PREFACE ..... 11
PART I. STARS, PLANETS, AND LIFE ..... 15
1 THE SIZE AND SCALE OF THE UNIVERSE ..... 17Neil deGrasse Tyson
2 FROM THE DAY AND NIGHT SKY TO PLANETARY ORBITS ..... 26
Neil deGrasse Tyson
3 NEWTON'S LAWS ..... 42
Michael A. Strauss
4 HOW STARS RADIATE ENERGY (I) ..... 54
Neil deGrasse Tyson
5 HOW STARS RADIATE ENERGY (II) ..... 71
Neil deGrasse Tyson
6 STELLAR SPECTRA ..... 81
Neil deGrasse Tyson
7 THE LIVES AND DEATHS OF STARS (I) ..... 93
Neil deGrasse Tyson
8 the lives and deaths of Stars (II) ..... 111
Michael A. Strauss
9 WHY PLUTO IS NOT A PLANET ..... 126
Neil deGrasse Tyson
10 THE SEARCH FOR LIFE IN THE GALAXY ..... 146
Neil deGrasse Tyson
PART II. GALAXIES ..... 171
11 THE INTERSTELLAR MEDIUM ..... 173
Michael A. Strauss
12 OUR MILKY WAY ..... 183
Michael A. Strauss
13 THE UNIVERSE OF GALAXIES ..... 197
Michael A. Strauss
14 THE EXPANSION OF THE UNIVERSE ..... 207
Michael A. Strauss
15 THE EARLY UNIVERSE ..... 222
Michael A. Strauss
16 QUASARS AND SUPERMASSIVE BLACK HOLES ..... 241
Michael A. Strauss
PART III. EINSTEIN AND THE UNIVERSE ..... 255
17 EINSTEIN'S ROAD TO RELATIVITY ..... 257
J. Richard Gott
18 IMPLICATIONS OF SPECIAL RELATIVITY ..... 270
J. Richard Gott
19 EINSTEIN'S GENERAL THEORY OF RELATIVITY ..... 289
J. Richard Gott
20 BLACK HOLES ..... 300
J. Richard Gott
21 COSMIC STRINGS, WORMHOLES, AND TIME TRAVEL ..... 321
J. Richard Gott
22 THE SHAPE OF THE UNIVERSE AND THE BIG BANG ..... 347
J. Richard Gott
23 INFLATION AND RECENT DEVELOPMENTS IN COSMOLOGY ..... 374
J. Richard Gott
24 OUR FUTURE IN THE UNIVERSE ..... 400
J. Richard Gott
ACKNOWLEDGMENTS ..... 425
APPENDIX 1
Derivation of $\mathrm{E}=\mathrm{mc}^{2}$ ..... 427
APPENDIX 2
Bekenstein, Entropy of Black Holes, and Information ..... 431
NOTES ..... 433
SUGGESTED READING ..... 439
INDEX ..... 441

## (1)

## THE SIZE AND SCALE OF THE UNIVERSE

NEIL DEGRASSE TYSON

We begin with the stars, then ascend up and away out to the galaxy, the universe, and beyond. What did Buzz Lightyear say in Toy Story? "To Infinity and Beyond!"

It's a big universe. I want to introduce you to the size and scale of the cosmos, which is bigger than you think. It's hotter than you think. It is denser than you think. It's more rarified than you think. Everything you think about the universe is less exotic than it actually is. Let's get some machinery together before we begin. I want to take you on a tour of numbers small and large, just so we can loosen up our vocabulary, loosen up our sense of the sizes of things in the universe. Let me just start out with the number 1. You've seen this number before. There are no zeros in it. If we wrote this in exponential notation, it is ten to the zero power, $10^{\circ}$. The number 1 has no zeros to the right of that 1 , as indicated by the zero exponent. Of course, 10 can be written as 10 to the first power, $10^{1}$. Let's go to a thousand $-10^{3}$. What's the metric prefix for a thousand? Kilo- kilogram-a thousand grams; kilometer-a thousand meters. Let's go up another 3 zeros, to a million, $10^{6}$, whose prefix is mega-. Maybe this is the highest they had learned how to count at the time they invented the megaphone; perhaps if they had known about a billion, by appending three more zeroes, giving $10^{9}$, they would have called them "gigaphones." If you study file sizes on your computer, then you're familiar with these two words, "megabytes" and "gigabytes." A gigabyte is a billion bytes. ${ }^{1}$ I'm not convinced you know how big a billion actually is. Let's look around the world and ask what kinds of things come in billions.

First, there are 7 billion people in the world.
Bill Gates? What's he up to? Last I checked, he's up to about 80 billion dollars. He's the patron saint of geeks; for the first time, geeks actually control the world. For most of human history that was not the case. Times have changed. Where have you seen 100 billion? Well, not quite 100 billion. McDonald's. "Over 99 Billion Served." That's the biggest number you ever see in the street. I remember when they started counting. My childhood McDonald's proudly displayed "Over 8 Billion Served." The McDonald's sign never displayed 100 billion, because they allocated only two numerical slots for their burger count, and so, they just stopped at 99 billion. Then they pulled a Carl Sagan on us all and now say, "billions and billions served."

Take 100 billion hamburgers, and lay them end to end. Start at New York City, and go west. Will you get to Chicago? Of course. Will you get to California? Yes, of course. Find some way to float them. This calculation works for the diameter of the bun (4 inches), because the burger itself is somewhat smaller than the bun. So for this calculation, it's all about the bun. Now float them across the ocean, along a great circle route, and you will cross the Pacific, pass Australia, Africa, and come back across the Atlantic Ocean, finally arriving back in New York City with your 100 billion hamburgers. That's a lot of hamburgers. But in fact you have some left over after you have circled the circumference of Earth. Do you know what you do with what you have left over? You make the trip all over again, 215 more times! Now you still have some left over. You're bored going around Earth, so what do you do? You stack them. So after you've gone around Earth 216 times, then you stack them. How high do you go? You'll go to the Moon, and back, with stacked hamburgers (each 2 inches tall) after you've already been around the world 216 times, and only then will you have used your 100 billion hamburgers. That's why cows are scared of McDonald's. By comparison, the Milky Way galaxy has about 300 billion stars. So McDonald's is gearing up for the cosmos.

When you are 31 years, 7 months, 9 hours, 4 minutes, and 20 seconds old, you've lived your billionth second. I celebrated with a bottle of champagne when I reached that age. It was a tiny bottle. You don't encounter a billion very often.

Let's keep going. What's the next one up? A trillion: $10^{12}$. We have a metric prefix for that: tera-. You can't count to a trillion. Of course you could try. But if you counted one number every second, it would take you a thousand times

31 years $-31,000$ years, which is why I don't recommend doing this, even at home. A trillion seconds ago, cave dwellers-troglodytes-were drawing pictures on their living room walls.

At New York City's Rose Center of Earth and Space, we display a timeline spiral of the Universe that begins at the Big Bang and unfolds 13.8 billion years. Uncurled, it's the length of a football field. Every step you take spans 50 million years. You get to the end of the ramp, and you ask, where are we? Where is the history of our human species? The entire period of time, from a trillion seconds ago to today, from graffiti-prone cave dwellers until now, occupies only the thickness of a single strand of human hair, which we have mounted at the end of that timeline. You think we live long lives, you think civilizations last a long time, but not from the view of the cosmos itself.

What's next? $10^{15}$. That's a quadrillion, with the metric prefix peta-. It's one of my favorite numbers. Between 1 and 10 quadrillion ants live on (and in) Earth, according to ant expert E. O. Wilson.

What's next? $10^{18}$, a quintillion, with metric prefix exa-. That's the estimated number of grains of sand on 10 large beaches. The most famous beach in the world is Copacabana Beach in Rio de Janeiro. It is 4.2 kilometers long, and was 55 meters wide before they widened it to 140 meters by dumping 3.5 million cubic meters of sand on it. The median size of grains of sand on Copacabana Beach at sea level is $1 / 3$ of a millimeter. That's 27 grains of sand per cubic millimeter, so 3.5 million cubic meters of that kind of sand is about $10^{17}$ grains of sand. That's most of the sand there today. So about 10 Copacabana beaches should have about $10^{18}$ grains of sand on them.

Up another factor of a thousand and we arrive at $10^{21}$, a sextillion. We have ascended from kilometers to megaphones to McDonald's hamburgers to CroMagnon artists to ants to grains of sand on beaches until finally arriving here: 10 sextillion-

## the number of stars in the observable universe.

There are people, who walk around every day, asserting that we are alone in this cosmos. They simply have no concept of large numbers, no concept of the size of the cosmos. Later, we'll learn more about what we mean by the observable universe, the part of the universe we can see.

While we're at it, let me jump beyond this. Let's take a number much larger than 1 sextillion-how about $10^{81}$ ? As far as I know, this number has no name.

It's the number of atoms in the observable universe. Why then would you ever need a number bigger than that? What "on Earth" could you be counting? How about $10^{100}$, a nice round-looking number. This is called a googol. Not to be confused with Google, the internet company that misspelled "googol" on purpose.

There are no objects to count in the observable universe to apply a googol to. It is just a fun number. We can write it as $10^{100}$, or if you don't have superscripts, this works too: $10^{\wedge} 100$. But you can still use such big numbers for some situations: don't count things, but instead count the ways things can happen. For example, how many possible chess games can be played? A game can be declared a draw by either player after a triple repetition of a position, or when each has made 50 moves in a row without a pawn move or a capture, or when there are not enough pieces left to produce a checkmate. If we say that one of the two players must take advantage of this rule in every game where it comes up, then we can calculate the number of possible chess games. Rich Gott did this and found the answer was a number less than $10^{\wedge}\left(10^{\wedge} 4.4\right)$. That's a lot bigger than a googol, which is $10^{\wedge}\left(10^{\wedge} 2\right)$. You're not counting things, but you are counting possible ways to do something. In that way, numbers can get very large.

I have a number still bigger than this. If a googol is 1 followed by 100 zeros, then how about 10 to the googol power? That has a name too: a googolplex. It is 1 , with a googol of zeroes after it. Can you even write out this number? Nope. Because it has a googol of zeroes, and a googol is larger than the number of atoms in the universe. So you're stuck writing it this way: $10^{\text {googol }}$, or $10^{10^{\wedge 100}}$ or $10^{\wedge}\left(10^{\wedge} 100\right)$. If you were so motivated, I suppose you could attempt to write $10^{19}$ zeros, on every atom in the universe. But you surely have better things to do.

I'm not doing this just to waste your time. I've got a number that's bigger than a googolplex. Jacob Bekenstein invented a formula allowing us to estimate the maximum number of different quantum states that could have a mass and size comparable to our observable universe. Given the quantum fuzziness we observe, that would be the maximum number of distinct observable universes like ours. It's $10^{\wedge}\left(10^{\wedge} 124\right)$, a number that has $10^{24}$ times as many zeros as a googolplex. These $10^{\wedge}\left(10^{\wedge} 124\right)$ universes range from ones that are scary, filled with mostly black holes, to ones that are exactly like ours but where your nostril is missing one oxygen molecule and some space alien's nostril has one more.

So, in fact, we do have some uses for some very large numbers. I know of no utility for numbers larger than this one, but mathematicians surely do.

A theorem once contained the badass number $10^{\wedge}\left(10^{\wedge}\left(10^{\wedge} 34\right)\right)$. It's called Skewe's number. Mathematicians derive pleasure from thinking far beyond physical realities.

Let me give you a sense of other extremes in the universe.
How about density? You intuitively know what density is, but let's think about density in the cosmos. First, explore the air around us. You're breathing $2.5 \times 10^{19}$ molecules per cubic centimeter-78\% nitrogen and $21 \%$ oxygen.

A density of $2.5 \times 10^{19}$ molecules per cubic centimeter is likely higher than you thought. But let's look at our best laboratory vacuums. We do pretty well today, bringing the density down to about 100 molecules per cubic centimeter. How about interplanetary space? The solar wind at Earth's distance from the Sun has about 10 protons per cubic centimeter. When I talk about density here, I'm referencing the number of molecules, atoms, or free particles that compose the gas. How about interstellar space, between the stars? Its density fluctuates, depending on where you're hanging out, but regions in which the density falls to 1 atom per cubic centimeter are not uncommon. In intergalactic space, that number is going to be much less: 1 per cubic meter.

We can't get vacuums that empty in our best laboratories. There is an old saying, "Nature abhors a vacuum." The people who said that never left Earth's surface. In fact, Nature just loves a vacuum, because that's what most of the universe is. When they said "Nature," they were just referring to where we are now, at the base of this blanket of air we call our atmosphere, which does indeed rush in to fill empty spaces whenever it can.

Suppose I smash a piece of chalk against a blackboard and pick up a fragment. I've smashed that chalk into smithereens. Let's say a smithereen is about 1 millimeter across. Imagine that's a proton. Do you know what the simplest atom is? Hydrogen, as you might have suspected. Its nucleus contains one proton, and normal hydrogen has an electron occupying an orbital that surrounds it. How big would that hydrogen atom be? If the chalk smithereen is the proton, would the atom be as big as a beach ball? No, much bigger. It would be 100 meters across-about the size of a 30 -story building. So what's going on here? Atoms are pretty empty. There are no particles between the nucleus and that lone electron, flying around in its first orbital, which, we learn from quantum mechanics, is spherically shaped around the nucleus. Let's go smaller and smaller and smaller, to get to another limit of the cosmos, represented by the measurement of things that are so tiny that
we can't even measure them. We do not yet know what the diameter of the electron is. It is smaller than we are able to measure. However, superstring theory suggests that it may be a tiny vibrating string as small as $1.6 \times 10^{-35}$ meters in length.

Atoms are about $10^{-10}$ (one ten-billionth) of a meter. But how about $10^{-12}$ or $10^{-13}$ meters? Known objects that size include uranium with only one electron, and an exotic form of hydrogen having one proton with a heavy cousin of the electron called a muon in orbit around it. About $1 / 200$ the size of a common hydrogen atom, it has a half-life of only about 2.2 microseconds due to the spontaneous decay of its muon. Only when you get down to $10^{-14}$ or $10^{-15}$ meters are you measuring the size of the atomic nucleus.

Now let's go the other way, ascending to higher and higher densities. How about the Sun? Is it very dense or not that dense? The Sun is quite dense (and crazy hot) in the center, but much less dense at its edge. The average density of the Sun is about 1.4 times that of water. And we know the density of water-1 gram per cubic centimeter. In its center, the Sun's density is 160 grams per cubic centimeter. But the Sun is quite ordinary in these matters. Stars can (mis)behave in amazing ways. Some expand to get big and bulbous with very low density, while others collapse to become small and dense. In fact, consider my proton smithereen and the lonely, empty space that surrounds it. There are processes in the universe that collapse matter down, crushing it until it reaches the density of an atomic nucleus. Within such stars, each nucleus rubs cheek to cheek with the neighboring nuclei. The objects out there with these extraordinary properties happen to be made mostly of neutrons-a super-highdensity realm of the universe.

In our profession, we tend to name things exactly as we see them. Big red stars we call red giants. Small white stars we call white dwarfs. When stars are made of neutrons, we call them neutron stars. Stars that pulse, we call them pulsars. In biology they come up with big Latin words for things. MDs write prescriptions in a cuneiform that patients can't understand, hand them to the pharmacist, who understands the cuneiform. It's some long fancy chemical thing, which we ingest. In biochemistry, the most popular molecule has ten syllables-deoxyribonucleic acid! Yet the beginning of all space, time, matter, and energy in the cosmos, we can describe in two simple words, Big Bang. We are a monosyllabic science, because the universe is hard enough. There is no point in making big words to confuse you further.

Want more? In the universe, there are places where the gravity is so strong that light doesn't come out. You fall in, and you don't come out either: black hole. Once again, with single syllables, we get the whole job done. Sorry, but I had to get all that off my chest.

How dense is a neutron star? Let's take a thimbleful of neutron star material. Long ago, people would sew everything by hand. A thimble protects your fingertip from getting impaled by the needle. To get the density of a neutron star, assemble a herd of 100 million elephants, and cram them into this thimble. In other words, if you put 100 million elephants on one side of a seesaw, and one thimble of neutron star material on the other side, they would balance. That's some dense stuff. A neutron star's gravity is also very high. How high? Let's go to its surface and find out.

