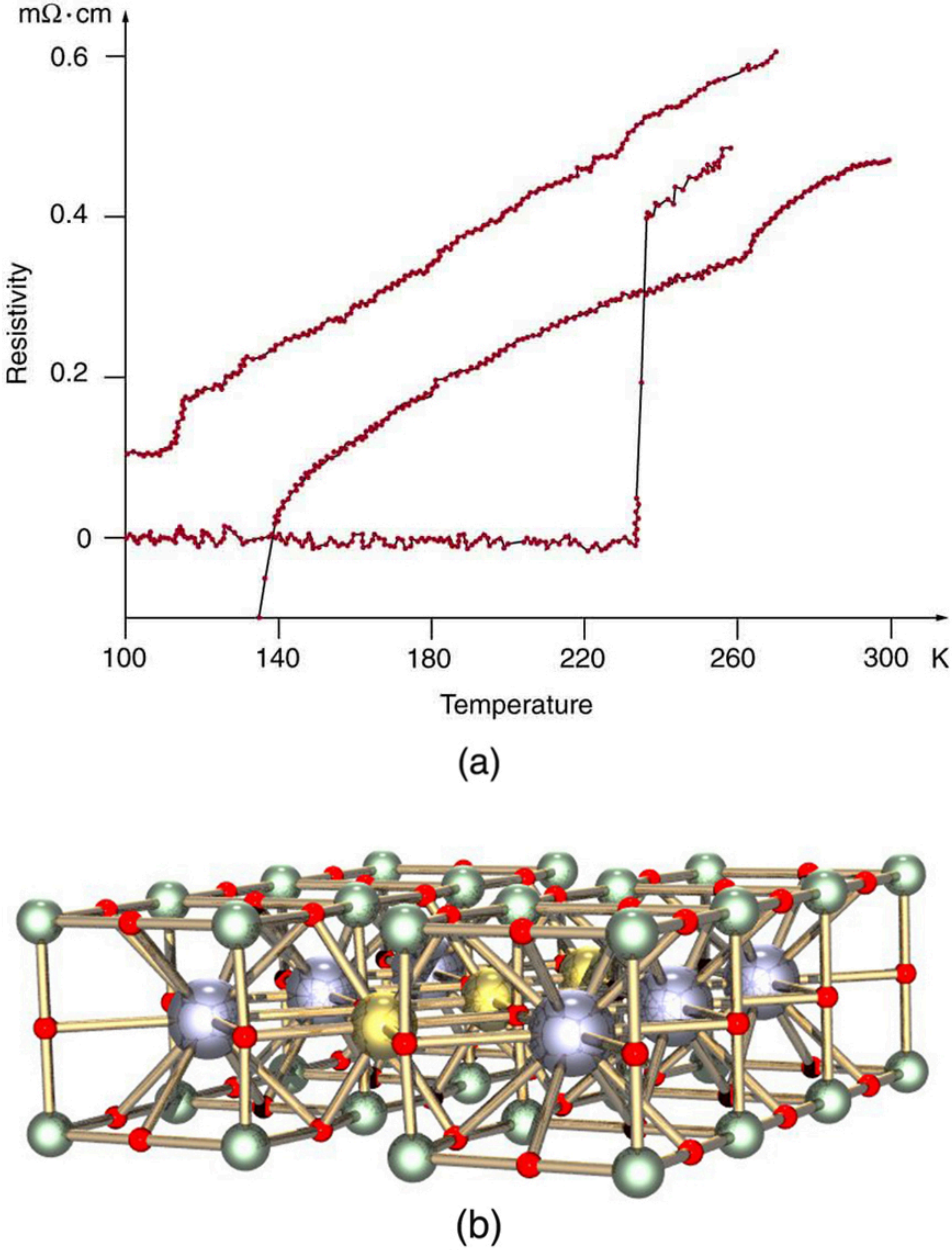


A graph of resistivity versus temperature for a superconductor shows a sharp transition to zero at the critical temperature Tc. High temperature superconductors have verifiable Tc s greater than 125 K, well above the easily achieved 77-K temperature of liquid nitrogen.

One characteristic of a superconductor is that it excludes magnetic flux and, thus, repels other magnets. The small magnet levitated above a high-temperature superconductor, which is cooled by liquid nitrogen, gives evidence that the material is superconducting. When the material warms and becomes conducting, magnetic flux can penetrate it, and the magnet will rest upon it. (credit: Saperaud)

The search is on for even higher T_C superconductors, many of complex and exotic copper oxide ceramics, sometimes including strontium, mercury, or yttrium as well as barium, calcium, and other elements. Room temperature (about 293 K) would be ideal, but any temperature close to room temperature is relatively cheap to produce and maintain. There are persistent reports of T_C s over 200 K and some in the vicinity of 270 K. Unfortunately, these observations are not routinely reproducible, with samples losing their superconducting nature once heated and recooled (cycled) a few times (see [Figure 3].) They are now called USOs or unidentified superconducting objects, out of frustration and the refusal of some samples to show high T_C even though produced in the same manner as others. Reproducibility is crucial to discovery, and researchers are justifiably reluctant to claim the breakthrough they all seek. Time will tell whether USOs are real or an experimental quirk.

