Everyone's Guide to

Atoms, Einstein, and the Universe

Real Science for Real People

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Contents

Part 2 – Stars

Part 3 – The Universe

List of Sidebars

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1

Once Over Lightly

You don't need to be a great musician to appreciate great music. Nor do you need great math or physics expertise to appreciate the exciting discoveries and intriguing mysteries of our universe.

We live in the Golden Age of Science. More has been discovered in the last century than in all prior history. We are the first generation to have seen almost to the edge of our universe and almost to the beginning of time. We have seen the largest structures that exist in nature, and have discovered its smallest parts. For the first time, physical science has a coherent story of almost everything.

Our adventure begins by diving into the infinitesimal, then soaring through the stars, and ultimately reaching the limits of the universe. We will discuss almost all the major discoveries of modern physics, astronomy, and cosmology, and encounter several recurring themes along the way:

- Everything is intimately connected, from the smallest to the largest, from atoms to people to the universe.
- Things that seem vastly different are often really the same.
- Einstein's belief in the simplicity and beauty of nature inspired him to find unity and elegance in science.
- Great minds have extraordinary vision and often see what others do not. But sometimes they can't see what others do.

Part 1 examines our long journey to discover the ***micro-world***—molecules, atoms, and everything smaller—and introduces those who led the way.

For 2500 years, some of the brightest minds struggled to discover what everything we see is made of. In 1905, Einstein provided the critical insights that firmly established that matter is made of atoms. But atoms are not the end of this quest. Atoms are composed of ***electrons*** and ***nuclei***. Nuclei are made of ***protons*** and ***neutrons*** that are themselves made of ***quarks***. Finally, we have reached the innermost layer of matter—twelve ***elementary particles***. We have also discovered an unexpected bonus: ***antimatter***.

The interactions of these elementary particles underlie everything in the universe through nature's four forces: ***gravity, electromagnetism, strong***, and ***weak***. These forces light up the stars, create the atoms in our bodies, enable all chemical and biological processes, preserve Earth's atmosphere, and shape planets, galaxies, and the universe itself.

We will learn how an obscure clerk, rejected by the academic establishment, single-handedly shook the foundations of science and forever changed our understanding of ***energy, mass, light, space***, and ***time***.

Einstein's most famous equation $E=mc^2$ provides a deeper understanding of mass and energy that can lead us to develop dramatically more abundant and less polluting sources of energy. Future energy production can be a million times more efficient and less polluting than current technology. Ultimately, by utilizing ***black holes***, we may be able to provide all the energy needs of a million people for 1¢ per day, and do so with zero pollution.

Einstein's two theories of Relativity are among the crowning achievements of 20TH century science. Building on the discoveries of Galileo, and extending the scope of Newton's laws, Einstein opened the universe to science. He said that different clocks, even perfect clocks, keep time differently depending on their speed and location. There is not just one right answer to the question, "What time is it?" Einstein explained why time is ***relative***, and why a jet looks shorter and heavier the faster it flies. Einstein's theories constrain and enable distant space travel and also raise puzzling questions, such as the twin paradox.

We will examine the mysteries of Quantum Mechanics and its startling view of reality in the micro-world. We'll also learn how Quantum Mechanics made possible the electronic revolution that permeates our lives through computers, cell phones, and all things digital. We will meet Schroedinger's Cat and discover who had the last meow. Einstein made several essential contributions to the development of Quantum Mechanics, including establishing the theoretical basis for the lasers that scan our bar codes, read our CDs, print our documents, and sculpt our corneas. His contributions ultimately led to a quantum view of reality filled with uncertainty. However, Einstein himself never accepted the uncertainty of Quantum Mechanics, declaring "God does not play with dice."

Part 2 explores how the ***micro-world*** impacts the ***macro-world*** (everything larger than molecules). In particular, the properties of particles control the stars that have transformed the cosmos from a cold, empty, lifeless void to a universe of spectacular sights and endless possibilities. Stars both enable life and frame our future.

We will follow the life cycle of stars: their birth, the exquisite balance of their prime, their rapid decline, and their ultimate deaths in immensely violent explosions called ***supernovae***. Through these explosive deaths, nature recycles vital resources, plants the seeds of rebirth, and leaves exotic remnants such as ***white dwarfs, neutron stars***, and ***black holes***. With spectacular celestial photographs, we will examine the bizarre nature of each of these exotic remnants, particularly the most enigmatic: black holes.

Einstein's Theory of General Relativity enables the Global Positioning System (GPS). It also provides the foundation for our understanding of stars, galaxies, and the universe. General Relativity is widely accepted as the most beautiful theory in physics, and many believe it is the greatest achievement of human thought. Can a theory really be considered beautiful?