One way to measure how much gravity you have is to ask, how much energy does it take to lift something? If the gravity is strong, you'll need more energy to do it. I exert a certain amount of energy climbing up a flight of stairs, which sits well within the bounds of my energetic reserves. But imagine a cliff face 20,000 kilometers tall on a hypothetical giant planet with Earthlike gravity. Measure the amount of energy you exert climbing from the bottom to the top fighting against the gravitational acceleration we experience on Earth for the whole climb. That's a lot of energy. That's more energy than you've stored within you, at the bottom of that cliff. You will need to eat energy bars or some other high-calorie, easily digested food on the way up. Okay. Climbing at a rapid rate of 100 meters per hour, you would spend more than 22 years climbing 24 hours a day to get to the top. That's how much energy you would need to step onto a single sheet of paper laid on the surface of a neutron star. Neutron stars probably don't have life on them.

We have gone from 1 proton per cubic meter to 100 million elephants per thimble. What have I left out? How about temperature? Let's talk hot. Start with the surface of the Sun. About 6,000 kelvins $-6,000 \mathrm{~K}$. That will vaporize anything you give it. That's why the Sun is gas, because that temperature vaporizes everything. (By comparison, the average temperature of Earth's surface is a mere 287 K .)

How about the temperature at the Sun's center? As you might guess, the Sun's center is hotter than its surface-there are cogent reasons for this, as we'll see later in the book. The Sun's center is about 15 million K. Amazing things happen at 15 million K . The protons are moving fast. Really fast, in fact.

Two protons normally repel each other, because they have the same (positive) charge. But if you move fast enough, you can overcome that repulsion. You can get close enough so that a brand-new force kicks in-not the repulsive electrostatic force, but an attractive force that manifests over a very short range. If you get two protons close enough, within that short range they will stick together. This force has a name. We call it the strongforce. Yes, that's the official name for it. This strong nuclear force can bind protons together and make new elements out of them, such as the next element after hydrogen on the periodic table, helium. Stars are in the business of making elements heavier than those they are born with. And this process happens deep in the core. We'll learn more about that in chapter 7 .

Let's go cool. What is the temperature of the whole universe? It does indeed have a temperature-left over from the Big Bang. Back then, 13.8 billion years ago, all the space, time, matter, and energy you can see, out to 13.8 billion light-years, was crushed together. The nascent universe was a hot, seething cauldron of matter and energy. Cosmic expansion since then has cooled the universe down to about 2.7 K .

Today we continue to expand and cool. As unsettling as it may be, the data show that we're on a one-way trip. We were birthed by the Big Bang, and we're going to expand forever. The temperature is going to continue to drop, eventually becoming 2 K , then 1 K , then half a kelvin, asymptotically approaching absolute zero. Ultimately, its temperature may bottom out at about $7 \times 10^{-31} \mathrm{~K}$ because of an effect discovered by Stephen Hawking that Rich will discuss in chapter 24. But that fact brings no comfort. The stars will finish fusing all their thermonuclear fuel, and one by one they will die out, disappearing from the sky. Interstellar gas clouds do make new stars, but of course this depletes their gas supply. You start with gas, you make stars, the stars evolve during their lives, and leave behind a corpse-the dead end-products of stellar evolution: black holes, neutron stars, and white dwarfs. This keeps going until all the lights of the galaxy turn off, one by one. The galaxy goes dark. The universe goes dark. Black holes are left, emitting only a feeble glow of light—again predicted by Stephen Hawking.

And the cosmos ends. Not with a bang, but with a whimper.
Way before that happens, the Sun, to talk about size, will grow. You don't want to be around when that happens, I promise you. When the Sun dies, complicated thermal physics happens inside, forcing the outer surface of the

Sun to expand. It will get bigger and bigger and bigger and bigger, as the Sun in the sky slowly occupies more and more and more of your field of view. The Sun eventually engulfs the orbit of Mercury, and then the orbit of Venus. In 5 billion years, the Earth will be a charred ember, orbiting just outside the Sun's surface. The oceans will have already come to a rolling boil, evaporating into the atmosphere. The atmosphere will have been heated to the point that all the atmospheric molecules escape into space. Life as we know it will cease to exist, while other forces, after about 7.6 billion years, cause the charred Earth to spiral into the Sun, vaporizing there.

Have a nice day!
What I've tried to give you is a sense of the magnitude and grandeur of what this book is about. And everything that I've just referenced here appears in much more depth and detail in subsequent chapters. Welcome to the universe.

## INDEX

Italic pages refer to figures and tables

Abbott, Edwin, 348
absorption spectra, 84, 87-89, 169, 176, 2079, 250-51
acceleration: astronaut time (AT) and, 276-82; black holes and, 303-4, 309-10; calculus and, 45 ; centripetal, 292; as change of velocity/time, 44; Doppler shift and, 64-65, 97, 208-9, 212, 214, 225, 231-32, 235, 245-46, 262, 284-86, 331, 429; Earth and, 49-51, 116, 282; Einstein and, 294; Equivalence Principle and, 290, 292, 298, 310; expansion and, 392, 409; general relativity and, 289-94, 298; gravity and, $23,47,49,52,116,158$, 294; inflation and, 376-81, 386, 389-92, 398; Moon and, 47-48; Newton's laws and, 44-52, 116, 259, 264, 289-90, 294; shape of universe and, $350-51$; special relativity and, 280, 282; Sun and, 46-47, 116; supernovae and, 389; Twin Paradox and, 280-83
action at a distance, 295-96, 319-20
After Man (Dixon), 417
Albrecht, Andreas, 386
Alcubierre, Miguel, 345
Aldebaran, 120
Aldrin, Buzz, 424

Ali, Muhammad, 260
Alien (film), 165-66
Allen, Chuck, 413-14
Alpert, Mark, 365, 435n1
Alpha Centauri, 59, 94, 125, 280-83, 341-44, 355, 423
alpha particles, 384-85
Alpher, Ralph, 224-25, 228-30, 375, 415
AM Canum Venaticorum stars, 190
American Astronomical Society, 136
American Museum of Natural History, 126
Ampère's law, 261
Andromeda Galaxy, 127, 195, 198-202, 204, 207-17, 232, 405
angular momentum, $39,124,204,247-48$, 314, 317, 319, 337
anisotropies, 235
antimatter, 99, 158-59, 286-87, 289, 319-20, 402, 404
Apache Point Telescope, 250-51
Apollo astronauts, 50, 302, 308, 422, 424
arc second, 58-59
Arcturus, 120
Aristarchus, 37, 59
Aristotle, 37, 50, 115, 269, 290
Armstrong, Neil, 424
asterisms, 30
asteroids, 111, 112, 127-28, 134, 140-44, 148, $164,253,355,416,423$
astronaut time (AT), 276-82
Astronomical Units (AU), 40, 42, 54, 115, 213
Astrophysical Journal, 229, 354
atomic bomb, 103, 259, 269, 287, 413
atomic clocks, 269
atomic number, 103-4
atoms: binding energy and, 86, 103-4; Bohr and, 258; dark matter and, 196 (see also dark matter); density and, 21; early universe and, 222, 227-28, 232-34; electrons and, 81-82 (see also electrons); electron volt (eV) and, 85-86, 103-4; energy levels and, $82-90,119,179,250,258$; fusion and, $99,102-5,111,114-15,117-18,121,158,181$, $222-23$; ionization and, $86-88,107,113$, 228,233 ; lives of stars and, $98,103,113,119$, 122; neutrons and, 13 (see also neutrons); nuclei, 13, 21-22, 81-85, 98-100, 102-5, $113,119,122,128,181,222-27,234,240,287$, $302,327,350-51,355,384-85$; number of, 20; photons and, 179 (see also photons); protons and, 21 (see also protons); quantum theory and, 21, 258 (see also quantum theory); quasars and, 245 ; recombination and, 236-37, 403, 405; scale of universe and, 128; Schrödinger and, 258; size of, 22; spectra and, $81-92,242,245$; strong nuclear force and, $24,99,351,384-85,402$; weak nuclear force and, 351, 402-3
axions, 232

Baade, Walter, 243-44
bacteria, 147, 161, 164-65
Bahcall, John, 5, 245
Bahcall, Neta, 12, 425
Balmer series, 86, 88, 90-92, 179, 242, 258
Barrabès, Claude, 399
barred spiral galaxies, 191
Barrow, Isaac, 257
baryons, 390-91, 407
Bayesian statistics, 418, 421, 436n5
Bayeux Tapestry, 53

Bekenstein, Jacob, 12-13, 20, 314-16, 431
Bell, Jocelyn, 125
Bell Laboratories, 229
Berlin Wall, 411-13, 424
Bessel, Friedrich, 59
Bethe, Hans, 224
Bhagavad Gita, 287
BICEP2, 393
Bienen, Henry, 436n5
Big Bang: beginning of time and, 368-69; black holes and, 250, 312, 327; CMB and, 229 (see also cosmic microwave background (CMB)); early universe and, 222-37, 240; empirical evidence for, 226; energy radiation and, 71 ; expansion and, 218-21; Friedmann and, 367-73, 375-76; Hayden Planetarium and, 127; as Hoyle term, 218; inflation and, 374-78, 381, 393, 398; Lemaître and, 363, 393-94; origin of all elements and, 224; predictions of model, 226-27; quasars and, 250; relativity and, 415; scale of universe and, 19 , 22,24 ; shape of universe and, 367-73; spectra and, 81-82; timeline of, 19; uniformity of, 376
Big Crunch, 367-68, 372, 373, 384
Big Dipper, 30-31
Bill and Ted's Excellent Adventure (film), 325
bimodal distribution, 61-62
binary stars, 97, 117, 157
binding energy, 86, 103-4
Binzel, Richard, 136
bismuth, 82
blackbodies, $72-74,77,113,154,222,225$, 228-31, 375
black holes: acceleration and, 303-4, 309-10; accretion disks and, 247, 249; action at a distance and, 295-96; Bekenstein and, 12-13, 20, 314-16, 431; Big Bang and, 250, 312, 327; Big Crunch and, 368; centers of galaxies and, 249; challenges in detecting, 249; circumferential radius and, 306; collapsing stars and, $100,247,302-3$, 312-13, 316, 336-37, 398, 401, 432; com-
puter simulations of, 314; cosmic microwave background (CMB) and, 318-19; as cosmic vacuum cleaners, 248; decay and, 314, 317, 407; Doppler shift and, 249; early universe and, 250; Einstein and, 300-303, 314, 317, 319-20; electromagnetism and, 317; electrons and, 317-20; energy density and, 318; entropy and, 315-16, 323, 431; evaporation of, 318-19; event horizons and, 305, 308-20, 337-38, 340, 344, 379-80, 386, 405-7, 431; firewalls and, 319 ; formation of, 252-53; future of universe and, 401, 403, 405, 407-8; general relativity and, 300-302, 314, 320; geometry and, $300,306-11,314,316$; gravity and, 13, 23, 122, 247, 249, 302-4, 314, 403; Hartle-Hawking vacuum and, 31819, 344; Hawking and, 314-20; Hawking radiation and, 317-19, 340, 406-8; Hubble Space Telescope and, 247-48, 306; inflation and, 380, 398; jet streams of, 24748; Karl Schwarzschild and, 300-302, 308; Kerr, 314-17, 337-39; lives of stars and, 123; lost information and, 316-17, 319, 431-32; Martin Schwarzschild and, 301-2; mass and, 121, 176, 196, 246-53, 300-311, 314-19, 338, 355, 403, 407-8; mass of, 121, 249-50, 252, 300-301, 303, 308; Mercury and, 300; Milky Way and, 247-49, 251; orbitals and, 314; Penrose and, 317; perturbations and, 300, 314; photons and, 310, 318; Planck length and, 302, 316, 407, 431; point-masses and, 300-301, 303, 309, 311; positrons and, 317-20; quantum theory and, 249,302 , 316-19; red giants and, 302-3; redshift and, 252-53, 318; Schwarzschild radius and, $301-10,313-15,318,401$; shape of universe and, $355,362,368$; singularities and, $302,305-6,309-13$; solar mass and, $247-49,252,303,305-6,314-16,318-19$, 338, 355, 403; spacetime and, 300-304, 309-17; spaghettification and, 305-6; speed of light and, $300,302,304-6,309-$

12, 316; Sun and, 237-50, 300-303, 313; supermassive, 121, 249-50, 252, 303, 308; temperature and, 247, 316-19; thermal, 314, 317-19; tidal forces and, 304, 306; time travel and, 337-41, 344; uncertainty principle and, 316-17, 381, 385, 393, 401, 403, 407; virtual pairs and, 317-18; wavelength and, 318; Wheeler and, 314-15; white dwarfs and, 303; white holes and, 312, 338; worldlines and, 309-13; wormholes and, 311-12, 319-20
blink comparator, 130, 134
BL Lacertae stars, 190
blueshift, 209, 217, 231, 245, 339, 341, 429
blue stars, 90, 93, 96-98, 180, 194, 204
Blumenthal, George, 234
Bode, Johann, 139
Bohr, Neils, 82, 92, 258
Boltzmann, Ludwig, 75, 80
Boltzmann constant, 73
Boötes, 120
Borde, Arvin, 384
Bradley, James, 263
Brahe, Tycho, 35-37, 43, 258
brightness: apparent, 169; eclipses and, 141; energy radiation and, 78-80; inverse-square law and, 78-79, 184, 188; lives of stars and, 116; quasars and, 246 (see also quasars); radio, 168; spectra and, 92; variable stars and, 189-90, 198, 200, 209-11, 213-15
Brokaw, Tom, 413
Brown, Mike, 144
brown dwarfs, 68, 117
bubble universes, 381-88, 394, 396, 402, 408, 431nnl-3
Buller, A.H.R., 326
Burney, Venetia, 130
calcium, 88-89, 169, 207
calculus, 40-41, 45, 50, 62, 74-75, 257, 261
Caldwell, Robert, 409
California Institute of Technology (Caltech), 144, 196, 242-44, 320, 334
Callisto, 139, 142

Campbell, W. W., 299
carbon: abundance of, 81-82; early universe and, 224, 251; interstellar medium and, 181; lives of stars and, 99, 102, 105, 119-21; nucleus of, 99 ; search for life and, 147, 162-63, 169, 410; spectra and, 88
carbon dioxide, 132, 147, 163, 169, 422
Carnegie Observatories, 215-16
Carter, Brandon, 410, 418
Cartesian coordinate system, 278
Cassidy, Michael J., 345
Cassini, Giovanni, 115, 262
Catholic Church, 37
Cauchy horizon, 335-41, 345, 396
Cavendish, Henry, 116
Celsius temperature scale, 69
centripetal acceleration, 292
Cepheid variables, 198, 200, 209-10, 213-15, 392
Ceres, 134, 138-40, 143-44, 355
CERN particle accelerator, 351
Chang, Kenneth, 135-36
chaotic inflation, 387, 393
Charon, 13, 130-31, 137-38, 141-45
Christodoulou, Demetrios, 317
Chronology Protection Conjecture, 345
Circleland, 365, 367
circumferential radius, 306
circumpolar stars, 30
Clairaut, Alexis, 53
Coalsack Nebula, 176, 178
Coat of the Future, 321-22, 323
Cold War, 103, 411-13
Coleman, Sidney, 381-82, 435n2
Colley, Wes, 331
Collins, Michael, 424
colonization, 414, 420-24
color temperature, 68-70
Columbus, Christopher, 31-32
Coma Cluster, 196
comets, 48, 53, 127-28, 131-32, 134, 137, 13942, 156, 163
computers: apps and, 35 ; black holes and, 314; blink comparators and, 130; first,

121; human, 93-94; megabytes and, 17; patterns and, 32; power of large, 238; simulations of early universe and, 238-40; supercomputers and, 314
Comte, Auguste, 92
conservation of angular momentum, 39
conservation of charge, 261
conservation of energy, 297, 334, 367, 380
conservation of momentum, 285, 429-30
constellations, 27-33, 57, 59, 92, 120, 123, 186, 189
Contact (film), 165-67
Contact (Sagan), 343
Copernican Principle: Drake equation and, 420; expansion and, 210; future of universe and, 411, 413, 415-16, 420, 422, 435 n 3 ; inflation and, 375 ; search for life and, 165 ; testing of, 436 n 5 ; shape of universe and, 370
Copernicus, Nicolaus, 165; Catholic church and, 37; De Revolutionibus orbium coelestium and, 36; Earth as planet and, 138; expansion and, 210 ; future of universe and, 411-22; heliocentric theory and, 36-37, $42,139,184-85$; inflation and, 375 ; known universe in day of, 183-85; Newton's laws and, 42-43; night sky and, 36-37; shape of universe and, 370
Cosmic Background Explorer (COBE), 23031, 234-35, 375-76
cosmic distance ladder, 215
cosmic microwave background (CMB): black holes and, 318-19; blueshift and, 231; cosmic strings and, 331; cosmological principle and, 230; dark matter and, 233-37; Doppler shift and, 232; early universe and, 71, 74, 216, 229, 235-40, 252, 318-19, 331, 352-55, 362, 373-76, 381, 386-93, 398, 403, 404-7, 415; expansion and, 216; future of universe and, 404-7, 415; Gibbons and Hawking radiation and, 406-7; Hubble's law and, 236-37; inflation and, 298, 375-76, 381, 386-92; Lyman series and, 252; Map of the Universe and, 354,