The theory of ordinary superconductors is difficult, involving quantum effects for widely separated electrons traveling through a material. Electrons couple in a manner that allows them to get through the material without losing energy to it, making it a superconductor. High- T_C superconductors are more difficult to understand theoretically, but theorists seem to be closing in on a workable theory. The difficulty of understanding how electrons can sneak through materials without losing energy in collisions is even greater at higher temperatures, where vibrating atoms should get in the way. Discoverers of high T_C may feel something analogous to what a politician once said upon an unexpected election victory—“I wonder what we did right?”



(a) This graph, adapted from an article in Physics Today, shows the behavior of a single sample of a high-temperature superconductor in three different trials. In one case the sample exhibited a T_C of about 230 K, whereas in the others it did not become superconducting at all. The lack of reproducibility is typical of forefront experiments and prohibits definitive conclusions. (b) This colorful diagram shows the complex but systematic nature of the lattice structure of a high-temperature superconducting ceramic. (credit: en:Cadmium, Wikimedia Commons)

Section Summary

- High-temperature superconductors are materials that become superconducting at temperatures well above a few kelvin.
- The critical temperature T_C is the temperature below which a material is superconducting.

- Some high-temperature superconductors have verified T_C s above 125 K, and there are reports of T_C s as high as 250 K.

Conceptual Questions

What is critical temperature T_C ? Do all materials have a critical temperature? Explain why or why not.

Explain how good thermal contact with liquid nitrogen can keep objects at a temperature of 77 K (liquid nitrogen's boiling point at atmospheric pressure).

Not only is liquid nitrogen a cheaper coolant than liquid helium, its boiling point is higher (77 K vs. 4.2 K). How does higher temperature help lower the cost of cooling a material? Explain in terms of the rate of heat transfer being related to the temperature difference between the sample and its surroundings.

Problem Exercises

A section of superconducting wire carries a current of 100 A and requires 1.00 L of liquid nitrogen per hour to keep it below its critical temperature. For it to be economically advantageous to use a superconducting wire, the cost of cooling the wire must be less than the cost of energy lost to heat in the wire. Assume that the cost of liquid nitrogen is 0.30$perliter, and that electric energy costs$0.10 per kW·h. What is the resistance of a normal wire that costs as much in wasted electric energy as the cost of liquid nitrogen for the superconductor?

Show Solution

0.30Ω

Glossary

Superconductors
: materials with resistivity of zero

critical temperature
: the temperature at which and below which a material becomes a superconductor

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Some Questions We Know to Ask

- Identify sample questions to be asked on the largest scales.
- Identify sample questions to be asked on the intermediate scale.
- Identify sample questions to be asked on the smallest scales.

Throughout the text we have noted how essential it is to be curious and to ask questions in order to first understand what is known, and then to go a little farther. Some questions may go unanswered for centuries; others may not have answers, but some bear delicious fruit. Part of discovery is knowing which questions to ask. You have to know something before you can even phrase a decent question. As you may have noticed, the mere act of asking a question can give you the answer. The following questions are a sample of those physicists now know to ask and are representative of the forefronts of physics. Although these questions are important, they will be replaced by others if answers are found to them. The fun continues.

On the Largest Scale

1. *Is the universe open or closed*? Theorists would like it to be just barely closed and evidence is building toward that conclusion. Recent measurements in the expansion rate of the universe and in CMBR support a flat universe. There is a connection to small-scale physics in the type and number of particles that may contribute to closing the universe.
2. *What is dark matter*? It is definitely there, but we really do not know what it is. Conventional possibilities are being ruled out, but one of them still may explain it. The answer could reveal whole new realms of physics and the disturbing possibility that most of what is out there is unknown to us, a completely different form of matter.
3. *How do galaxies form*? They exist since very early in the evolution of the universe and it remains difficult to understand how they evolved so quickly. The recent finer measurements of fluctuations in the CMBR may yet allow us to explain galaxy formation.
4. *What is the nature of various-mass black holes*? Only recently have we become confident that many black hole candidates cannot be explained by other, less exotic possibilities. But we still do not know much about how they form, what their role in the history of galactic evolution has been, and the nature of space in their vicinity. However, so many black holes are now known that correlations between black hole mass and galactic nuclei characteristics are being studied.
5. *What is the mechanism for the energy output of quasars*? These distant and extraordinarily energetic objects now seem to be early stages of galactic evolution with a supermassive black-hole-devouring material. Connections are now being made with galaxies having energetic cores, and there is evidence consistent with less consuming, supermassive black holes at the center of older galaxies. New instruments are allowing us to see deeper into our own galaxy for evidence of our own massive black hole.
6. *Where do the γ bursts come from*? We see bursts of γ rays coming from all directions in space, indicating the sources are very distant objects rather than something associated with our own galaxy. Some γ bursts finally are being correlated with known sources so that the possibility they may originate in binary neutron star interactions or black holes eating a companion neutron star can be explored.