We will examine NASA's wonderful space telescopes, particularly the Hubble Space Telescope, the greatest advance in astronomy since Galileo pointed the first telescope toward the heavens 400 years ago. NASA's space telescopes have opened up the heavens as never before.

Part 3 builds on our knowledge of both the micro-world and the macro-world of stars to illuminate the mysteries of the universe. We begin with an exploration of our universe as it is today. How big are galaxies? How many galaxies are in the universe? How large is the universe? How small is its smallest part? Where do we fit into all this? What do we know, what don't we know, and what might we never know?

Next, we turn to cosmology and explore how the universe, and our understanding of it, has evolved. Cosmology became a quantitative science in the 20TH century with Einstein's Theory of General Relativity, the observations of Henrietta Leavitt and Edwin Hubble, and the meticulous study of starlight.

Everything astronomers know about the cosmos comes from observing starlight. It's amazing how much we can learn from the charming twinkle of stars. From the array of "colors" in starlight, astronomers can precisely measure what stars are made of. From changes in these color patterns—***redshifts*** and ***blueshifts***—they measure the motions of stars and the universe.

Leavitt discovered the key to measuring the distances to very remote stars. Hubble built on Leavitt's discovery to demonstrate that there are galaxies far beyond our own Milky Way. Then, Hubble used redshifts, as well as distances derived from Leavitt's technique, to discover that the universe is expanding. We will learn the meaning of this expansion, what is expanding, and what is not.

Some discoveries are the result of many years of careful preparation and precise observation. Others are fortuitous accidents, such as the detection of the afterglow of the Big Bang. This accidental discovery, followed by decades of meticulous measurement, provides a grand story about the very early universe.

Further, we will examine the special and wonderful place mankind occupies in this vast universe, in a most favorable place, at a most favorable time, and enjoying a most fertile habitat.

Next, we turn to cosmology's greatest achievement, the Big Bang Theory, starting with the beginning of space and time. We will examine the critical role played by the dark side of our universe: ***dark matter*** and ***dark energy***.

Finally, we will explore the most promising ideas about what came before the beginning and what lies beyond. While the rest of this book is based on well-established science, this last discussion involves intriguing speculations.

Our quest is similar to a grand buffet. Feel free to pick and choose. If you don't care for anchovies, don't fret, just skip on to the next delight. If you don't delight in Quantum Mechanics, simply move on to Stars. To make these cutting-edge concepts as accessible as possible, we translate physics into English, replace equations by graphics, and provide a gallery of heavenly pictures.

But the science is not "dumbed down."

This is real science for real people, like you.

You will have much to think about.

For your convenience, a Glossary of Terms, a List of Symbols, and a Summary of Key Principles of major physical theories are provided at the back of the book. You will sometimes see bracketed numbers such as [1] that indicate further discussion is in notes at the end of that chapter.

I hope you enjoy and benefit from reading this book. If you have any comments, suggestions, or questions, please contact me at:
www.guidetothecosmos.com.

NOTES

[1] For those not allergic to math, some more technical matters are explored in notes at the end of chapters

PART 1

The Micro-World

Atoms

Particles

Forces

Energy

Relativity

Quantum Mechanics

19

Newton and Einstein on Gravity

Gravity appears to be the simplest of nature's forces, perhaps because it is the most familiar. It may also seem incredibly weak compared with other forces because it is 10^{37} times weaker than the strong force. (For an explanation of what 10^{37} is, see note [1] at the end of chapter 5.) Yet gravity is in many ways the most complex and the most powerful force of nature. It controls the fate of the universe and everything in it.

Galileo Galilei was the first to study gravity scientifically. He discovered that, ignoring air resistance, all bodies fall at the same rate—a simple but powerful law. Galileo also discovered the moons of Jupiter, the first objects ever seen that unquestionably orbit something other than Earth. Rather than burn at the stake for heresy, Galileo reluctantly recanted some of his discoveries.

GRAVITY ACCORDING TO NEWTON

Sir Isaac Newton was the next to advance our understanding of gravity, publishing in 1687 his ***Principia Mathematica***, thought by many to be the most influential book in science. Newton was prolific as a physicist, mathematician, alchemist, and theologian. His other scientific discoveries include his laws of motion, the reflecting telescope, and the theory of

Figure 19.1. Newton understood why the Moon orbits Earth. At each moment, the Moon moves forward in the direction of its current velocity (dotted arrow) and it also falls toward Earth (solid arrow). The sum of these two motions produces its orbital rotation around Earth.

color. However, Newton is said to have spent more time on his unorthodox biblical interpretations than on science. As England's Master of the Mint for 28 years, he reformed the currency, routed out counterfeiters, and greatly increased England's wealth and fiscal stability. For this, and not for his outstanding contributions to science, Queen Ann knighted him in 1705. A postmortem found very high levels of mercury in his body, no doubt due to his extensive work in alchemy. This could explain his "erratic" behavior in later life.