362; Penzias and, 71, 229-30, 373, 375, 415; redshift and, 252; shape of universe and, $352-55,362,373$; undulations in, 232-36; uniformity of, 230-31, 252-53; Wilson and, 71, 229-30, 373, 375, 415; WMAP and, 235-40
cosmic strings: cosmic microwave background (CMB) and, 331; Cutler and, 334-35, 339; Einstein and, 327, 331; Flatland and, 340, 435nl; general relativity and, 327,331 ; gravity and, 331 ; length of, 328-29; mass of, 330; oscillation of, 331; quasars and, 330; shape of universe and, 351 ; shortcuts and, 327, 330-32; spacelike separation and, 332 ; speed of light and, 331; tension of, 331; time travel and, 327-37, 340
cosmic web, 404
Cosmic Web, The (Gott), 381
cosmological constant: as big blunder, 369 ; as correct, 391; Einstein and, 363-70, 377-$78,380,389,391,393-94,409-10$; future of universe and, 409-10; inflation and, 377-78, 380, 389, 391, 393-94; phantom energy and, 409-10; shape of universe and, 363-70
cosmological models: all possible, 389; closed, 365; Einstein and, 364-65; expansion and, 221 ; gravity and, 364-65; inflation and, 388-92; parameters of, 388-89; standard, 13, 391
cosmological principle, 225-26, 230, 23738, 248
Cosmos: A Spacetime Odyssey (film), 33
Cosmos (TV series), 165
Cotham, Frank, 164
Coulomb's law, 261
Crab Nebula, 123-25
Crick, Francis, 352
Curie, Marie, 288
Curtis, Heber, 198, 201
Cutler, Curt, 334-35, 339
cyanobacteria, 147, 161-62
Cygnus X-1, 355
dark energy: decay and, 402; early universe and, 236 ; future of universe and, 402,405 , 408-10; inflation and, 236, 389-92, 398; shape of universe and, 364-65, 370; slowroll, 409; standard cosmological model and, 13
dark matter: amount of, 13, 195; axions and, 232; composition of, 222, 232-34; cosmic microwave background (CMB) and, 233-37; early universe and, 222, 232-34, 236-37; gravitational lensing and, 253; gravitinos and, 234; inferred existence of, 243; inflation and, 388, 390-91; Milky Way and, 195-96; photinos and, 232; selectrons and, 232; shape of universe and, 351; standard cosmological model and, 13; supersymmetry and, 232; Zwicky and, 196, 243-44
d'Arrest, Heinrich Louis, 53
Davis, Marc, 230
decay: asymmetric, 402, 404; beryllium to lithium, 224; black holes, 314, 317, 407; dark energy, 402; fission and, 287; gravitinos, 234; Hawking radiation and, 407; muons, 268-69; neutrons, 223; protons, $223,403,407$; quantum theory and, 403; radioactivity and, $103,114,218,226,351$, 384; timescale for, 407; uranium, 114, 384-85; vacuum energy, 328, 381-82, 403
density wave, 194
deoxyribonucleic acid (DNA), 22, 66, 161, 213, 352
De Revolutionibus orbium coelestium (Copernicus), 36
de Sitter, Willem, 378, 380, 382-85, 393-99, 405-6
deuterium, 99, 117, 158, 223-25, 227, 233, 240, 375, 404
deuterons, 223-24
Deutsch, David, 326
Dewdney, A., 435n2
Dewynne, J. N., 436n5
Dicke, Robert, 228-29, 375, 410
differential calculus, 45
distance: action at, 295-96, 319-20; arc second and, 58-59; Astronomical Unit (AU), $40,42,54,115,213$; Cepheid variables and, 198, 200, 209-10, 213-15, 392; co-moving, 250; Copernican Principle and, 165, 210, $370,375,411,413,415-16,420,422,435 n 3$, 436nn3,4; cosmic distance ladder and, 215; geometry and, 39,58 ; Hubble's law and, 210-17, 220, 236-37; light-year and, 54, 58-59; parallax and, 55-60, 115, 213-14, 262, 434nl; parsec and, 58-59, 159, 215, 218; redshift and, 208 (see also redshift)
distribution functions, 60-62, 67, 73
Dixon, Dougal, 417
Dog Star (Sirius), 29
Doppler, Christian, 208
Doppler shift, 97, 331; black holes and, 249; derivation of $\mathrm{E}=\mathrm{mc}^{2}$ and, 428-29; early universe and, 225, 231-32, 235; energy radiation and, 64-65; expansion and, 208-9, 212, 214; quasars and, 245-46; relativity and, 262, 284-86; speed of sound and, 208
Drake equation, 147-49, 157-60, 162, 165-69, 193, 420
Druyan, Ann, 165, 166
Dumbbell Nebula, 119, 120
dwarf planet, 144
Dysnomia, 144
Dyson, Freeman, 406
$\mathrm{E}=\mathrm{h} \nu, 67,83,84,259-60,284,286,401,427$, 429
$\mathrm{E}=\mathrm{mc}^{2}$ : conservation of momentum and, 429-30; derivation of, 427-30; Doppler shift and, 428-29; future of universe and, 401-2; mass-energy relationship and, $9,99,101-2,115,158,223,259-60,269$, 284-86, 318, 401-2, 427-30
early universe: Alpher and, 224-25, 228-30; atoms and, 222, 227-28, 232-34; Big Bang and, 222-37, 240; blackbodies and, 222, 225, 228-31; black holes and, 250; carbon and, 224, 251; computer simulations of,

238-40; cosmic microwave background (CMB) and, $71,74,216,229,235-40,252$, $318-19,331,352-55,362,373-76,381$, 386-93, 398, 403, 404-7, 415; cosmological principle and, 225-26, 230, 237-38, 248; dark energy and, 236; dark matter and, 222, 232-34, 236-37; deuterium and, 223-25, 227, 233, 240; deuterons and, 223-24; Dicke and, 228-29; Doppler shift and, 225, 231-32, 235; electrons and, 222-23, 227-28, 233-34; formation of structure in, 232-33; fusion and, 222-23; future of universe and, 404-5; Gamow and, 224-25, 228, 374-75; gravity and, 232-34, 238, 240; helium and, 22327, 233, 240; Herman and, 225, 228-30; Hoyle and, 224, 226-27, 230; hydrogen and, 11, 223-25, 227-28, 232, 240, 403, 404-5; iron and, 224; mass and, 223, 226, 232, 234; microwaves and, 229; Milky Way and, 232-39; neutrons and, 222-24, 227, 233-34; oxygen and, 224; Peebles and, 228-30, 232-35, 243, 409; Penzias and, 71, 229-30, 373, 375, 415; photons and, 222, 225, 227-28, 233-34, 236; plasma and, 227; positrons and, 222-23, 227; protons and, 222-24, 227-28, 233-34; quantum theory and, 403-4; quark soup and, 403; quasars and, 245-46, 250; recombination and, 236-37, 403, 405; redshift and, 225, 228, 231, 237-38; Roll and, 228-29; scattering and, 227-28, 233-34, 236; silicon and, 224; spectra and, 238; speed of light and, 231; Sun and, 222-23, 226-27, 231-32; temperature and, 24, 219-20, 222-31, 235, 237, 240; thermal radiation and, 228,231 ; water and, 222 ; wavelength and, 225, 228-29, 231, 250-53; Wilkinson and, 228-32, 235; Wilson and, 71, 229-30, 373, 375, 415
Earth: acceleration and, 49-51, 116, 282; age of, $95,114-15,227$; angular momentum of, 248; asteroid hitting, 148; Astronomical Unit (AU) and, 40, 42, 115, 213; atmo-
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sphere of, $90,112-13,147,152,154,176$; axis of, 11, 26-27, 30 ; center of, 47,51 , $116,294,355$; as center of universe, 184, 210; circumference of, 115; Copernican Principle and, $165,210,370,375,411,413$, 415-16, 420, 422, 435n3, 436nn4,5; crust of, 137; diameter of, 135, 140, 151, 186; distance to Mars, 115; distance to Sun, 21, 115-16; end of life on, 118; energy radiation and, 54-62, 77, 80 ; equator of, 238, 291-95, 308, 352-55, 365; equilibrium temperature and, 153-54; equinox and, 30; formation of, 146-47; gravity and, 23, $46,49,51-52,111,192$; great circle and, 18, 291-94; half-illumination from Sun and, 33; heat from Sun, 29, 153; iron and, 181; Kepler's laws and, 37-41; life on, 146-65, 169, 403, 416-17, 419-23; major elements of, 82,224 ; mantle of, 355 ; Map of the Universe and, 355; mass of, 48-49, 116, 135, 137-38, 194, 302, 392, 432; Moon and, 131 (see also Moon); Newton's laws and, 42-52, 130; night sky and, 26-40; Northern Hemisphere and, 28-31, 173, 186, 308; official IAU listing of planets and, 144; orbit of, 11, 26-27, 34, 37, $42-46,51,55,57-58,80,115,128,137-38$, $153,156,193,210,213,218,232,248,262$, 270-72, 283; planetary family of, 132, 141; polar caps of, 27-28, 30; radius of, 11516,388 ; relativity and, $262-66,269-83$, 289-98; Rose Center display and, 129, 135; rotation of, 32 ; scale of universe and, $18-25,110$; size of, 133,185 ; solstice and, 28; Southern Hemisphere of, 28, 30, 173,186 ; speed of sound on, 208; surface of, 21, 23, 28-29, 47, 51, 113-16, 153-54, $158,161,169,270,290,295,327,355,394$; temperature of, 78, 135; time travel and, 324, 327-31, 341-43; wobble of, 32-33, 137-38
eccentricity, 38, 134, 156-57
eclipses, 34-35, 92, 115, 130, 141, 260, 262, 298-99

Eddington, Arthur, 260, 299
Efron, Bradley, 257
Einstein, Albert, 12; action at a distance and, 295-96, 319-20; anecdotes about, 25960 ; atomic bombs and, 259; black holes and, 300-303, 314, 317, 319-20; cosmic strings and, 327, 331; cosmological constant and, 363-70, 377-78, 380, 389, 391, 393-94, 409-10; cosmological principle and, 225-26, 230, 237-38, 248; curved spacetime and, 260 (see also spacetime); deflection prediction of, $260 ; \mathrm{E}=\mathrm{h} v$ and, 67, 83, 84, 259-60, 284, 286, 401, 427, 429; $\mathrm{E}=\mathrm{mc}^{2}$ and, $9,99,101-2,115,158$, 223, 259-60, 269, 284-86, 318, 401-2, 427-30; eclipse of 1919 and, 298-99; education of, 260-61; electromagnetism and, 261; Equivalence Principle and, 290, 292, 298, 310; expansion and, 220; field equations of, 296-98, 300-301, 314, 323, 327, 331, 337, 367, 369, 375, 378, 402; Flatland and, 365 ; future of universe and, 402-3, 405, 409-10, 417; general relativity and, 11 (see also general relativity); genius of, 257-60, 289; gravitational waves and, 402-3; inflation and, 375-78, 383, 389, 391-95; influence of, 258, 288, 299; Kerr and, 314 ; lasers and, 259, 317, 403; Maxwell and, 261, 349; Michelson-Morley experiment and, 265-66; Minkowski and, 270; Newton and, 257-60, 296-98; Nobel Prize in Physics and, 260; photoelectric effect and, 260; photon energy and, 67; pressure/energy density ratio and, 391; Riemann curvature tensors and, 2, 295-96, 301, 434nnl,2; Roosevelt letter of, 259, 287; shape of universe and, 347-52, 355, 362-70; special relativity and, 101, 260, 264, 270-87, 300-301, 326, $347,371,377,380$; speed of light and, 263-64; static model of, 362-65, 369, 393; thought experiments of, 263-65, 273, 275, 280, 285-86; 3-sphere geometry and, 365-67; time travel and, 323, 326-27, 331,

## Einstein, Albert (continued)

337, 339, 341, 345-46; uniform motion and, 264, 280
Einstein-Rosen bridge, 320
electric fields, 261-62, 290, 320, 350
electromagnetism: black holes and, 317; Einstein and, 261; energy radiation and, 66, 406; fields and, 290; Hertz and, 263; inflation and, 375, 377, 381, 399; lives of stars and, 125; Maxwell and, 11, 261-65, 290, 296-97, 349-50, 402; photons and, 402-3 (see also photons); radio telescopes and, 241; relativity and, 290, 294, 297; shape of universe and, 348-52; time travel and, 330
electrons: binding energy and, 86, 103-4; black holes and, 317-20; early universe and, 222-23, 227-28, 233-34; energy levels and, $82-90,119,179,250,258$; ground state and, $82-84,86,91,250$; inflation and, 402; interstellar medium and, 179 ; ionization and, $86-88,107,113,228,233$; lives of stars and, $98-99,103,107,113,119,122$; orbitals and, $21,82-85,92,162$; positrons and, 99 , 222-23, 227, 317-20, 402, 403, 407; quantum theory and, $83-84$; recombination and, $236-37,403,405$; relativity and, 266, 268, 299; selectrons and, 232 ; shape of universe and, $350-51$; spectra and, $81-92$; time travel and, 324 ; weak force and, 402-3
electron shell, 81
electron volt (eV), 85-86, 103-4
electrostatic forces, 24, 98-99, 261, 385
Elements in the Theory of Astronomy, The (textbook), 139-40
eleven dimensions, 351-52, 397-98
elliptical galaxies, 202, 204, 248-49, 303
elliptical orbits: Kepler and, 37-42, 53, 156, 196, 297; planetary motion and, 37-42, 53, 131, 134, 156, 196, 271, 297
emission lines, $90,179,242,245-46,250-51$
emission nebulae, 90, 179-80
$e$ (natural logarithm), 73
endothermic process, 103-4
energy density: as attractive force, 364 ; black holes and, 318 ; future of universe and, 405, 408-9; inflation and, 377-81, 384, 38691, 394; radiation and, 76; relativity and, 434 n 2 ; shape of universe and, 362-64; slow-roll dark energy and, 409; spacetime and, 76, 318, 327, 340, 344, 362-64, 377-81, 384-91, 394, 405, 408-9, 434n2; time travel and, 327, 340, 344
energy levels, 119,179 ; equilibrium and, 85 , 89, 153; excited electrons and, 81-92; ground state and, 82-84, 86, 91, 250; ionization and, $86-88,107,113,228,233$; Paschen series and, 86, 90-92; relativity and, 258
Englert, François, 327-28
entropy, 315-16, 323, 431
equator, Earth's, 238, 291-95, 308, 352-55, 365
equilibrium, 407; energy levels and, 85,89 , 153; gravity and, 112-13, 122, 189; internal stellar pressure and, 112-13, 122, 189; static, 144; thermal, 376, 380
Equivalence Principle, 290, 292, 298, 310
Eratosthenes, 115
Eris, 141, 144, 355
ET (film), 165-66
Euclidean geometry, 58, 278, 290-92, 330, 365-66, 371, 387
Europa, 139-40, 142-43, 160
event horizon: firewalls and, 319; future of universe and, 405-7; Hawking radiation and, 406; inflation and, 379-80, 386; Planck length and, 431; spacetime and, 305, 308-20, 337-38, 340, 344, 379-80, 386, 405-7, 431; time travel and, 337-38, 340, 344
exoplanets, 149-51, 362
exothermic process, 102-4
expansion: acceleration and, 392, 409; Big Bang and, 218-21; Big Crunch and, 367-68, 372, 373, 384; Copernican Principle and, 210; cosmic distance ladder and, 215; cosmological constant and, 362-70, 377-78,

380, 389, 391, 393-94, 409-10; cosmological models and, 221; cosmological principle and, 225-26, 230, 237-38, 248; decreasing density and, 219-20; Doppler effect and, 208-9, 212, 214; general relativity and, 212, 220-21; geometry and, 216, 221; gravity and, 217, 232-34, 238; Hubble and, 207-20, $363,367,369-70,373$; isotropy and, 367 , 375, 380, 415; luminosity and, 213-14; main sequence stars and, 214, 219; mass and, 207, 219; Milky Way and, 209-12, 217, 221; nebulae and, 207, 209; photons and, 221; recombination and, 236-37, 403, 405; redshift and, 207-11, 213, 215, 225, 228, 231, 237-38, $242-53,284,318,353,375,379,389,393$, 405, 428; Slipher and, 209; spectra and, 208-9; speed of light and, 208-9, 212, 408; temperature and, 207, 214, 219-20; variable stars and, 209-11, 213-15; wavelength and, 208-9, 250; white dwarfs and, 242
exponential measurement, 17, 74, 379, 381, 394, 406, 408
extraterrestrials, $148,156,161,165,167-68$, 185, 212, 312, 405, 419-20, 433n1