On the Intermediate Scale

1. *How do phase transitions take place on the microscopic scale*? We know a lot about phase transitions, such as water freezing, but the details of how they occur molecule by molecule are not well understood. Similar questions about specific heat a century ago led to early quantum mechanics. It is also an example of a complex adaptive system that may yield insights into other self-organizing systems.
2. *Is there a way to deal with nonlinear phenomena that reveals underlying connections*? Nonlinear phenomena lack a direct or linear proportionality that makes analysis and understanding a little easier. There are implications for nonlinear optics and broader topics such as chaos.
3. _How do high- T_{c} superconductors become resistanceless at such high temperatures_? Understanding how they work may help make them more practical or may result in surprises as unexpected as the discovery of superconductivity itself.
4. *There are magnetic effects in materials we do not understand—how do they work*? Although beyond the scope of this text, there is a great deal to learn in condensed matter physics (the physics of solids and liquids). We may find surprises analogous to lasing, the quantum Hall effect, and the quantization of magnetic flux. Complexity may play a role here, too.

On the Smallest Scale

1. *Are quarks and leptons fundamental, or do they have a substructure*? The higher energy accelerators that are just completed or being constructed may supply some answers, but there will also be input from cosmology and other systematics.
2. *Why do leptons have integral charge while quarks have fractional charge*? If both are fundamental and analogous as thought, this question deserves an answer. It is obviously related to the previous question.
3. *Why are there three families of quarks and leptons*? First, does this imply some relationship? Second, why three and only three families?
4. *Are all forces truly equal (unified) under certain circumstances*? They don’t have to be equal just because we want them to be. The answer may have to be indirectly obtained because of the extreme energy at which we think they are unified.
5. *Are there other fundamental forces*? There was a flurry of activity with claims of a fifth and even a sixth force a few years ago. Interest has subsided, since those forces have not been detected consistently. Moreover, the proposed forces have strengths similar to gravity, making them extraordinarily difficult to detect in the presence of stronger forces. But the question remains; and if there are no other forces, we need to ask why only four and why these four.
6. *Is the proton stable*? We have discussed this in some detail, but the question is related to fundamental aspects of the unification of forces. We may never know from experiment that the proton is stable, only that it is very long lived.
7. *Are there magnetic monopoles*? Many particle theories call for very massive individual north- and south-pole particles—magnetic monopoles. If they exist, why are they so different in mass and elusiveness from electric charges, and if they do not exist, why not?
8. *Do neutrinos have mass*? Definitive evidence has emerged for neutrinos having mass. The implications are significant, as discussed in this chapter. There are effects on the closure of the universe and on the patterns in particle physics.
9. *What are the systematic characteristics of high- Z nuclei*? All elements with $Z = 118$ or less (with the exception of 115 and 117) have now been discovered. It has long been conjectured that there may be an island of relative stability

near $Z = 114$, and the study of the most recently discovered nuclei will contribute to our understanding of nuclear forces.

These lists of questions are not meant to be complete or consistently important—you can no doubt add to it yourself. There are also important questions in topics not broached in this text, such as certain particle symmetries, that are of current interest to physicists. Hopefully, the point is clear that no matter how much we learn, there always seems to be more to know. Although we are fortunate to have the hard-won wisdom of those who preceded us, we can look forward to new enlightenment, undoubtedly sprinkled with surprise.

Section Summary

- On the largest scale, the questions which can be asked may be about dark matter, dark energy, black holes, quasars, and other aspects of the universe.
- On the intermediate scale, we can query about gravity, phase transitions, nonlinear phenomena, high- T_c superconductors, and magnetic effects on materials.
- On the smallest scale, questions may be about quarks and leptons, fundamental forces, stability of protons, and existence of monopoles.

Conceptual Questions

For experimental evidence, particularly of previously unobserved phenomena, to be taken seriously it must be reproducible or of sufficiently high quality that a single observation is meaningful. Supernova 1987A is not reproducible. How do we know observations of it were valid? The fifth force is not broadly accepted. Is this due to lack of reproducibility or poor-quality experiments (or both)? Discuss why forefront experiments are more subject to observational problems than those involving established phenomena.

Discuss whether you think there are limits to what humans can understand about the laws of physics. Support your arguments.