Newton and Gottfried Wilhelm Leibniz independently invented an entirely new branch of mathematics: ***calculus***. This enabled Newton to formulate physical laws by relating forces to small changes, and relating sequences of small changes to global motion. This was the dawn of a new age of analytical science. Newton showed there is one law for all things gravitational: a universal law of gravity that works for apples, the Moon, and everything else. Never before did science have such sweeping reach.

Let's explore how Newton explained our Moon's orbit, as illustrated in figure 19.1. The dotted arrow indicates the Moon's velocity at a particular moment. An object's velocity is its speed and direction of motion, such as "60 mph due north." If it maintains that velocity for 1 hour, it will move 60 miles north. Maintaining that velocity for 1 minute moves it 1 mile north.

A stable orbit requires a balance of gravity and velocity. Without gravity, the Moon would forever move in a straight line in the direction of its velocity. It would leave Earth and never look back. But because of gravity, at every moment the Moon also falls toward the Earth, just as apples fall from trees, as indicated by the short solid arrow in the figure. If the Moon ever had zero velocity, it would begin falling straight toward Earth; its impact would vaporize our oceans and melt the planet's surface. Fortunately, what actually happens is the sum of both arrows; the Moon falls toward Earth and at the same time also moves forward with its current velocity. Each minute, the Moon moves forward 38 miles and drops 16 feet toward Earth. A 16-foot drop seems tiny compared with 38 miles, but it's exactly the right amount to turn the Moon from its straight line path into its orbit around Earth. By staring at apples, Newton understood the motion of the Moon. (Ain't physics cool.)

Newton said that gravity is caused by mass and that only mass responds to gravity. Since we now know light is made of photons that have zero mass, Newton's laws say light is not affected by gravity. He also said changes in the positions of massive objects are felt instantaneously throughout the universe. For example, if the Sun vanished, Earth would stop feeling its pull immediately. For that to be true, whatever "causes" gravity must travel with infinite velocity, which doesn't seem reasonable. And by the way, what is it that actually "causes" gravity? What is the mechanism by which the Sun reaches out and pulls on Earth across 93 million miles of empty space? No one knew, not even Newton. This mysterious, unseen mechanism is called an ***action-at-a-distance***. Not understanding gravity's mechanism bothered physicists, including Newton. But since his laws explained what gravity did remarkably well, everyone just accepted them.

Such were the laws of gravity for over 200 years.

GRAVITY ACCORDING TO EINSTEIN

Einstein changed everything. He said gravity is not a force after all, but is the effect of the geometry of our universe being curved. If the geometry of the universe were Euclidean, rather than curved, there would be no gravity and all objects would move in straight lines. Earth orbits the Sun, Einstein said, because the Sun curves the geometry of the solar system and Earth follows the straightest possible path in that curved geometry, as shown in figure 19.2.

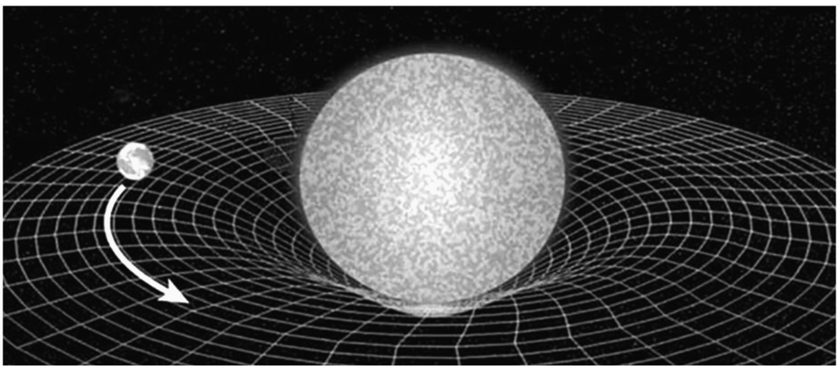


Figure 19.2. Einstein said that gravity is not a force but is the result of the curvature of spacetime. The Sun curves the geometry of our solar system, somewhat like a bowling ball would deform a bed sheet. The Earth follows the straightest possible path through this curved geometry—an orbit around the Sun.

Figure 19.2 shows only two dimensions of our universe's four-dimensional spacetime. No one I know can draw, or even imagine, all four dimensions at once; we can only draw part of the geometry and hope that conveys the key ideas. In this figure, our universe is represented by only the deformed two-dimensional surface with crisscrossed white lines. To make them easier to see, the Sun and Earth are shown as balls laying on that surface, but they should really be drawn as flat disks entirely within the two-dimensional surface of our universe. Anything outside this two-dimensional surface is outside our universe.