Fan, Xiaohui, 250
Faraday's law, 261
Feynman, Richard, 326
firewall, 319
first-quarter Moon, 34-35
fission, 103-4, 287
Flatland: Circleland and, 365, 367; cosmic strings and, 340, 435n1; Einstein and, 365; inflation and, 398; Lineland and, 348-49, 351,365 ; shape of universe and, 347-49, 365, 371; Sphereland and, 365; time travel and, 340
Flatland (Abbott), 348
Foreman, George, 260
Foster, Jodie, 166-67, 433n1
four-dimensional universe: Euclidean geometry and, 366; inflation and, 394-95; Kaluza-Klein dimensions and, 349-50, 352,397 ; relativity and, 270-76, 290, 296,

324, 326, 349, 366, 394-95, 434nl; time travel and, 324, 326
Freedman, Wendy, 215-16
frequency, 65-67, $84,208,259,284-85$, 400-401, 427-29
friction, 44, 51, 65, 247, 308
Friedmann, Alexander: Big Bang and, 36776; Einstein and, 369,375 ; football spacetime of, 367-70, 376-77, 381; inflation and, 374-78, 381-83, 386, 388-89, 393; shape of universe and, 367-73; 3-sphere geometry and, 365-67, 370, 373, 374-75, 378-79, 382-83, 388-89, 394
Frolov, Valeri, 399
full Moon, 30, 34-35, 109
FU Orionis stars, 190
fusion: early universe and, 222-24; as energy source, 121; future of universe and, 403-4; heavy elements and, 181; helium and, 158; hydrogen and, 118, 158, 287; lives of stars and, $99,102-5,111,114-15,117-18,121,123$; strong nuclear force and, 99
future of universe: black holes and, 401, 403, 405, 407-8; colonization and, 414, 420-24; Copernican Principle and, 411, 413, 415-16, 420, 422; cosmic microwave background (CMB) and, 404-7, 415; cosmological constant and, 409-10; dark energy and, 402, 405, 408-10; Drake equation and, $420 ; \mathrm{E}=\mathrm{mc}^{2}$ and, 401-2; early universe and, 404-5; Einstein and, 402-3, 405, 409-10, 417; energy density and, 405, 408-9; event horizon and, 4057; general relativity and, 402, 415; gravitational waves and, 402-3, 406; Hawking on, 423; helium and, 403, 404; inflation and, 402, 404, 408-9; intelligent lineage and, 417, 436n4; longevity measurement and, 411-24; phantom energy and, 409-10; photons and, 400-406; Planck density and, 401; Planck mass and, 401; Planck time and, 401, 403; recombination and, 403, 405; singularities and, 401, 409; spacetime and, 401-2, 405, 418, 428-29;
future of universe (continued)
temperature and, 403, 405-7; thermal radiation and, 402-3, 406; timeline for, 400, $403,413,420$; vacuum energy and, 408-9; white dwarfs and, 403, 405, 407

Gaia spacecraft, 434n1
galactic equator, 173, 236
galactic plane, 185-86, 313
galaxies: Andromeda, 127, 195, 198-202, 204, 207-17, 232, 405; barred spiral, 191; Big Crunch and, 367-68, 372, 373, 384; blueshift and, 209, 217, 231, 245, 339, 341, 429; Cepheid variables and, 198, 200, 209-10, 213-15, 392; Coma Cluster and, 196; cosmological principle and, 225-26, 230, 237-38, 248; dark matter and, 243 (see also dark matter); distances between, 202, 204; dust and, 197, 201-2, 204; early universe and, 222-40; elliptical, 202, 204, 248-49, 303; expansion and, 207-21; future of universe and, 400-424; galactic plane and, 185-86, 313; Geller-Huchra Great Wall and, 355,362 ; gravitational lensing and, 244, 253, 313, 330-31, 391; halos of, 192; Hubble and, 198, 200-202, 207; intergalactic space and, 21, 204, 227; irregular, 202; as island universes, 198, 200; Local Group and, 127; luminosity and, 200; M31, 355; M51, 105-6; M81, 355; M87, 248, 306-8, 355; Magellanic Clouds and, 125, 137, 187, 188, 202; Map of the Universe and, 35462; Milky Way, 127 (see also Milky Way); nebulae and, 197-201; Pinwheel, 198, 199, 201-2; quasars and, 244-46 (see also quasars); red giants and, 197; redshift and, 207-11, 213, 215, 225, 228, 231, 237-38, 242-53, 284, 318, 353, 375, 379, 389, 393, 405, 428; RR Lyraes and, 189-90, 198; Sloan Great Wall and, 238, 353, 362; spectra and, 207-8, 238, 244; spiral, 105-6, 111, 190-92, 194, 197-201, 204, 214, 245, 249; static model of, 362-65, 369, 393; Sombrero, 202, 203, Subaru, 362; Sun and,

204, 210, 213, 217-19; Tadpole, 204-5; temperature and, 201; variable stars and, 189-90, 198, 200, 209-11, 213-15
Galileo, 44, 46, 50, 125, 137, 140, 175, 183, 198, 232
Galle, Johann Gottfried, 53
gamma rays, 63, 66-67, 73, 125, 222, 263, 319, 339, 362
Gamow, George: cosmological constant and, 369 ; early universe and, 224-25, 228; future of universe and, 404, 415; inflation and, 374-75, 384-85, 391; quantum tunneling and, 392-95
Ganymede, 139-40, 142
gas clouds, 24, 82, 85, 89-91, 96, 105, 107, 163, 179
Gauss, Carl Friedrich, 296, 371
Geller, Margaret J., 355, 362
Geller-Huchra Great Wall, 355, 362
general relativity: acceleration and, 289-94, 298; action at a distance and, 295-96; black holes and, 300-302, 314, 320; cosmic strings and, 327, 331; cosmology and, 362-63; eclipse of 1919 and, 298-99; Equivalence Principle and, 290, 292, 298, 310; expansion and, 212, 220-21; fourdimensional universe and, 290, 296, 324, $326,347,349,366,394-95,434 \mathrm{nl}$; future of universe and, 402, 415; GPS and, 11 ; gravity and, 244, 260, 289-90, 292, 294-99, 4023; great circle and, 291-94; inflation and, 380, 386, 396-99; interstellar medium and, 182; mass and, 289, 294-98; quantum theory and, 339; Riemann curvature tensors and, 295-96; shape of universe and, 34950, 362-63, 367, 369-70, 435nl; spacetime and, 289-98; speed of light and, 296; time travel and, 283, 321, 323, 327, 331, 334, 339, 341, 345-46; verification of, 11; Wheeler and, 314; worldlines and, 294-95, 297
geometry: arc second and, 58-59; black holes and, 300, 306-11, 314, 316; cosmic strings and, 327-33, 336-37, 340, 351, 435n1; distance and, 39, 58; DNA
and, 352; Euclidean, 58, 278, 290-92, 330, 365-66, 371, 387; expansion and, 216, 221, four-dimensional universe and, $270-76,290,296,324,326,347,349,366$, 394-95, 434nl; great circle and, 18, 29194; inflation and, 383, 386-87, 393-94; Kepler and, 39; relativity and, 270, 278, 290-92, 294, 296; shape of universe and, 362, 364-65, 367, 371, 405, 435nl; spacetime and, 260, 270-76, 280-81, 285-86, 289-98, 401 (see also spacetime); 3-sphere geometry and, 365-70, 373, 374, 378-79, 382-83, 388-89, 394; time travel and, 327, 329-30, 332-33, 343
George III, king of England, 138-39
Gibbons, Gary, 403, 405-7
Glashow, Sheldon, 351
Gliese 581, 100
globular clusters, 96-97, 127, 168, 184-91, 214, 219
Gödel, Kurt, 341
Google, 20, 354
googol, 20
googolplex, 20
Gott, J. Richard, 11, 12, 13, 122, 411; Berlin
Wall and, 411-13, 424; black holes and, 300-320; Coat of the Future of, 321-22, 323; cosmic strings and, 327-341; future of universe and, 400-424; Guinness Book of Records and, 362; Hubble constant and, 216; inflation and, 374-99; Map of the Universe and, 354-62; relativity and, 257-99; shape of universe and, 347-73; time travel and, 321-46; undergraduate course of, 12; Zwicky and, 244
Gott-Li model, 396-98
Gould, Stephen Jay, 417
grandmother paradox, 324-26
gravitational instability, 232, 238, 240
gravitational lens, 244, 253, 313, 330-31, 391
gravitational mass, 289
gravitational waves: black holes and, 13, 314, 403; cosmic strings and, 331; Einstein and, 402-3; existence of, 403; future of
universe and, 402-3, 406; inflation and, 393; interstellar medium and, 182; LIGO and, 13, 314-15, 331, 402-3, 406; Maxwell and, 402; pulsars and, 355
gravitinos, 232
gravity, 13; acceleration and, 23, 47, 49, 52, $116,158,294$; black holes and, 23,122 , 247, 249, 302-4; cosmic strings and, 331; cosmological constant and, 363-70, 377-78, 380, 389, 391, 393-94, 409-10; cosmological models and, 364-65; curved spacetime and, 260 (see also spacetime); dark matter and, 234 (see also dark matter); early universe and, 232-34, 238; Earth and, 23, 46, 49, 51-52, 111, 192; equilibrium and, 112-13, 122, 189; Equivalence Principle and, 290, 292, 298, 310; expansion and, 217, 232-34, 238; general relativity and, 260, 289-90, 292, 294-99; great circle and, 291-94; inflation and, 376, 392, 398; interstellar medium and, 180; inverse-square law and, 47, 49, 79, 116, 125, 168, 188, 213, 243; Kepler's law and, 37-39; Lagrange points and, 144; lives of stars and, $104,107,111-19,122,156$, 197; Mars and, 422; measuring, 3; Milky Way and, 189, 192-95, 204; Newton's laws and, 41-45, 79, 82, 97, 192-93, 195, 246, 259, 264, 302; perturbations and, 53, 131, 160, 300, 314; Planet X and, 130-31; Pluto and, 134, 144; quantum, 339, 341, 345, 398, 402; Schwarzschild radius and, 301-10, 313, 315, 318, 401; self-gravitating objects and, 111-12; shape of universe and, 349-52, 363; singularities and, 302, 305-6, 309-13, 337-40, 344, 368, 381, 396, $399,401,409$; spaghettification and, 305-6, 339; special relativity and, 282-83; static model and, 362-65, 369, 393; Sun and, $32,111,114-15$; supernovae and, 100 , $106-7,121-25,181,216,219,243-44,247$, 252-53, 362, 389-92; temperature and, 134; tidal forces and, $118,151,160,192,204$, 304, 306, 337, 339; time travel and, 339,
gravity (continued)
341, 345; universal law of, 40-41, 48-49;
Uranus and, 53
great circle, 18, 291-94
Great Dark Spot, 133
Great Red Spot, 133
Great Wall of China, 413
Greeks, 37, 39, 59-60
greenhouse effect, 132, 147, 154-57, 169
Greenstein, Jesse, 243
Greenwich Mean Time, 355, 367
G stars, 100, 151-52, 155, 156
guest star, 123-24
Guinness Book of Records, 362
Gunn, Jim, 244, 252
Guth, Alan, 376-82, 388
Hale-Bopp, 433n1
half-Moon, 34-35
Halley, Edmund, 48, 53
H-alpha protons, 87, 90, 179
Hamlet (Shakespeare), 287-88
Hartle, James, 319, 394
Hartle-Hawking vacuum, 318-19, 344
Harvard College Observatory, 93
Hawking, Stephen: Bekenstein and, 12-13; black holes and, 314-20; bubble universes and, 386; Cauchy horizon and, 340; Chronology Protection Conjecture and, 345 ; on future of universe, 423 ; inflation and, 386,394 ; intelligence of, 107 ; no boundary condition and, 394-95; Planck length and, 431; The Theory of Everything and, 12, 320; time travel and, 336, 340, 344-45
Hawking radiation, 317-19, 340, 406-8
Hawking temperature, 403, 406-7
Hayden Planetarium, 11
heavy elements, $105,123,181,219,224$
Heisenberg, Werner, 316-17, 381, 385, 393
heliocentric theory, 36-37, 42, 139, 184-85
helium, 24 ; alpha particles and, 384-85; early universe and, 223-27, 233, 240; fusion and, 158; HR diagram and, 189; interstellar medium and, 181; Jupiter and, 133; lives
of stars and, 99-105, 118-21; ppn nucleus, 99-100, 105; spectra and, 81-82, 99; Sun and, $121,134,181,287$; timeline of universe and, 403, 404
Helmholtz, Hermann von, 114, 117
Herman, Robert, 225, 228-30, 375, 415
Herschel, William, 62-63, 138, 140, 183-84
Hertz, Heinrich, 263
Hertzsprung, Ejnar, 93-94, 184
Hertzsprung-Russell (HR) diagram, 93-96, 98, 100, 121, 160, 189, 207, 219
Hewish, Antony, 125
Higgs, Peter, 327-28
Higgs boson, 13, 327, 351, 402
Higgs field, 327, 351, 377, 384, 402
Higgs vacuum, 408
Hiscock, William, 327
Hitler, Adolf, 287
Holst, Sören, 340
Homo sapiens, 410, 413, 416-17, 420, 436n4
How I Killed Pluto and Why It Had It Coming (Brown), 144
Hoyle, Fred, 218, 224, 226-27, 230, 248
Hubble, Edwin, 92; Andromeda and, 214; Cepheid variables and, 198-99, 210, 214; death of, 215; early universe and, 226 ; expansion and, 207-20, 363, 367, 369-70, 373; galaxies and, 198, 200-202, 207; isotropy and, $367,375,380,415$; Leavitt and, 200; redshift and, 209-10, 250, 393; scale of universe and, 226 ; shape of universe and, 367; universal uniformity and, 226
Hubble constant, 210, 215-16, 218, 227, 24243, 388, 390, 392
Hubble expansion, 217, 363, 369-70, 373
Hubble's law, 210-17, 220, 236-37
Hubble Space Telescope, 13; black holes and, 247-48, 306; clarity of, 59, 215; distance of galaxies and, 210; Freedman and, 215-16; long exposures of galaxies and, 206; Map of the Universe and, 352, 355; Neptune's Great Dark Spot and, 133; orbit of, 51; Pluto and, 130; quasars and, 244-45, 253; as reflecting telescope, 259 ; resolution of,

159; Sandage and, 215-16; scale of universe and, 108-9; Spitzer and, 121
Hubble Ultra-Deep Field, 108-9
Huchra, John, 355, 362
Hulse-Taylor binary pulsar, 182, 355, 402
Humason, Milton, 210
Huygens, Christiaan, 262-63
hydrogen: abundance of, 81; Balmer lines and, 86, 88, 90-92, 179, 242, 258; Cavendish and, 116 ; cosmic clouds and, 82 ; deuterium, $99,117,158,223-25,227,233,240$, 375,404 ; early universe and, $11,223-25$, 227-28, 232, 240, 403, 404-5; fusion and, 158, 287; HR diagram and, 189; in human body, 11 ; interstellar medium and, 176,179 , 181; Jupiter and, 133; lives of stars and, 94, 98-107, 116-18, 121, 407; Lyman series and, $86,91-92,250,252$; periodic table and, 24 ; quantum understanding of, 258; quasars and, 250-52; scale of universe and, 128 ; as simplest atom, 21 ; spectra and, 81-92, 250; structure of, 21; Sun and, 94, 134, 217, 223, 227, 287
hyperbolic universe, 371-73, 382-83
inertia, 43-44, 289
inflation: acceleration and, 376-81, 386, 38992, 398; Big Bang and, 374-78, 381, 393, 398; Big Crunch and, 384; black holes and, 380, 398; bubble universes and, 381-88, 394, 396, 402, 408, 431nn1-3; chaotic, 387, 393; cosmic microwave background (CMB) and, 298, 375-76, 381, 386-92; cosmological constant and, 377-78, 380, 389, 391, 393-94; cosmological models and, 388-92; dark energy and, 236, 38992, 398; dark matter and, 388, 390-91; de Sitter spacetime and, 378, 380, 382-85, 393-99, 405-6; Einstein and, 375-78, 383, 389, 391-95; electromagnetism and, 375, 377, 381, 399; electrons and, 402; energy density and, 377-81, 384, 386-91, 394; event horizon and, 379-80, 386; Flatland and, 398; four-dimensional universe and,