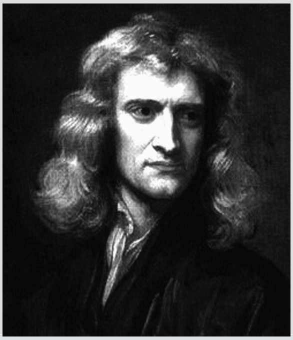
Perhaps our universe bends in a fifth dimension, corresponding to the vertical direction of this figure. That larger space, with five or more dimensions, is called a ***hyperspace***.

Euclidean geometry is what we all learned in high school: parallel lines never cross, and all that. All this is true on a ***flat*** surface, like a sheet of paper, but it is not true on a curved surface, like the surface of a sphere. For example, on Earth's surface, the meridians are parallel at the equator, but intersect at both poles. We'll say more about curved geometries in the next chapter.

Clearly Einstein's concept is very different from Newton's, as shown in figure 19.3. Einstein said that all forms of energy, not just mass, cause gravity and that gravity affects all forms of energy, not just mass. Since Einstein previously said mass and energy were equivalent, we should have seen that coming. In Einstein's gravity, there is no action-at-a-distance; the Sun curves geometry where it is, and Earth responds to the geometry where it is. Geometry is the mechanism that links the Sun and Earth; curving the geometry in one location affects the geometry everywhere (like pulling on one end of a bed sheet).

Einstein said that changes in gravity are really changes in geometry. He called these changes ***gravity waves*** that ripple through space and time like ripples on the surface of a pond, except that gravity waves travel at the speed of light. If the Sun were to vanish, we would continue to see its light and feel its gravity for another 500 seconds because that's how long it takes light and gravity to travel 93 million miles. After 500 seconds, both the Sun's light and its gravity would vanish together.

Einstein also changed our entire understanding of space and time. Newton thought there could never be any disagreements about the length of a mile or the duration of a second because he believed space and time were absolute and fixed—the same for every observer, everywhere and always. He also believed space and time were two completely unrelated entities. Einstein showed that space and time are relative—different observers measure different values for distance and time, and that space and time are intimately united as one entity: ***spacetime***. They are really two sides of the same coin. When one changes reference frames, some of what was space can become time and some of what was time can



- Gravity is a force
- Mechanism is unknown
- Acts at a distance
- Moves at infinite speed
- Gravity is tied to mass
- Space and time
    - Two distinct entities
    - Absolute
    - Fixed

- Gravity is geometry
- Mechanism is curvature
- Acts locally
- Moves at light speed
- Gravity is tied to energy
- Spacetime
    - One united entity
    - Relative to observer
    - Dynamic

Figure 19.3. The two greatest physicists had very different theories of gravity, as shown by this comparison. Left: Sir Isaac Newton (1642–1727)

become space. In Einstein's Theory of General Relativity, spacetime is dynamic—the geometry of spacetime is constantly changing as mass and energy move.

Newton viewed space and time as a fixed stage on which the drama of the universe is played out. Einstein viewed spacetime as a dynamic stage that is part of the drama and that controls the motions of the actors.

Einstein explained why, ignoring air resistance, all freely-moving objects fall at the same rate, as Galileo had discovered. This is because all freely-moving objects travel through the same curved, four-dimensional geometry, along the same curved paths—paths that have nothing to do with their masses. In fact, light, which has zero mass, also moves along these same curved paths. Therefore, Einstein said, light bends as it passes a massive body like the Sun.

GRAVITY BENDS STARLIGHT

According to Einstein, starlight passing just above the Sun's surface bends by 1/2000TH of a degree. Light passing twice as far from the Sun's center bends half as much. Consider the situation shown in figure 19.4. Normally, the Sun is not in our line of sight to star A; then, light from that star is not bent by the Sun and we observe the star in its actual location. However, when the Sun moves into our line of sight, light from star A bends as it passes very close to the Sun. As we look back along the light ray that reaches us, the light appears to come from location A* instead of location A. Therefore, we see star A appearing to be closer to star B than it actually is.

When Einstein published General Relativity in 1915, the small bending angle he predicted could be measured (barely), but the challenge was that this measurement could only be done during a total solar eclipse. Stars near the Sun are visible only when the Moon blocks the Sun.

Total solar eclipses are infrequent, brief, and localized. They occur about once every 18 months, often in inaccessible places. Totality lasts only a few minutes, and covers only a tiny sliver of Earth's surface. At any one location, a total solar eclipse occurs only once every 370 years. Astronomers have little chance to overcome error or bad luck—if the sky is cloudy, the opportunity to see stars near the Sun is lost.

The solar eclipse of 1919 was centered in the South Atlantic. British astronomer Sir Arthur Eddington, shown in figure 19.5, made an extraordinary effort to get the most from this less than ideal opportunity to test Einstein's revolutionary theory. Eddington, a Quaker and a conscientious objector, refused military conscription, which wasn't well-accepted during the war. Only with the aid of powerful friends was he able to avoid prison and continue his research. Eddington led expeditions to both sides of the South Atlantic, to Brazil and to the island of Principe near Africa. During the eclipse, his teams feverishly took picture after picture, through partially cloudy skies, hoping at least one would succeed.

Standing under an immense portrait of Sir Isaac Newton, Eddington formally announced his findings at a meeting of Britain's Royal Society. He declared that Einstein's prediction of the bending of starlight was

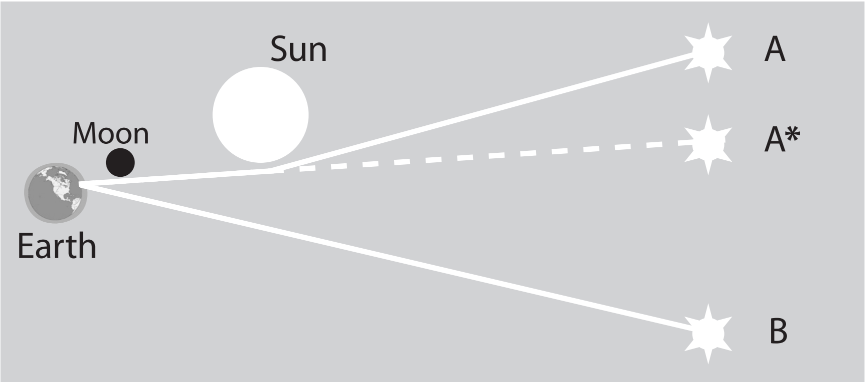


Figure 19.4. During a total solar eclipse, light from star A bends as it passes the Sun. We see that light as coming from location A*—star A appears to be closer than normal to star B, a star whose light is bent much less.

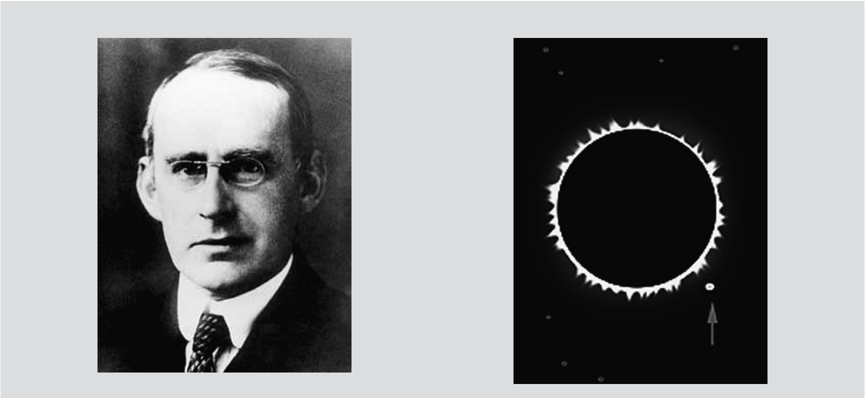


Figure 19.5. Sir Arthur Eddington (1882–1944) and an image from the 1919 solar eclipse. The indicated star's position confirms General Relativity.

correct and that Newton's theory of gravity must give way to General Relativity. Again, a better understanding of gravity ushered in a new age of science.

It is a tribute to international scientific cooperation that near the end of the catastrophe that was World War I, a British scientist devoted so much effort to test a radical revision of Newton's theory of gravity that was proposed by a German scientist.

Glossary of Terms

Abell: catalog of galaxy clusters by George Abell

absolute zero: the coldest possible temperature, 0 Kelvin or 0 K (–460 °F), at which there is no heat and all atomic motion stops

acceleration: ***a***, the rate of change of velocity; a car going from 0 to 60 mph in 6 seconds has ***a=10*** mph/second

accretion disk: a cloud of material swirling around a massive body, such as a black hole

action-at-a-distance: the purported ability of one object to affect another without direct contact, now discredited

amplitude: half the difference between a wave's maximum and minimum values

annihilate: to destroy completely leaving no material residue; antimatter and matter annihilate one another leaving only energy

anti-: prefix identifying an antimatter entity such as antiquark, antiproton, antielectron, etc.

Arp: catalog of "peculiar" galaxies by Halton Arp

atom: a component of matter consisting of a massive but minute nucleus surrounded by a diffuse cloud of electrons

AUI: American Universities Inc.