394-95; Friedmann and, 374-78, 381-83, $386,388-89,393$; future of universe and, 402, 404, 408-9; general relativity and, $380,386,396-99$; geometry and, 383, 386-87, 393-94; Gott-Li model and, 396-98; gravity and, 376, 392-93, 398; Guth and, 376-82, 388; Hawking and, 386, 394; Higgs field and, 377, 384; highdensity vacuum state and, 380-82, 399; Kaluza-Klein dimensions and, 397; mass and, 302, 390; mechanisms for beginning, 398-99; M-theory and, 397-98; multiverse and, 382-84, 386-87, 397-99, 402, 409; neutrons and, 384, 390; no boundary condition and, 394-95; photons and, 37475; pressure/energy density ratio and, 391; quantum theory and, $381,384-87,393-96$, 398-99; redshift and, 375, 379, 389, 393; singularities and, $381,384,396,399$; spacetime and, 376-83, 388, 393-98; speed of light and, 374-75, 378-80, 382, 386, 393; surface of constant epoch and, 382; temperature and, 375-77, 387; thermal radiation and, 374-75; 3-sphere geometry and, $374-75,378-79,382-83,388-89,394$; vacuum energy and, 377-92; wavelength and, 375; worldlines and, 378, 379-81
information: Bekenstein limit and, 13; black holes and, 316-17, 319, 431-32; Planck length and, 431; time travel and, 323
infrared (IR) light: greenhouse effect and, 154; interstellar medium and, 176-77; mapping Milky Way and, 186-88, 196; quasars and, $250,252-53$; radiation and, $29,62-70,75,77-78,86,90,117,153-54$, 161, 176-77, 186-88, 196, 250, 252-53, 263, 406; search for life and, 161 ; thermal radiation and, 153-54
integral calculus, 50, 62, 257, 261
internal pressure, 112-13, 115, 189
International Astronomical Union (IAU), 13, 137, 144
International Space Station (ISS), 52, 283, 355

Interstellar (film), 342
interstellar medium: carbon and, 181; dust and, 176-81; electrons and, 179; gravity and, 180, 182; helium and, 181; hydrogen and, 176, 179,181 ; lives of stars and, 105; mass and, 176, 180-82; Milky Way and, 173-82; nebulae and, 176-81; neutrons and, 181; opaqueness of, 176; oxygen and, 176, 179, 181; photons and, 179 ; red giants and, 181; silicon and, 181; Sun and, 180-96; telescopes and, 174, 180; 2MASS and, 176, 188; visible light and, 176; wavelength and, 176-79
inverse-square law: brightness and, 78-79, 184,188 ; distance and, $116,125,188,213$, 243; gravity and, 79; luminosity and, 116, 125, 168, 213, 243; Newton and, 47, 49, 79, 116, 125, 168, 188, 213, 243
Io, 139
ionization, 86-88, 107, 113, 228, 233
iron: early universe and, 224; Earth and, 181; lives of stars and, $102-5,107,120,123$; nuclear energy and, 287; Sun's core and, 132; Vesta and, 141
Iron Maiden, 305, 337
irregular galaxies, 202
isotopes, $82,102-4,114$
isotropy, $367,375,380,415$

Jeans, James, 74
Jet Propulsion Labs, 131
jinn particles, 322-24
Juno, 139-40
Jupiter: Callisto and, 139, 142; eclipses and, 262; Europa and, 139-40, 142-43, 160; fusion and, 117; Ganymede and, 139-40, 142; as gas planet, 131; Great Red Spot of, 133; helium and, 133; historical perspective on, 138-39; hydrogen and, 133; Io and, 262; Jupiter/Mars gap and, 138; Kepler satellite and, 150; Kepler's time and, 39; Map of the Universe and, 355; mass of, 131; moons of, 139-43, 160, 262; Newton's laws and, 53, 130; official IAU listing of planets and, 144; radius of, 149;
rapid spin of, 111 ; relative size of, 133,143 ; rings of, 133; Rose Center display and, 19, 128, 129-30, 135; Shoemaker-Levy 9 and, 137; Standish and, 131; statistics of, 135;
Trojan asteroids of, 144
Jurić, Mario, 354, 362

Kaluza, Theodor, 349
Kaluza-Klein dimensions, 349-50, 352, 397
Kamionkowski, Mark, 409
Kant, Immanuel, 198
Kapteyn, Jacobus, 183-85, 210
Keck Telescope, 259, 393
Kelly, Mark, 283
Kelvin temperature scale, 69
Kennedy Space Flight Center, 422
Kepler, Johannes: Brahe data and, 36-37, 43, 258; Copernicus and, 37; elliptical orbits and, $37-42,53,156,196,297$; first law of, 38, 41; geometrical approach of, 39; Newton's laws and, 40-41, 43, 46-47, 49, $52-53$; night sky and, $33,36-42$; planetary motion and, 36-43, 46-47, 49, 52-53, 157, 196, 258, 297; second law of, 38, 39, 41; solar system model and, 115; third law of, 38, 39-41, 43, 46-47, 49, 52, 157, 258
Kepler satellite, 149-51, 155-57, 160
Kepler 62e, 151, 152
Kerr, Roy, 314-17, 337-39
Kierland, Brian, 436n5
Kirhakos, Sofia, 245
Kirshner, Robert, 321
Klaproth, Martin, 139
Klein, Oskar, 349-50, 352, 397
Kruskal, Martin, 308-9, 314-15
Kruskal diagram, 309-12, 314, 320
K stars, 69, 85, 87-88, 151, 155, 156
Kuiper, Gerard, 134
Kuiper Belt, 134-36, 140-44, 253, 355, 362
Kundić, Tomislav, 331
ladder diagram, 85, 88-89
Lagrange points, 144
LaLande, Jérôme, 53
lambda, 63, 73
Landsberg, P. T., 436n5
Large Hadron Collider, 13, 234, 327, 351
Large Magellanic Cloud, 125, 202
Large Synoptic Survey Telescope, 253
Laser Interferometer Gravitational-Wave Observatory (LIGO), 13, 314-15, 331, 402-3, 406
lasers, 259, 266, 274-77, 314, 317, 402-3
LAWKI, 162
law of charge conservation, 261
Leavitt, Henrietta, 93, 200
Leibnitz, Gottfried Wilhelm, 257-58
Lemaître, Georges, 363, 393-94
Lemonick, Michael, 138
Lepaute, Nicole-Reine, 53
Leslie, John, 418
Le Verrier, Urbain, 53
Levy, David, 137
Li, Li-Xin, 345, 396-98, 401
Lick Observatory, 198
light elements, 102-3, 105, 123, 134, 222, 224, 287, 403-4
light-year, 54, 58-59
Linde, Andrei, 384, 386-87, 395-96, 398, 408
Lineland, 348-49, 351, 365
lithium, 81, 224, 227, 404
lives of stars: atoms and, $98,103,113,119,122$; birth and, 180-81; black holes and, 123; blue stars and, 90, 93, 96-98; brightness and, 116; carbon and, $99,102,105,119-21$; death of, 106, 117, 117-19; electromagnetism and, 125; electrons and, 98-99, $103,107,113,119,122$; endothermic process and, 103-4; equilibrium and, 112-13, 122, 189; exothermic process and, 102-4; fission and, 103-4; fusion and, 99, 102-5, 111, 114-15, 117-18, 121; globular clusters and, 96-97, 127, 168, 184-91, 214, 219; gravity and, $104,107,111-19,122,156,197 ;$ helium and, 99-105, 118-21; HertzsprungRussell (HR) diagram and, 93-96, 98, 100, 121, 160, 189, 207, 219; hydrogen and, 94, 98-107, 116-18, 121, 407; internal pressure
and, 112-13, 115, 189; interstellar medium and, 105 ; iron and, $102-5,107,120,123$; luminosity and, $93-101,107,114-20,125$, 151; main sequence stars and, $94,95-104$, 115-23; mass and, 97-104, 107, 111, 115-23, 147; Milky Way and, 106, 125; nebulae and, 107-8, 119-20, 123-25; neutrons and, 99-105, 122; neutron stars and, 100,105 , 107, 122-25; O B A F G K M L T Y scheme and, 100-101; oxygen and, $99,102,105,107$, 119-21; Pauli exclusion principle and, 119, 122; photons and, $99,107,113-14$; positrons and, 99; protons and, 98-105, 122; quantum theory and, 100,119 ; red giants and, $95-97,100,102,118,120-21,123$; red stars and, $93,96,98,120$; self-gravitating objects and, 111-12; silicon and, 107, 120; speed of light and, 123; star cluster and, 95-97, 137, 180; strong nuclear force and, 99; Sun and, 94-105, 111-21, 125, 146-61, 168-69; supernovae and, $100,106-7,121-$ $25,181,216,219,243-44,247,252-53,362$, 389-92; temperature and, 93-100, 105, 113-14, 117-18; visible light and, 114,117 , 125; white dwarfs and, $94,95,100,119-23$
Local Group, 127
logarithms, 73, 101, 155, 231, 431
London Times, 299
Los Angeles Times, 354
Lowell, Percival, 129-30
Lowell Observatory, 130, 209
luminosity: energy radiation and, 60, 76-80; expansion and, 213-14; galaxies and, 200; Hertzsprung-Russell (HR) diagram and, $93-96,98,100,121,160,189,207,219$; inverse-square law and, $116,125,168,213$, 243; lives of stars and, 93-101, 107, 114-20, 125, 151; Milky Way and, 184, 188-90, 252; O B A F G K ML TY scheme and, 100-101; quasars and, 244-52; search for life and, $146-47,151,153,168$; spectra and, 251-52 (see also spectra); temperature and, 214; Zipf's law and, 168
lunar eclipse, 34, 92, 115, 298

Lyman series, 86, 91-92, 250, 252
Lyra, 27, 57, 189-90, 198

M13 globular cluster, 96-97, 168, 184
M31 galaxy, 355
M51 galaxy, 105-6
M81 galaxy, 355
M87 galaxy, 248, 306-8, 355
M101 nebula, 198, 199
Magellanic Clouds, 125, 137, 187, 188, 202
magnesium, 181, 207
main sequence stars: death of, $403,405,418$; expansion and, 214,219 ; lives of stars and, 94, 95-104, 115-23; Milky Way and, 18889,192 ; search for life and, $151,160,169$
Maldacena, Juan, 319-20
Manhattan Project, 259, 287
many-worlds theory, 325-26
Map of the Universe, 354-62
Mars: asteroids and, 140; atmosphere of, 422; canals of, 129-30; colonization of, 421-23; distance to, $115,213,262$; gravity of, 422 ; historical perspective on, 138-39; Jupiter/ Mars gap and, 138; Kepler's time and, 39; life on, 65, 129-30, 422; Lowell and, 12930; Map of the Universe and, 355; Newton's laws and, 130; official IAU listing of planets and, 144; oxygen and, 422; parallax and, 115; planetary motion and, 36 ; as the red planet, 133; relative size of, 132; Rose Center display and, 129, 135; statistics of, 135; terrestrial family and, 132,141 ; water and, $129,133,422$; worldline of, 271, 272
Mars One group, 421-22
mass: acceleration and, 44; black holes and, $121,176,196,246-53,300-311,314-19,338$, $355,403,407-8$; brain to body, 163; center of, 49,137 ; cosmic strings and, 330 ; Doppler shifts and, 97-98; $\mathrm{E}=\mathrm{mc}^{2}$ and, 9,99 , $101-2,115,158,223,259-60,269,284-86$, 318, 401-2, 427-30; early universe and, 223, 226, 232, 234; Earth and, 49, 116; expansion and, 207, 219; gas giants and, 134; Higgs boson and, 351; inertial, 43-44,

289; inflation and, 302, 390; Jupiter and, 131; law of universal gravitation and, 49; lives of stars and, 97-104, 107, 111, 115-23, 147; of local planets, 135 ; methods for figuring, 97-98; Milky Way and, 192-96; Neptune and, 131; neutron stars and, 303; Newton's laws and, 41, 44, 48-52, 49, 97-98, 196, 259, 289; Planet X and, 131; Pluto and, 131, 138, 144; point, 300-301, 303, $309,311,365,435 \mathrm{nl}$; quasars and, 245-47, 252; relativity and, $158,259,284,286-89$, 294-98; Saturn and, 131; shape of universe and, 300-301, 303, 309, 311, 351, 355, 365, 368, 435n1; solar, 102, 121-23, 176, 181-82, $247-49,252,303,305-6,314-16,318-19$, $338,344,355,403$; spectra and, $97-98$; Sun and, 49; time travel and, 323-24, 329-30, 334-38, 341-44; Uranus and, 131
Mather, John, 375
Matschull, Hans-Jürgen, 340
Maxwell's equations, 11, 261-65, 290, 296-97, 349-50, 402
McConaughey, Matthew, 166-67
McNeil/Lehrer Newshour (TV show), 306
megaparsec, 215, 218
Mercator maps, 354
Mercury, 25; black holes and, 300; clocks on, 283; historical perspective on, 138-39; iron core of, 132; Kepler's time and, 39; Lowell's time and, 130; Map of the Universe and, 355; as nearest planet to Sun, 132; Newton's laws and, 130, 350; official IAU listing of planets and, 144; planetary motion and, 39 ; relative size of, 132 ; relativity and, 271-72, 283, 297-98, 350; Rose Center display and, 129, 135; statistics of, 135; terrestrial family and, 141; worldline of, 271-72
meteorites, 218
Michelson, Albert, 265-66
microwaves, 64-67, 263. See also cosmic microwave background (CMB)
Milky Way: Andromeda nebula and, 200-201; average distance between stars in, 185-86;
black holes and, 247-49, 251; brightness and, 184, 188; Cepheid variables and, 198, 200, 209-10, 213-15, 392; dark matter and, 195-96; dark regions of, 175-76; density wave and, 194; Drake's equation and, 193; dust and, 184-90, 196, 238; early universe and, 232-39; exoplanets and, 14951, 362; expansion and, 209-12, 217, 221; fuzzy appearance of, 197; galactic plane and, 185-86, 313; Galileo and, 183; globular clusters and, 184-91; gravity and, 189, 192-95, 204; halo of, 192; Herschel and, 183; Hubble and, 92; infrared light view of, 186-88, 196; interstellar medium and, 173-82; inverse-square law and, 184, 188; as island universe, 198, 200; Kapteyn and, 183-85, 210; lives of stars and, 106, 125; as living ecosystem, 181-82; Local Group and, 127; luminosity and, 184, 188-90, 252; main sequence stars and, 188-89, 192; Map of the Universe and, 353-55; mass and, 192-96; number of stars in, 18, 149, 193; orbit of, 232; quasars and, 245-46; red giants and, 189; Rose Center display and, 127; RR Lyraes and, 189-90; search for life and, $149,151-52,159,166,168$; shape of universe and, 363; Shapley and, 184-85, 187, 189-90; size of, 185-86, 197, 212; spiral arms of, 106, 190-92, 194; star orbits in, 193-94; stars beyond, 92; structure of, 174-76, 190-91; Sun's location in, 184-86, 194-95; supernovae and, 100, $106-7,121-25,181,216,219,243-44,247$, 252-53, 362, 389-92; 2MASS telescopes and, 176,188 ; visible light and, 186
Minkowski, Hermann, 270
Miranda, 139
Misner, Charles W., 314
Mitochondrial Eve, 413
mobile phones, 11, 64-65
molecules: atmospheric, 20-21, 25, 156; complex, 161, 163; DNA, 22, 352; energy levels and, 84,89 ; formation of, $161,163,222$; water, 65, 81-82, 161

Montond, Bradley, 436n5
Moon, 131; acceleration and, 47-48; age of, 218; atmosphere of, $50,156,422$; center of mass of, 137; distance to, 54, 283; Earth's wobble and, 32 ; half-illumination from Sun and, 33; landing on, 158, 326, 423-24; lunar eclipse and, 34, 92, 115, 298; Map of the Universe and, 355 ; Newton's laws and, 47-51, 290; night sky and, 32-36, 40, 137$39,241,355$; phases of, 30, 33-35, 109; relative size of, 132 ; tides and, 151
Mordor, 145
Morley, Edward, 265-66
Morris, Mike, 341
Mount Wilson Observatory, 198, 201
M-theory, 351-52, 397-98
multiverse, 382-84, 386-87, 397-99, 402, 409
muon, 22, 269, 402
Musk, Elon, 422-23
mythology, 130, 138-39