AURA: Association of Universities for Research in Astronomy

Big Bang: expansion of the universe from an original infinitesimal object of immense temperature

Big Bounce: cosmological scenario with a collapse prior to current expansion phase of the universe

Big Crunch: possible recollapse of the universe, now deemed unlikely

Big Rip: accelerating expansion of the universe; distant objects will disappear as they move away faster than the speed of light

black body spectrum: intensity of thermal radiation that varies in a specific way at different frequencies

black hole: a collapsed mass within a singularity of almost zero size surrounded by an event horizon at which the escape velocity equals the speed of light

blueshift: increase of frequency of light due to the source moving toward us, opposite of redshift

blue-white supergiant: a very massive, very hot, short-lived star

Bose-Einstein statistics: property of bosons to be gregarious.

bosons: a group of gregarious particles, carriers of nature's forces, preferring to coexist in a common state with others of the same type

brown dwarf: a proto-star without enough mass to sustain nuclear fusion and thereby become a true star

calculus: branch of mathematics for analyzing small changes (differential calculus) and combining these to determine global effects (integral calculus)

Caltech: abbreviation for the California Institute of Technology

Cepheid variables: stars whose brightness oscillates in consistent cycles and whose cycle duration is related to their maximum brightness

CFHT: Canada-France-Hawaii Telescope atop Mauna Kea, Hawaii

Chandrasekhar limit: maximum mass of a white dwarf

CMB: the first light, the radiation released when the universe first became transparent, now at a temperature of 2.725 K

CP-symmetry: the equality of particles and antiparticles

coherence: when multiple waves have the same frequency and fixed phase shifts

continuous: (1) of uniform composition without internal structure and not made of smaller parts; (2) without voids or abrupt changes

Cosmic Microwave Background radiation: see CMB

Cosmological Constant: Einstein's attempt to model a static universe

Cosmological Natural Selection: Lee Smolin's hypothesis that universes evolve to produce the greatest number of black holes

cosmology: the study of the universe as a whole entity

curvature: the bending of space or spacetime, as in Einstein's Theory of General Relativity

dark energy: an incompletely understood form of energy with repulsive gravity pushing the universe to expand at an ever faster rate

dark matter: an unknown form of matter exerting a gravitational force, not affected by the strong or electromagnetic forces

deuterium: an atom whose nucleus has one proton and one neutron; a rare isotope of hydrogen

diffraction: a wave spreading after passing through a small opening

discrete: made of individual, identifiable pieces

duality: two seemingly incompatible properties within a single entity

Einstein Field Equations: $G=8\pi T$, of General Relativity. T represents mass and energy, G represents curvature of space and time. Mass and energy tell space and time how to curve; space and time tell mass and energy how to move.

Einstein rings: light from distant sources focused into circular arcs by the gravity of intervening massive bodies

electromagnetic force: the force between charged or magnetic bodies; the force that hold atoms and molecules together

electron: an elementary particle with negative electric charge typically surrounding atomic nuclei

energy: the currency of existence. Its many forms include: potential, kinetic, mass, work, and heat. Energy is conserved—its total amount never changes; it can neither be created nor destroyed.

ether (luminiferous): purported medium through which light travels, no longer thought to exist

ESA: European Space Agency

ESO: European organization for astronomy, southern hemisphere

escape velocity: the speed required to escape from the gravitational field of a massive body

Euclidean: obeying Euclidean geometry, in particular having the interior angles of all triangles sum to 180 degrees

event: a location in four-dimensional spacetime

event horizon: the set of all points where the escape velocity from a black hole equals the speed of light

Fermi-Dirac statistics: property of fermions to be antisocial

fermions: a group of antisocial particles that are constituents of matter and do not share states with others of the same type

flat: having Euclidean geometry, used even when describing spaces with three or more dimensions

frequency: *f*, the number of full cycles per second of a wave

FRW equation: relates universe's expansion rate to its average energy density; a solution of Einstein's Field Equations in a homogenous, Euclidean universe

gamma ray: a photon whose energy is in the highest range, with wavelength less than 10^{-12} meters

General Relativity: Einstein's theory of gravity and the curvature of space and time

generation: elementary particles are grouped into three generations of increasing mass; does not imply some are descendants of others.

Goldilocks Zone: an optimal region for the existence of life

gluon: an exchange boson of the strong force

GPS: Global Positioning System providing precise position and velocity using satellites

gravitational lensing: focusing of light by massive bodies in accordance with Einstein's Theory of General Relativity

graviton: assumed exchange boson of gravity, not yet observed

gravity: described by Newton as a force attracting massive objects to one another; described by Einstein as the effect of spacetime curvature caused by all forms of energy

gravity waves: ripples in curved spacetime moving at the speed of light caused by the motion of massive bodies

habitable zone: where water may be liquid, typically a zone near a star

Hawking radiation: the light emitted near the event horizon of a black hole, reducing its mass, and eventually leading to its evaporation

heat: energy due to temperature, the kinetic energy of vibrating atoms

heavy water: a water molecule in which a normal hydrogen atom is replaced by deuterium, which is a heavier isotope of hydrogen

Hubble's Law: all distant galaxies are moving away from us at speeds v proportional to their distances d: v=Hd

HUDF: Hubble space telescope Ultra-Deep Field image
homogeneous: the same everywhere
hyperspace: a space with more dimensions than normal; in the context of cosmology and General Relativity, a five- or more dimensional space within which our four-dimensional spacetime may exist
incoherent: waves with different frequencies or varying phase shifts
inertial frame: a reference system that moves with constant velocity. Earth's surface is generally accepted as an inertial frame. Newton's Laws and Einstein's Special Relativity apply only in inertial frames.
Inflation: a brief era of extraordinarily rapid expansion of the universe
infrared (IR): light with energy below visible light and above microwave, with wavelength in the range of 10^{-5} meters
interference: two or more waves combining
interference, constructive: waves combining with zero phase shift and reinforcing one another
interference, destructive: waves combining with phase shift of one-half wavelength and cancelling one another
interferometer: high-precision optical device to compare light travel times along two different paths
ion: an atom with a non-zero electric charge
isotope: an atom of the same element with the same number of protons but a different number of neutrons in its nucleus
invariant: having the same value in all reference frames
jet: a collimated stream of particles expelled from an energetic source, such as an accretion disk of a black hole
JPL: Jet Propulsion Laboratory, operated for NASA by Caltech
koan: an unstable particle formed from a quark and an antiquark
kinetic energy: the energy an object has due to its motion
lepton: an elementary particle unaffected by the strong force
light: electromagnetic radiation composed of oscillating electric and magnetic fields, and made of individual particles—photons
light echoes: light received after an initial flash due to the echo traveling a longer path
light-year: the distance light travels in one year, about 6 trillion miles

Local Group: the galaxy cluster containing our Milky Way, Andromeda, and about 30 much smaller galaxies

lookback time: how long ago light that we see today was emitted, allowing us to observe the past

LQG: Loop Quantum Gravity, a theory combing Quantum Mechanics and General Relativity, now in development

LSP: Least-massive Super-symmetric Partner, possibly dark matter

luminosity: amount of radiated energy, such as by a star

M1-M110: objects known not to be comets catalogued by Messier

MACHO: Massive Compact Halo Object, possibly dark matter

macro-world: everything larger than a molecule, where Quantum Mechanics has negligible effects

Maxwell's equations: the equations of electromagnetism

mass: a measure of the amount of material in an object

matter: normal matter is made of protons, neutrons, and electrons

medium: the material waves travel through; air is a medium for sound

metric: equation for distance between points in a curved geometry

microwave: light with energy between infrared and radio wave, with wavelength in the range of 10^{-2} meters

micro-world: everything the size of a molecule or smaller, where the rules of Quantum Mechanics dominate

Milky Way: our galaxy, containing over 200 billion stars

Miracle Year: 1905, during which Einstein published five spectacular papers revolutionizing physics

molecule: two or more atoms bound together by sharing electrons

Msun: abbreviation for the mass of our Sun

muon: an elementary particle, a heavier version of electron

NRAO: U.S. National Radio Astronomy Observatory.

NOAO: U.S. National Optical Astronomy Observatory.

NASA: U.S. National Aeronautics and Space Administration, launches and operates most of the world's great space telescopes

natural units: a system of measurement units in which the speed of light c=1 and Newton's constant G=1

NGC: New General Catalog of galaxies by Dreyer and Herschel

nebula (nebulae): a cosmic cloud (clouds) of illuminated gas
neutral: having zero net electric charge
neutrino: an uncharged lepton, an elementary particle with extremely small mass and weak interactions with all types of particles
neutron: a particle with zero electric charge, made of 3 quarks, typically found only within an atomic nucleus
neutron star: a collapsed star with mid-range mass consisting primarily of neutrons
nuclear fission: splitting of a large atomic nucleus
nuclear fusion: small nuclei merging to make a larger one
nucleus: the core of an atom containing almost all its mass and energy
particle: one of a group of subatomic pieces of matter; particles of the same type are absolutely identical
particle, elementary: a particle not composed of other particles
particle-wave duality: the property of an entity having both particle and wave characteristics that seem incompatible
Periodic Table: chart of the elements arranged according to their chemical properties and the number of protons in their nuclei
phase shift: difference between positions of crests of two waves of same frequency
photoelectric effect: light incident on metal surface ejects electrons if its frequency is high enough
photon: a particle of light, exchange boson of electromagnetic force
Planck length: perhaps the smallest distance that exists in our universe, equal to 6×10^{-34} inches or 1.6×10^{-35} meters
Planck mass: possibly the total mass of the universe at the moment it came into existence, equal to 3×10^{-7} ounces or 2.2×10^{-5} grams
Planck time: possibly the smallest time interval that can exist, equal to 5×10^{-44} seconds
planetary nebula: a cloud of gas blown away by a dying star; it is made of star dust and has nothing to do with planets
plasma: a state of hot matter in which electrons separate from nuclei; plasma is opaque
potential energy: the energy an object has due to its distance from the center of a gravitational field