NASA, 137, 144, 159, 164, 230, 235, 282, 422
nebulae: emission, 90, 179-80; expansion and, 207, 209; galaxies and, 197-201; interstellar medium and, 176-81; lives of stars and, 107-8, 119-20, 123-25; reflection, 180; spectra and, 90-91; spiral, 197-98, 200
Neptune: distance to, 80 ; as gas planet, 131; Great Dark Spot and, 133; historical perspective on, 139; Hubble Space Telescope and, 133; Kepler satellite and, 150; Kuiper Belt and, 136; Lowell's time and, 130; Map of the Universe and, 355; mass of, 131; moons of, 140, 142; Newton's laws and, 53, 130; official IAU listing of planets and, 144; Planet X and, 131; Pluto's orbit across, 134; relative size of, 133; Rose Center display and, 129, 135; Standish and, 131; statistics of, 135; variant orbit of, 131
neutrinos, $99,122,222-23,227,351,402-3$
neutrons: atomic nucleus and, $13,82,99-104$, 122, 181, 222-24, 227, 233-34, 349, 384, 390, 403, 404; decay and, 223; early universe and, 222-24, 227, 233-34;
neutrons (continued)
fusion and, 99, 102-5, 111, 114-15, 117-18, $121,158,181,222-23$; interstellar medium and, 181; lives of stars and, 99-105, 122; quantum tunneling and, 384-85; quarks and, 403, 404
neutron stars, 22-24, 100, 105, 107, 122-25, 181-82, 243, 303, 355, 402, 403, 407
New Horizons spacecraft, 13, 144, 145
new Moon, 34-35
New Scientist journal, 354
Newton, Isaac: calculus and, 40-41, 45, 50, 75 ; Cambridge University and, 47-48; corpuscles of light and, 62 ; deflection prediction of, 260; Einstein and, 257-60; genius of, 257-60; home of, 33; influence of, 43, 52-53, 258; Leibniz and, 257-58; reflecting telescope and, 259; Royal Mint and, 259
Newton's laws, 12; acceleration and, 44-52, 116, 259, 264, 289-90, 294; action at a distance and, 295-96; calculus and, 40-41; Cavendish and, 116; Earth and, 42-52, 130; eclipse of 1915 and, 298-99; Einstein and, 296-98; first law of motion, 43-44; force and, 44, 49, 259, 289; friction and, 44, 51; genius of, 257; gravity and, 41-45, 79, 82, 97, 192-93, 195, 246, 259, 264, 302; Halley's comet and, 53; inertia and, 43-44; inverse-square law and, 47, 49, 79, 116, $125,168,188,213,243$; Jupiter and, 53, 130; Kepler and, 40-41, 43, 46-47, 49, 52-53; Mars and, 130; mass and, 41, 44, 48-52, 97-98, 196, 259, 289; Mercury and, 130, 350; Moon and, 47-51, 290, 302; Neptune and, 130; planetary motion and, 42-43, 46-47, 52-53; Planet X and, 130; quasars and, 246; Saturn and, 53,130 ; second law of motion, 44,52 ; shape of universe and, 352; Sun and, 42-53; third law of motion, 44, 49; time travel and, 283-84, 286, 345; uniform velocity and, 43-45; universal law of gravitation and, 40-41, 48, 48-49; Uranus and, 53, 130; Venus and, 130
New Yorker, 164, 354

New York Times, 129, 135-36, 299, 354
nickel, 224
Nielson, Holgar, 418-19
night sky: arc second and, 58-59; constellations, 27-33, 57, 59, 92, 120, 123, 186, 189; Hayden Planetarium and, 11; Kepler and, 33, 36-42; Moon and, 32-36, 40, 137-39, 241, 355; visible light and, 29
nitrogen, 21, 81-82, 140, 181, 224
Nobel Prize, 125, 182, 230, 260, 299, 318, 328, 350-51, 355, 375, 385, 389
no boundary condition, 394-95
North Celestial Pole, 30
Northern Cross, 27-28
Northern Hemisphere, 28, 30-31, 173, 186, 308
North Star (Polaris), 28-32, 214
nuclear bomb, 101
nuclear energy, 92, 115, 287
nuclei, 327,355 ; early universe and, 222-27, 234, 240; electron volt (eV) and, 85-86, 103-4; fusion and, 99, 102-5, 111, 114-15, 117-18, 121, 158, 181, 222-23; interstellar medium and, 181 ; lives of stars and, 98-100, 102-5, 113, 119, 122; neutrons and, 13, 82, 99-104, 122, 181, 222-24, 227, 233-34, 349, 384, 390, 403, 404; Planck length and, 302; protons and, 13, 21-24, 62, 82, 85-88, 98-105, 122, 222-24, 227-28, 233-34, 266, 282, 350, 384, 390, 402-7; quantum tunneling and, 384-85, 394-95, 398, 408, 435 n 2 ; relativity and, 287 ; scale of the universe and, 128 ; spectra and, $81-85$; strong nuclear force and, $24,99,351,384-85$, 402; weak nuclear force and, 351, 402-3 null separation, 277

O B A F G K M L T Y (star classification scheme), 100, 117
Of Time and Power (Bienen and van de Walle), 436n5
O'Neill, Gerard, 422
Oort Cloud, 127, 141
open clusters, 96

Oppenheimer, Robert, 287
orbits: black holes and, 314; Earth and, 232; eccentric, $38,134,156-57$; eclipses and, $34-35,92,115,130,141,260,262,298-99$; electrons and, 21, 82-85, 92, 162; elliptical, $37-42,53,131,134,156,196,271,297$; Kepler's laws and, 36-43, 46-47, 49, $52-53,157,196,258,297$; lives of stars and, 146, 151, 156-57; major axis and, 40; minor axis and, 40; Moon and, 51; planets and, 39-40, 46, 131, 134, 135, 144, 193, 263, 272, 428; Planet X and, 130-31; solar system and, 39; stars and, 193-95; Sun and, 232; transit and, 130, 149-51, 213
Ori, Amos, 345
Orion Nebula, 27, 107-8, 120, 178, 179, 197
osmium, 113
Ostriker, Jeremiah P., 243
Ouranos, 139
Owens, Jesse, 260
oxygen: abundance of, 81-82; atmospheric, $20-21,65$; interstellar medium and, 176, 179,181 ; lives of stars and, $99,102,105$, 107, 119-21; Mars and, 422; ozone, 65, 147; search for life and, $147,159,169$; spectra and, 88
ozone, 65, 147

Paczyński, Bohdan, 5
Padalka, Gennady, 283
Page, Don, 317, 319, 435n1
Pagels, Heinz, 234
Pale Blue Dot (Sagan), 110
Pallas, 139-40
Palomar Observatory, 215, 241-42, 244
parallax, 55-60, 115, 213-14, 262, 434n1
parsec, 58-59, 159, 215, 218
Paschen series, 86, 90-92
Pauli, Wolfgang, 119
Pauli exclusion principle, 119, 122
Payne, Cecilia, 93-94, 224, 227
Peebles, Jim, 228-30, 232-35, 243, 409
Penrose, Roger, 317
Penzias, Arno, 71, 229-30, 373, 375, 415
perfect cosmological principle, 226, 248
periodic table, 24, 81, 102, 120, 162
Perseus cluster, 202, 203
perturbations, 53, 131, 160, 300, 314, 341
phantom energy, 409-10
Philosophical Monthly, The, 436n5
photinos, 232
photoelectric effect, 260
photons: black holes and, 310, 318; blueshift and, 209, 217, 231, 245, 339, 341, 429; color and, 62; deflection and, 260; derivation of $\mathrm{E}=\mathrm{mc}^{2}$ and, 427-30; $\mathrm{E}=\mathrm{h} v$ and, 67, 83, 84, 259-60, 284, 286, 401, 427, 429; early universe and, 222, 225, 227-28, 233-34, 236; Einstein and, 62, 67; energy levels and, 82-90, 119, 179, 250, 258; expansion and, 221 ; frequency and, 67 ; future issues and, 400-406; H-alpha, 87, 90, 179; inflation and, 374-75; infrared (IR) light and, 29, $62-65,67-70,75,77-78,86,90,117,153-$ $54,161,176-77,186-88,196,250,252-53$, 263,406 ; interstellar medium and, 179 ; lives of stars and, 99, 107, 113-14; Newton and, 62; as particles, 63; Paschen series and, 86, 90-92; Planck's constant and, 67; proportionality constant and, 67; radiation and, $62-67,75,80$; rainbow and, 41, 62, 67-68, 71 ; redshift and, 207-11, 213, 215, 225, 228, 231, 237-38, 242-53, 284, 318, 353, 375, $379,389,393,405,428$; relativity and, 259 , 284-86, 427-30; scattering and, 227-28, 233-34, 236; spectra and, 81,90 ; speed of, 66; Sun and, 67-68; time travel and, 28486, 327, 338-39, 341; ultraviolet (UV) light and, $62-63,65,69,74,86,91,107,119-20$, 179, 263; wavelength and, 66; as waves, 63; X-rays and, 63, 65-68, 113-14, 263
Physical Review, 315, 337
Piazzi, Giuseppe, 138
Pinwheel galaxy, 198, 199, 201-2
Planck, Max, 67, 73-75, 80, 92, 288
Planck curve, 87, 153, 231
Planck density, 401
Planck function, 73, 75, 92, 95

Planck length, 302, 316, 401, 431
Planck mass, 401
Planck satellite, 13, 216, 218, 236, 240, 373, 387, 391-93, 409
Planck's constant, 67, 73, 84, 92, 259, 284, 316, 401
Planck spectrum, 87, 225, 231, 407
Planck time, 401, 403
planetary motion: Brahe and, 35-37, 43, 258; changing speed of, 37-38; Copernicus and, 36-37, 42-43, 138-39, 165, 183-85, $210,370,375,411-18,420-22$; elliptical orbits and, $37-42,53,131,134,156,196$, 271, 297; gravity and, 130 (see also gravity); Kepler and, 36-43, 46-47, 49, 52-53, 157, 196, 258, 297; Newton's laws and, 42-43, 46-47, 52-53; parallax and, 55-60, 115, 213-14, 262, 434nl; retrograde, 36; transit and, 130, 149-51, 213
planetary nebulae, 119-20, 123, 181, 197
planetos (wanderer), 39-40
Planet X, 130-31
Planiverse (Dewdney), 435n2
plasma, 113, 121, 227, 405
Please, C. P., 436n5
Pleiades, 96, 180
plutinos, 135
Pluto: Charon and, 13, 130-31, 137-38, 14145; controversy over, 129, 135-37, 141-45; defining planet and, 139-40; discovery of, 130,138 ; downgrading of, 39, 126-45; gravity and, 134, 144; Hubble Space Telescope and, 130; Kuiper Belt and, 134-36, 140-44; Lowell and, 129-30, 209; Map of the Universe and, 355 ; mass and, 131, 138, 144; moons of, 130-31; naming of, 130; New York Times article and, 129, 135-36; official IAU listing of planets and, 144; orbit of, 40, 134-36, 144; relative size of, 131-32, 140; Rose Center display and, 126$28,132,135,141,144$; Sun and, 128-34, 139-44; Tombaugh and, $130,138,144-45$; uniqueness of, 132, 134
Pluto (Disney character), 138

Pluto Files, The: The Rise and Fall of America's Favorite Planet (Tyson), 144
Poldowski, Boris, 320
Polshek, Jim, 126
Popper, Karl, 434n1
Positive Philosophy, The (Comte), 92
positrons: black holes and, 317-20; early universe and, 222-23, 227; formation of, 99 ; future of universe and, 402, 403, 407; lives of stars and, 99
precession, 33, 297-98
President's Award for Distinguished Teaching, 12
Primack, Joel, 234
prime meridian, 367
Procyon, 100
Project Daedalus, 158
proportionality constant, 49, 67, 210, 213
protons: alpha particles and, 384; atomic nuclei and, $13,21-24,62,82,85-88$, 98-105, 122, 222-24, 227-28, 233-34, $266,282,350,384,390,402-7$; as baryon, 390; decay and, 223, 403, 407; density of in Sun, 21; early universe and, 222-24, $227-28,233-34$; fusion and, $99,102-5,111$, 114-15, 117-18, 121, 158, 181, 222-23; lives of stars and, $98-105,122$; proton-proton collisions and, 223; quantum tunneling and, $384-85$; quarks and, 403, 404-5; relativity and, 266, 282; spectra and, 85-86, 88; strong force and, $24,351,384$
Proxima Centauri, 59, 94, 355
Ptolemy, Claudius, 33, 37, 210
public policy prior, 436 n 5
pulsars, 22, 59, 125, 182, 244, 355, 382, 402
Pythagorean theorem, 268, 278, 434n2

QSO 0957+561, 331
quantum theory: atomic nuclei and, 21; Bekenstein formula and, 20; black holes and, 249, 302, 316-19; Bohr and, 258; decay and, 403; early universe and, 403-4; electrons and, 83-84; energy levels and, 82-90, $119,179,250,258$; entanglement and, 319,

344; fuzziness and, 73; general relativity and, 339 ; gravity and, $339,341,345,398$, 402; Hartle-Hawking vacuum and, 31819, 344; Hawking mechanism and, 406; HR diagram and, 100; inflation and, 381, 384-87, 393-96, 398-99; lives of stars and, 100,119 ; many-worlds theory and, 325-26; no boundary condition and, 394-95; Pauli exclusion principle and, 119, 122; Planck length and, 302, 316, 401, 431; Planck's constant and, 67, 73, 84, 259, 284, 316, 401; radiation and, 73-74; relativity and, 258-59, 345-46, 402; Schrödinger and, 258; supersymmetry and, 234, 402; time travel and, 322, 325-27, 337, 339-41, 34446 (see also time travel); tunneling and, 384-85, 394-95, 398, 408, 435n2; uncertainty principle and, $316-17,381,385,393$, 401, 403, 407; vacuum energy and, 327-28, 364, 377-78, 381-82, 408-9; vacuum state and, $318-19,327,340,344-45,396,398$, 403; virtual pairs and, 317-18; wormholes and, 311-12, 319-21, 327, 336, 341-44
Quaoar, 355
quarks, $351,402-5$
quasars: atoms and, 245; Big Bang and, 250; as black holes, 247; centers of galaxies and, 244-46; cosmic strings and, 330; cosmological principle and, 248; Doppler shift and, 245-46; early universe and, 250; gas speeds in, 246; Hubble Space Telescope and, 244-45, 253; hydrogen and, 250-52; luminosity and, 244-52; Map of the Universe and, 354-55; mass of, 245-47, 252; Milky Way and, 245-46; Newton's laws and, 246; rarity of, 248; redshift and, 250-53; Schmidt and, 242-44; spectra and, 242-43, 245-46, 249-53; speed of light and, 245-47; Strauss's discovery and, 12; Sun and, 246; 3C 273, 238, 241-45, 362; variable brightness of, 246; wavelength and, 241-42, 245, 253; Zwicky and, 243-44
radar, 64-65, 132
radiation: Big Bang and, 71; binding energy and, 86, 103-4; blackbody, 72-74, 77, 113, 154, 222, 225, 228-31, 375; brightness and, 78-80; distance to stars and, 54-59; Earth and, 54-62, 77, 80; Einstein's mass-energy equation and, $99,101,104,115,158,223$, 259-60, 269, 284-86, 318, 401-2, 427-30; electromagnetism and, 66, 406; excited electrons and, 81-92; frequency and, 65-67, 84, 208, 259, 284-85, 400-401, 427-29; fusion and, $99,102-5,111,114-15$, 117-18, 121, 158, 181, 222-23; gamma rays and, $63,66-67,73,125,222,263,319,339$, 362; infrared (IR) light and, 29, 62-70, 75, $77-78,86,90,117,153-54,161,176-77$, 186-88, 196, 250, 252-53, 263, 406; ladder diagrams and, 85, 88-89; luminosity and, $60,76-80$; photons and, $62-67,75$, 80; Planck functions and, 73 ; proportionality constant and, 67; quantum theory and, $73-74$; radar and, $64-65,132$; radio waves and, 63, 65-67, 73, 125, 229, 263, 310, 318; Raleigh-Jeans Law and, 74; red giants and, 74 ; speed of light and, 54-55, 66-67, 73; Sun and, 54-81, 424; temperature and, 67-78; thermal, 71, 74-76, 87, 89, $153,228,231,314,317-19,374-75,402-3$, 406; ultraviolet (UV) light and, 62-63, 65, $69,74,86,91,107,119-20,179,263$; visible light and, 65-71, 77-78; wavelength and, 64-68, 71-75 (see also wavelength); X-rays and, 63, 65-68, 113-14, 263
radioactivity, 103, 114, 218, 226, 351,384
radio telescopes, $71,158,168,229-30,241$
radio waves, $63,65-67,73,125,229,263,310$, 318
Raleigh-Jeans Law, 74
Ramirez-Ruiz, Enrico, 182
Randall, Lisa, 352
Ratra, Bharat, 409
recombination, 236-37, 403, 405
red giants: black holes and, 302-3; energy radiation and, 74; galaxies and, 197;
red giants (continued)
interstellar medium and, 181; lives of stars and, $95-97,100,102,118,120-21,123$; Milky Way and, 189; scale of universe and, 22; search for life and, 157; Sun becoming a, 217
Redmayne, Eddie, 12, 320
redshift: black holes and, 252-53, 318; early universe and, 225, 228, 231, 237-38; expansion and, 207-11, 213, 215, 225, 228, 231, 237-38, 242-53, 284, 318, 353, 375, 379, 389, 393, 405, 428; galaxies and, 207-$11,213,215,225,228,231,237-38,242-53$, 284, 318, 353, 375, 379, 389, 393, 405, 428; Hubble and, 209-10, 250; inflation and, 375, 379, 389, 393; Lemaître and, 393-94; quasars and, 242-45, 248-53, 405; relativity and, 284
red stars, $22,59,93,96,98,120$
red supergiants, 95,120
Rees, Martin, 384, 398
reflecting telescopes, 41,259
reflection nebulae, 180
relativity, 232; action at a distance and, 29596, 319-20; Big Bang and, 415; cosmic strings and, 327-33, 336-37, 340, 351, 435nl; $\mathrm{E}=\mathrm{mc}^{2}$ and, $9,99,101-2,115,158$, 223, 259-60, 269, 284-86, 318, 401, 42730; Earth and, 262-66, 269-83, 289-98; electromagnetism and, 290, 294, 297; electrons and, 266, 268, 299; energy density and, 434 n 2 ; event horizons and, 305 , 308-20, 337-38, 340, 344, 379-80, 386, 405-7, 431; expansion and, 220, 220-21; field equations and, 296-98, 300-301, 314, $323,327,331,337,367,369,375,378,402$; four-dimensional universe and, 270-76, $290,296,324,326,347,349,366,394-95$, 434nl; general, 11, 182 (see also general relativity); geometry and, 270, 278, 290-92, 294, 296; gravity and, 257-58, 260, 264, 282, 289-90, 292, 294, 298; importance of, 213; lensing and, 244, 253, 313, 33031, 391; mass and, 158, 259, 284, 286-89, 294-98; Maxwell and, 261-65, 290, 296-