Principle of…: see Summary of Key Principles on page 319

properly written: defined here to be equations expressed in tensors in four-dimensional spacetime, making them valid in all reference frames and for all observers, regardless of motion or gravity

proton: a particle with positive electric charge, made of three quarks, component of atomic nuclei

proto-planet: a body that may develop into a planet

proto-star: a body that may develop into a star

pulsar: a neutron star with an immense magnetic field aligned askew to its axis of rotation

quantum: smallest possible unit, such as of energy; a penny is the quantum of U.S. currency

quantum fluctuation: a miniscule variation required by the Uncertainty Principle of Quantum Mechanics

quantum foam: breakdown of continuous spacetime at minute distances

Quantum Gravity: a hoped-for theory that will unite General Relativity and Quantum Mechanics

Quantum Mechanics: physical theory of the very small

quantum superposition: existing simultaneously in different states

quark: an elementary particle affected by the strong force, components of protons and neutrons; 6 types exist: up (u), down (d), charm (c), strange (s), top (t), and bottom (b)

quasar: a superluminous galaxy driven by a voracious black hole

qubit: a single storage element in a quantum computer

radio telescope: a telescope to image sources that emit radio waves

radio wave: light whose wavelength is more than 1 meter

redshift: reduction of frequency of light due to any of the following:

(1) light source moving away from us

(2) expansion of space

(3) light moving against the force of gravity

red giant: a greatly expanded star near end of life

red dwarf: a dim star with minimum mass to sustain nuclear fusion

resolution: ability to distinguish two slightly separated sources of light; higher resolution provides more detailed images

Schwarzchild metric: an important solution of Einstein's Field Equations for the spacetime curvature around a massive, round object

Schwarzchild radius: the radius of the event horizon of a symmetric, non-rotating, black hole

singularity: place where mass is concentrated in almost zero volume: center of a black hole, or the instant the universe came into existence

SOHO: Solar and Heliospheric Observatory satellite

solar wind: radiation and charged particles emitted by the Sun

spacetime: four-dimensional union of space and time

spacetime curvature: deviation from flat Euclidean geometry due to any form of energy, resulting in "gravity"

spaghettification: tidal forces stretching objects in the radial direction to a gravitating mass and squeezing them laterally

Special Relativity: Einstein's theory of space, time, and motion, excluding gravity and other forces

spectrum: collection of light frequencies an object emits or absorbs

star: a ball of gas so massive it sustains nuclear fusion in its core

standard candle: a distant source emitting a known amount of light

stellar wind: radiation and charged particles emitted by a star

strong force: force that holds together quarks and nuclei

supernova: explosion of a star releasing immense energy, and possibly creating a collapsed core: a neutron star or black hole

tensor: mathematical entity conforming to Special Relativity; tensor equations are valid in all references frames, even with gravity.

Thermodynamics: the physical theory of heat

thought experiment: a mental exercise focusing on key physical questions in an idealized situation

tic: defined here to be 10^{-30} seconds

time dilation: the slowing down of time that we perceive: (1) in a system with high relative velocity, due to Special Relativity; or (2) near a massive body, due to General Relativity

tidal force: differential forces of gravity that cause tides on Earth due to Moon and Sun, and spaghettification of objects near black holes

TLA: Three-Letter Acronym, a NASA specialty

ultraviolet (UV): light with energy above that of visible light and below x-rays, with wavelength in the range of 10^{-8} meters

universe: defined to be all we can observe or be influenced by, in any conceivable manner

universe, expansion: increase in the distance between any two distant points in the universe

variable stars: stars whose brightness cycles periodically

velocity: v, an object's speed and direction, e.g. 60 mph due north

velocity, absolute: discredited notion that velocities measured in a special, "absolute" frame of reference have greater importance than those measured in other frames

velocity, relative: motion measured with respect to something else, e.g. Earth moves 70,000 mph relative to the solar system

virtual particles: particle-antiparticle pairs spontaneously created, existing briefly, and vanishing as allowed by the Uncertainty Principle

wave: an assembly of many small objects moving together in an oscillatory manner

wavelength: w, the distance between wave crests

wave packet: a partially localized combination of waves of different frequencies

weak force: the force enabling radioactive decay and allowing more matter than antimatter to develop in first 1 second after Big Bang

white dwarf: a collapsed star with mass < 1.4 ***Msun***

WIMP: Weakly Interacting Massive Particle, possibly dark matter

WMAP: NASA's Wilkinson Microwave Anisotropy Probe satellite

x-ray: a photon with energy between gamma rays and ultraviolet, with wavelength in the range of 10^{-10} meters

yellow dwarf: a star like our Sun, sustained by hydrogen fusion, with mid-range mass and temperature

Index

The most important references are shown in **bold** type.