97; Mercury and, 271-72, 283, 297-98, 350; photons and, 259, 284-86, 427-30; protons and, 266, 282; quantum theory and, 258-59, 345-46, 402; redshift and, 284; Riemann curvature tensors and, 2, 295-96, 301, 434nn1,2; solar system and, 367; spacetime and, 2, 260, 270-76, 28081, 285-86, 289-304, 309-17, 428-29, 434nn1,2; special, 101, 260, 264, 270-87, $300-301,326,347,371,377,380$; speed of light and, 101, 260, 263-69, 274-80, 282, 284, 288, 296, 402, 427; Sun and, 259-65, 270-72, 283, 287, 294, 297-99, 428; time travel and, 345-46 (see also time travel); uniform motion and, 264, 280; wavelength and, 285; worldlines and, 271-74, 278-79, 281-82, 284-86, 294-95, 297, 309-13, 322-27, 334-35, 364, 365, 367-$69,378,379-81,427$; wormholes and, 311-12, 319-21, 327, 336, 341-44
retrograde motion, 36
Riemann curvature tensors, 2, 295-96, 301, 434nn1,2
ring singularity, 337-38
Roberts, Morton, 243
Robertson, Howard, 372
Roll, Peter, 228-29
Rømer, Ole, 262
Roosevelt, Franklin D., 259, 287
Rose Center for Earth and Space, 19, 39, 126$29,132,135,141,144$
Rosen, Nathan, 320
Rosette Nebula, 90
Royal Astronomical Society, 299
Royal Society, 299
Roy G Biv (colors of rainbow), 62
RR Lyrae variable star, 189-90, 198
Rubbia, Carlo, 351
Rubin, Vera, 243
Rumsfeld, Donald, 253
Russell, Henry Norris, 93-94, 121, 182, 184
saddle, 301, 371-72, 389
Sagan, Carl, 18, 110, 165-67, 193, 218, 343-44

Salam, Abdus, 351
Sandage, Allan, 215-16, 243-44
Saturn: ancient Greece and, 40; as gas planet, 131; historical perspective on, 138-39; Kepler's time and, 39; Map of the Universe and, 355 ; mass of, 131; moons of, 141, 142, 160; Newton's laws and, 53, 130; official IAU listing of planets and, 144; relative size of, 133; Rose Center display and, 12829, 135; Standish and, 131; statistics of, 135
Saturn V rocket, 158, 422, 424
scalar fields, 350-51
scale of universe: atoms and, 128; Big Bang and, 19, 22, 24; cosmological principle and, 225-26, 230, 237-38, 248; Earth and, 18-25, 110, 153; Hubble and, 226; Hubble Space Telescope and, 108-9; hydrogen and, 128; Milky Way and, 185-86; red giants and, 22; Rose Center display and, 126-29; static model of, 362-65, 369, 393; temperatures and, 23-24, 67-69; trying to comprehend, 17-25; white dwarfs and, 22, 24
scattering, 227-28, 233-34, 236
Schiaparelli, Giovanni, 129
Schmidt, Brian, 389
Schmidt, Maarten, 242-44
Schneider, Don, 245
Schrödinger, Edwin, 258
Schwarzschild, Karl, 121, 300-302, 308
Schwarzschild, Martin, 5, 121, 122, 301-2
Schwarzschild radius, 301-10, 313-15, 318, 401
Search for Extraterrestrial Intelligence (SETI), 148, 165
search for life: bacteria and, $147,161,164-65$; carbon and, 147, 162-63, 169, 410; communication attempts and, 148-49, 159-60, 163-68; conditions needed for life and, 146-52, 155-69, 193, 420; cyanobacteria and, 147, 161-62; Drake equation and, 14749, 157-60, 162, 165-69, 193, 420; Dyson and, 406; Earth's diversity and, 160-62; exoplanets and, 149-51, 362; extraterrestrials and, $148,156,161,165,167,168,185$, 212, 312, 405, 419-20, 433nl; Gibbons and

Hawking radiation and, 406-7; habitable zone and, 146-47, 149, 151-52, 155-60, 162-63, 169; intelligent lineage and, 417, 436n4; LAWKI and, 162; luminosity and, 146-47, 151, 153, 168; main sequence stars and, $151,160,169$; measuring intelligence and, 163-64; Milky Way and, 149, 151-52, $159,166,168$; motivation for, 146-47; oxygen and, 147, 159, 169; picturing aliens and, 165-66; Project Daedalus and, 158; red giants and, 157 ; silicon and, 162-63; speed of light and, 158 ; technology and, 165; telescopes and, 158-59, 166, 168; temperature and, $151-56,169$; thermal radiation and, 153; visible light and, 406; water and, 146, 149, 154-61; Weak Anthropic Principle and, 410; Zipf's law and, 168-69
Secretariat, 260
selectrons, 232
self-gravitating objects, 111-12
Shakespeare, 139, 257-58
shape of universe: acceleration and, 350-51; Big Bang and, 367-73; Big Crunch and, 367-68, 372, 373, 384; black holes and, 355, 362, 368; cosmic microwave background (CMB) and, 352-55, 362, 373; cosmic strings and, 351 ; cosmological constant and, 363-70; dark energy and, 36465, 370; dark matter and, 351; Einstein and, 347-52, 355, 362-70; electromagnetism and, 348-52; electrons and, 35051; energy density and, 362-64; Flatland and, 347-49, 365, 371; four-dimensional universe and, 270-76, 290, 296, 324, 326, 347, 349, 366, 394-95, 434n1; Friedmann football space and, 367-70, 376-77, 381; general relativity and, 349-50, 362-63, 367, 369-70, 435nl; geometry and, 362, 364-65, 367, 371, 405, 435nl; gravity and, 349-52, 355, 363; Hubble Space Telescope and, 352, 355; hyperbolic, 371-73, 382-83; Kaluza-Klein dimensions and, 349-50, 352, 397; map of visible universe and, $352-62$; mass and, $351,355,365,368$;
shape of universe (continued)
Maxwell's equations and, 349-50; Milky Way and, 353, 363; M-theory and, 351-52, 397-98; Newton's laws and, 352; photons and, 351,363 ; point-masses and, 300-301, 303, 309, 311, 365, 435nl; saddle, 301, 371-72, 389; scalar fields and, 350-51; singularities and, 368 ; spacetime and, 347-51, 362-64, 367-72, 376-77, 381; speed of light and, 363; Standard Model and, 351; static model of, 362-65, 369, 393; stress energy tensor and, 364, 434n2; Sun and, 352, 355, 363 ; superstring theory and, $22,351,397$; 3 -sphere, 365-67, 370, 373, 374, 378-79, $382-83,388-89,394$; vacuum energy and, 364; vector fields and, 350
Shapley, Harlow, 94, 184-85, 187, 189-90, 197-98, 201, 210
Shoemaker-Levy 9, 137
silicon, 107, 120, 162-63, 181, 224
Simpson, Fergus, 419
singularities: black holes and, 302, 305-6, 309-13; future of universe and, 401, 409; inflation and, 381, 384, 396, 399; ring, 337-38; shape of universe and, 368 ; spacetime and, 302, 305-6, 309-13, 337-40, 344, 368, 381, 396, 399, 401, 409; time travel and, 337-40, 344
Sirius, 415
Skewe's number, 21
Slepian, Zack, 409
Slipher, Vesto, 209, 393
Sloan Digital Sky Survey, 13, 216, 237-40, 249-53, 353, 355, 391-92, 409
Sloan Great Wall, 238, 353, 362
slow-roll dark energy, 409
Small Magellanic Cloud, 187-88
Smolin, Lee, 398-99
Smoot, George, 375
sodium, 207
solar eclipse, 35, 260, 298-99
solar mass: black holes and, 247-49, 252, $303,305-6,314-16,318-19,338,355$, 403; interstellar medium and, 176, 182;
lives of stars and, 102, 121-23; wormholes and, 344
solar system, 32; age of, 218; Astronomical Unit (AU) and, 213; Brahe and, 35; comparative size of, 352 ; early, 161 ; families of, 141 ; heliocentric theory and, $36-37,42,139,184-85$; increasing knowledge of, 183; inner, 127, 134, 272; mass of, 226; movement of, 264; new solar systems and, 107; outer, 33, 126$27,134,195$; planetary motion and, 40 (see also planetary motion); relative size of, 415; relativity and, 367; scale model and, 115 . See also specific object
solar wind, 21, 180
solstice, 28
Sombrero galaxy, 202, 203
Soter, Steven, 165
Southern Cross, 28-29
Southern Hemisphere, 28, 30, 173, 186
Space Age, 229
Space Chronicles (Tyson), 423
spacelike separation, 277, 332
spacetime: action at a distance and, 295-96, 319-20; astronaut time (AT) and, 276-82; black holes and, 300-304, 309-17; bubble universes and, 381-88, 394, 396, 402, 408, 431nn1-3; Cauchy horizon and, 335-41, 345, 396; cosmic strings and, 327-33, 336-37, 340, 351, 435nl; cosmological constant and, 369 (see also cosmological constant); curvature and, 2, 291-93, 306, 313, 337, 339, 366-73, 377, 379, 382, 387-88, 396, 434nn1,2; derivation of E $=\mathrm{mc}^{2}$ and, 427-30; de Sitter, 378, 380, 382-85, 393-99, 405-6; diagrams of, 270-73, 281, 285, 286, 294, 309, 322-23, $325,334,335,338,364,367,368,376,378$, 393-96, 428-29; Einstein-Rosen bridge and, 320 ; energy density and, $76,318,327$, 340, 344, 362-64, 377-81, 384-91, 394, 405, 408-9, 434n2; entropy and, 315-16, 323, 431; Equivalence Principle and, 290, 292, 298, 310; event horizons and, 305, 308-20, 337-38, 340, 344, 379-80, 386,

405-7, 431; four-dimensional universe and, 270-76, 290, 296, 324, 326, 347, 349, 366, 394-95, 434n1; Friedmann football, 367-70, 376-77, 381; future of universe and, 400-424, 428-29; Gaussian curvature and, 371; gravitational waves and, 402-3, 406 (see also gravitational waves); great circle and, 18, 291-94; hyperbolic, 371-73, 382-83; inflation and, 376-83, 388, 393-98; jinn particles and, 322-24; Kruskal diagram and, 309-12, 314; Minkowski and, 270; M-theory and, 351-52, 397-98; multiverse and, 382-84, 386-87, 397-99, 402, 409; no boundary condition and, 394-95; null separation and, 277; Planck time and, 401, 403; quantum entanglement and, 319, 344; relativity and, $2,260,270-76,280-81,285-86,289-304$, 309-17, 428-29, 434nn1,2; Riemann curvature tensors and, 2, 295-96, 301, $434 \mathrm{nn} 1,2$; saddle shape and, $301,371-72$, 389; Schwarzschild radius and, 301-10, $313,315,318,401$; shape of universe and, 347-51, 362-64, 367-72, 376-77, 381; singularities and, 302, 305-6, 309-13, 337-40, 344, 368, 381, 396, 399, 401, 409; spacelike separation and, 277,332 ; spaghettification and, 305-6, 339; stress energy tensor and, $364,434 n 2$; superstring theory and, 22 , 351, 397; 3-sphere geometry and, 365-67, $370,373,374-75,378-79,382-83,388-89$, 394; time travel and, 300-304, 309-17, 322-28, 331-45; Twin Paradox and, 280-83; uncertainty principle and, 401; virtual pairs and, 317-18; warp drives and, 185, 336, 342, 344-45; white holes and, 312, 338; worldlines and, 271-74, 278-86, 294-95, 297, 309-13, 322-27, 334-35, 364, 365, 367-69, 378, 379-81, 427; wormholes and, 311-12, 319-20, 327, 336, 341-44
Space X, 422
spaghettification, 305-6, 339
special relativity, 101, 260; acceleration and, 280, 282; astronaut time (AT) and, 276-

82; atomic clocks and, 269; black holes and, 300-301; four-dimensional universe and, 270-76; gravity and, 282-83; implications of, 270-88; inflation and, 377, 380; light clock experiment and, 266-69; mass and, 284, 286-88; Michelson-Morley experiment and, 265-66; "motion is relative" postulate and, 264, 290; null separation and, 277; second postulate of, 265-69; shape of universe and, 347, 371; spacelike separation and, 277; spacetime and, 270-76, 280-81, 285-86; speed of light and, 265-69, 274-80, 282, 284, 288; time travel and, 276-84, 326; trusting, 269; Twin Paradox and, 280-83; uniform motion and, 264, 280; worldlines and, 271-74, 278-79, 281-86
spectra: absorption, $84,87-89,169,176$, 207-9, 250-51; atoms and, 81-92, 242, 245; Balmer lines and, 86, 88, 90-92, 179, 242, 258; Big Bang and, 81-82; blackbody, $72-74,77,113,154,222,225,228-31,375$; blueshift and, 209, 217, 231, 245, 339, 341, 429; brightness and, 92; carbon and, 88; computers and, 93-94; Doppler shift and, 97 (see also Doppler shift); early universe and, 238; electrons and, 81-92; elements and, 81-82; emission lines, $90,179,242$, 245-46, 250-51; energy levels and, $82-90,119,179,250,258$; excited electrons and, 81-92; expansion and, 208-9; galaxies and, 207-8, 238, 244; gamma rays and, $63,66-67,73,125,222,263,319,339$, 362; helium and, 81-82, 99; HertzsprungRussell (HR) diagram and, 93-96, 98, $100,121,160,189,207,219$; hydrogen and, 81-92, 250; infrared (IR) light and, 29, $62-70,75,77-78,86,90,117,153-54,161$, 176-77, 186-88, 196, 250, 252-53, 263, 406; interstellar medium and, 176-79; Lyman series and, 86, 91-92, 250, 252; mass and, 97-98; microwaves and, 63-67, $216,229,235,263,318,352,373,375$, 387, 393, 403, 407; nebulae and, 90-91;
spectra (continued)
neutrons and, 82; nitrogen and, 81-82; O B A F G K M L T Y scheme and, 100-101; oxygen and, 88; Paschen series and, 86, 90-92; Payne and, 94; photons and, 81 , 90; Planck, $87,225,231,407$; protons and, $82,85-86,88$; quasars and, $242-43,245-$ 46, 249-53; radar and, 64-65, 132; radio waves and, $63,65-67,73,125,229,263$, 310, 318; red objects and, 250-52; redshift and, 207-11, 213, 215, 225, 228, 231, 237-38, $242-53,284,318,353,375,379,389,393$, 405,428 ; speed of light and, 81 ; star classification and, 100-101; star measurements and, 60 ; temperature and, $68-70,84-85$, 87; thermal emission and, 68-72, 87, 89; ultraviolet (UV) light and, 62-69, 74, 86, $91,107,119-20,179,263$; visible light and, $84,86,90$; wavelength and, $87-90,113,125$; white dwarfs and, 242; white light and, 41, 62, 68; X-rays and, 63, 65-68, 113-14, 263
speed of light: Astronomical Unit (AU) and, 54; black holes and, 300, 302, 304-6, 309-12, 316; Bradley and, 263; Buller and, 326; as constant, 264; as cosmic speed limit, 54 ; cosmic strings and, 331; Doppler effect and, 208; $\mathrm{E}=\mathrm{mc}^{2}$ and, 9, 99, 101-2, 115, 158, 223, 259-60, 269, 284-86, 318, 401-2, 427, 429-30; early universe and, 231; eclipses of Jupiter and, 262; Einstein and, 263-64; energy radiation and, 54-55, 66-67, 73; expansion and, 208-9, 212, 408; gravitational waves and, 403; gravitons and, 403; inflation and, 374-75, 378-80, 382, 386, 393; light clock experiment and, 266-69; light-year and, $54,58-59$; lives of stars and, 123; Maxwell's equations and, 11, 261-65, 290, 296-97, 349-50, 402; Michelson-Morley experiment and, 265-66; photons and, 66; Planck time and, 401; quasars and, 245-47; relativity and, 101, 260, 263-69, 274-80, 282, 284, 288, 296, 402, 427; search for life and, 158; shape of universe
and, 363 ; spectra and, 81 ; stellar aberration and, 263; time delay from, 55; time travel and, 276-86, 324, 326-27, 330-33, 336, 342-43; Twin Paradox and, 280-83; wormholes and, 341-43
speed of sound, 208
Sphereland, 365
Spica, 100
spiral galaxies, 105-6, 111, 190-92, 194, 198, 201, 204, 214, 245, 249
spiral nebulae, 197-98, 200
Spitzer, Lyman, 5, 121, 122
standard candles, 60, 190, 213-15, 389
standard cosmological model, 13, 351, 391
Standish, Myles, 131
star clusters, 95-97, 137, 180
stars: black holes and, 100, 247 (see also black holes); formation of, 180-81; heavy elements and, $105,123,181,219,224$; Hertzsprung-Russell (HR) diagram and, 93-96, 98, 100, 121, 160, 189, 207, 219; lives of, 93-125; Map of the Universe and, 355; Milky Way and, 183-96; spectra and, 100. See also specific type
Star Trek series, 58, 158, 162, 185, 344
Star Wars IV (film), 157
static model, 362-65, 369, 393
Stefan, Josef, 75
Stefan-Boltzmann law, 75, 78, 95
Steinberg, Saul, 354
Steinhardt, Paul, 386
stellar aberration, 263, 265
stereoscopic art, 56, 272
Stonehenge, 424
Strauss, Michael A., 12; black holes and, 24753; early universe and, 222-40; expansion and, 207-21; galaxies and, 197-206; interstellar medium and, 173-82; Milky Way and, 183-96; Newton's laws and, 42-53; quasars and, 241-53
stress energy tensor, 364, 434n2
strong nuclear force, $24,99,351,384-85,402$
Subaru galaxy: 362
Subaru Telescope, 253

Sun: acceleration and, 46-47, 116; angular size of, 116; Astronomical Unit (AU) and, 40, 42, 115-16, 213; becoming white dwarf, 403, 405; becoming red giant, 217; black holes and, 237-50, 300-303, 313; Catholic Church and, 37; color of, 68; Copernicus and, 36-37; core of, 113; death of, $24-25,403,405$; density of, 22; distance to Earth, 115-16; early universe and, 22223, 226-27, 231-32; Earth's orbit around, $11,26-27,34,37,42-46,51,55,57-58,80$, $115,128,137-38,153,156,193,210,213,218$, 232, 248, 262, 270-72, 283; energy radiation and, $54-81,424$; equinox and, 30 ; fusion and, 103, 105, 111, 114-15, 117-18, 181, 222-23; galaxies and, 204, 210, 213, 217-19; gravity and, $32,111,114-15$; heat from, 29-30; heliocentric theory and, $36-37,42,139,184-85$; helium and, 121, 134, 181, 287; hydrogen and, $94,134,217$, 223, 227, 287; interstellar medium and, 180-96; Kepler's laws and, 37-41; lives of stars and, 94-105, 111-21, 125; location in Milky Way, 184-86, 194-95; as main sequence star, 403; Map of the Universe and, 355; Newton's laws and, 42-53; orbit of, 232; as ordinary star, 415; phases of Moon and, 33-36; photons and, 67-68; Pluto and, 128-34, 139-44; quasars and, 246; relativity and, 259-65, 270-72, 283, 287, 294, 297-99, 428; search for life and, 146-61, 168-69; size of, 185; solar eclipse and, $35,260,298-99$; solar mass and, 49, $117,102,121-23,176,181-82,247-49,252$, $303,305-6,314-16,318-19,338,344,355$, 403; solar wind and, 21, 180; solstice of, 28 ; temperatures of, 23-24, 69, 78; as white star, 68-69; worldline of, 271-72
Sundrum, Raman, 352
supernovae: acceleration and, 389; Baade and, 244; heavy elements and, 105,123 , 181, 219, 224; lives of stars and, 100, 106-7, 121-25, 181, 216, 219, 243-44, 247, 252-53, 362, 389-92; Zwicky and, 244
superstring theory, 22, 351, 397
supersymmetry, 234, 402
surface of constant epoch, 382
Susskind, Leonard, 319-20
Sykes, Mark, 136
symmetry, 184, 234, 279, 284, 301, 402, 404, 427
Szekeres, George, 308-9

Tadpole galaxy, 204-5
Taurus, 120, 123-24
Taylor, Joe, 182, 355, 402
telescopes: Apache Point, 250; arc second and, 58-59; balloon, 389; black holes and, 306; brightness and, 78; early universe and, 229-30, 236-37; galaxies and, 19798, 201, 205-6; Galileo and, 140; Herschel and, 139; Hubble, 13 (see also Hubble Space Telescope); interstellar medium and, 174, 180; invention of, 13,60 ; Keck, 259, 393; lives of stars and, 108-9, 117, 119, 121, 12425; Lowell and, 129-30; microwave, 229; Milky Way and, 183, 186-87, 189; Palomar Mountain, 215, 241, 244; quasars and, $242-47$; radio, $71,158,168,229-30,241$; reflecting, 41,259 ; relativity and, 259,263 ; remote control of, 251; resolution of, 246; search for life and, 158-59, 166, 168; Sloan Digital Sky Survey, 13, 216, 237-40, 24953, 353, 355, 391-92, 409; Subaru, 253; as time machines, 205, 249; 2MASS, 176, 188; universal expansion and, 207, 209-10, 215 temperature: black holes and, 247, 316-19; Celsius scale, 69; CMB and, 229 (see also cosmic microwave background (CMB)); early universe and, 24, 219-20, 222-31, 235, 237, 240; Earth's surface and, 78; equilibrium, 153-54; expansion and, 207, 214, 219-20; future of universe and, 403, 405-7; galaxies and, 201; Gibbons-Hawking, 403, 405-7; gravity and, 134; Hertzsprung-Russell (HR) diagram and, 93-96, 98, 100, 121, 160, 189, 207, 219; human body, 69-70, 77-78;
temperature (continued)
inflation and, 375-77, 387; Jupiter and, 135; Kelvin scale, 69; lives of stars and, 93-100, 105, 113-14, 117-18; of local planets, 135; luminosity and, 214; Mars and, 135; Mercury and, 135; Neptune and, 135; radiation and, 67-78; red objects and, 251-52; red stars and, 251; Saturn and, 135; scale of universe and, 23-24; search for life and, 151-56, 169; spectra and, 84-85, 87; StefanBoltzmann constant and, 75, 78, 95; Sun and, 23, 67-69, 78; terrestrial planets and, 134; Uranus and, 135; Venus and, 132, 135; wavelength and, 74-75; of whole universe, 71; Wien's Law and, 75
theory of everything, 13, 320, 399
Theory of Everything, The (film), 12, 320
thermal emission, 68-72
thermal radiation: black holes and, 314, 317-19; early universe and, 223, 228, 231; Earth's, 153; future of universe and, 402-3, 406; Hawking radiation and, 317-19, 340, 406-8, 435nl; inflation and, 374-75; radiation and, $71,74-76$; spectra and, 87,89
thermodynamics, $75,315-16,323,431$
3C 48, 243
3C 273, 238, 241-45, 362
3 -sphere geometry, 365-67, 370, 373, 374-75, 378-79, 382-83, 388-89, 394
third-quarter Moon, 34-35
Thisted, Ronald, 257
Thorne, Kip, 306, 314, 320, 325, 341-44
thought experiments, 263-65, 273, 275, 280, 285, 316, 325, 386, 429, 431
tidal forces, $118,151,160,192,204,304,306$, 337, 339
Time Machine, The (Wells), 283, 345-46
Time magazine, 12, 258
time travel: black holes and, 337-41, 344; Cauchy horizon and, 335-41, 345, 396; Coat of the Future and, 321-22; cosmic strings and, 327-37, 340; Earth and, 324, 327-31, 341-43; Einstein and, 323, 32627, 331, 337, 339, 341, 345-46; electro-
magnetism and, 330; electrons and, 324; energy density and, $327,340,344$; event horizon and, 337-38, 340, 344; Flatland and, 340 ; four-dimensional universe and, 324, 326; general relativity and, 283, 321, 323, 327, 331, 334, 339, 341, 345-46; geometry and, 327, 329-30, 332-33, 343; grandmother paradox and, 324-26; gravity and, 331, 339, 341, 345; Hawking and, 336, 340, 344-45; inflation and, 396-97; information and, 323 ; jinn particles and, 322-24; mass and, 323-24, 329-30, 334, 336-38, 341-44; Newton's laws and, 28384, 286, 345; Padalka and, 283; photons and, 284-86, 327, 338-39, 341; quantum theory and, 322, 325-27, 337, 339-41, $344-46$; shortcuts and, $327,330-32,342$, 344-45; singularities and, 337-40, 344; spacelike separation and, 332 ; spacetime and, 300-304, 309-17, 322-28, 331-45; spaghettification and, 339 ; special relativity and, 276-84, 326; speed of light and, 276-86, 324, 326-27, 330-33, 336, 342-43; Sun and, 324, 330; tidal forces and, 337, 339; time machines and, 205, 249, 321-46, 396-97; vacuum energy and, 327-28; warp drives and, 185, 336, 342, 344-45; worldlines and, 322-27, 334-35, 364-69; wormholes and, 327, 336, 341-44
Time Travel in Einstein's Universe (Gott), 346
Tipler, Frank, 341
Tombaugh, Clyde, 130, 138, 144
Tombaugh Regio, 145
transit, 130, 149-51, 213
Trifid Nebula, 179, 180
Triton, 140, 142
Truman, Harry S., 287-88
Trumpler, R., 299
Turner, Ed, 331
Twin Paradox, 280-83
Two Micron All-Sky Survey (2MASS), 176, 188
Tyson, Neil de Grasse, 12; Hayden Planetarium and, 11 ; Levy on, 137; lives of stars and, 93-110; Newton's laws and, 26-41; Pluto
and, 126-45; The Pluto Files: the Rise and Fall of America's Favorite Planet and, 144; radiation and, $54-80$; scale of universe and, 17-25; search for life and, 146-69; signature sayings of, 11; Space Chronicles and, 423; spectra and, 81-92; Sykes debate and, 136; undergraduate course of, 12
ultraviolet catastrophe, 74
ultraviolet (UV) light, 62-69, 74, 86, 91, 107, 119-20, 179, 263
uncertainty principle, $316-17,381,385,393$, 401, 403, 407
uniform velocity, 43-45
United Nations, 436n5
universal law of gravitation, 40-41, 48-49
University of California, Santa Cruz, 182
uranium, 102-3, 114, 139, 181, 287, 384-85
Uranus: as gas planet, 131; gravity and, 53; Herschel and, 138, 183; historical perspective on, 138-39; Lowell's time and, 130; Map of the Universe and, 355; mass of, 131; moons of, 139, 142; Newton's laws and, 53, 130; official IAU listing of planets and, 144; Planet $X$ and, 131 ; relative size of, 133 ; rings of, 133; Rose Center display and, 129, 135; Standish and, 131; statistics of, 135
Urtsever, Ulvi, 341
U.S. Declaration of Independence, 138
U.S. Naval Observatory, 131
vacuum energy: future of universe and, 4089; inflation and, 377-92; phantom energy and, 409-10; quantum theory and, 327-$28,364,377-78,381-82,408-9$; shape of universe and, 364; time travel and, 327-28
vague (Jeffreys) Bayesian prior, 436n5
Vanderbei, Bob, 354
van der Meer, Simon, 351
van de Walle, Nicholas, 436n5
variable stars, 189-90, 198, 200, 209-11, 213-15
vector fields, 350
Vega, 56-58, 343

Venus, 25; atmosphere of, 132; AU measurement and, 213; clouds of, 132; Frigga and, 40; historical perspective on, 138-39; Kepler's time and, 39-40; Map of the Universe and, 355; Newton's laws and, 130; official IAU listing of planets and, 144 ; relative size of, 132; Rose Center display and, 129; statistics of, 135; temperature of, 132, 135 ; terrestrial family and, 132,141 ; worldline of, 271-72
Vesta, 139-41, 143
Vilenkin, Alex, 327, 384, 394, 408
Virgo Supercluster, 127
virtual pairs, 317-18
visible light: interstellar medium and, 176; lives of stars and, 114, 117, 125; Maxwell and, 263; Milky Way and, 186; night sky and, 29; radiation and, 65-71, 77-78; search for life and, 406; spectra and, 84 , 86, 90; telescopes and, 241 (see also telescopes); wavelength and, 263
Voyager spacecraft, 131, 133
warp drives, $185,336,342,344-45$
water: abundance of, 81-82; boiling point of, $69,154-155$; density of, $22,113,141$; early universe and, 222; entropy and, 315-16; Europa and, 140 ; freezing point of, 69,154 155; Mars and, 129, 133, 422; microwaves and, 65 ; nonuniform distribution in boiling, 382; search for life and, 146, 149, 154-61
Watson, James, 352
wattage, 78
wavelength: black holes and, 318; blueshift and, 209, 217, 231, 245, 339, 341, 429; color and, 208-9; early universe and, 225, 228-29, 231, 250-53; expansion and, 250 ; frequency and, $65-67,84,208$, 259, 284-85, 400-401, 427-29; Gibbons and Hawking radiation and, 406; inflation and, 375; Kaluza-Klein dimension and, 350; Maxwell and, 263; Milky Way observations and, 188; photons and, 66; Planck and, 73-74; quasars and, 241-42, 245, 253;
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wavelength (continued)
radiation and, 64-68, 71-75, 87-90, 113, 125, 176-79, 188, 207-9, 225, 228-29, 231, 241-42, 245, 250-53, 258, 263, 285, 318, $350,375,400,406,428$; radio and, 67; redshift and, 207-11, 213, 215, 225, 228, 231, 237-38, 242-53, 284, 318, 353, 375, 379, 389, 393, 405, 428; relativity and, 285; spectra and, $87-90,113,125$; temperature and, 74-75; thermal emission and, 68-72; ultraviolet catastrophe and, 74 ; visible light and, 263; Wien's Law and, 75
wavicles, 63
waxing gibbous Moon, 35
Weak Anthropic Principle, 410
weakly interacting massive particles (WIMPs), 234
weak nuclear force, 351, 402-3
Weinberg, Nevin, 409
Weinberg, Steven, 351, 398, 408
Wells, H. G., 283, 345-46
Wheeler, John Archibald, 314-15, 317
white dwarfs: black holes and, 303; expansion
and, 242; future of universe and, 403, 405,
407; HR diagram and, 94; lives of stars and, $94,95,100,119-23$; Milky Way and, 189; scale of universe and, 22,24 ; spectra and, 242; Sun becoming a, 403, 405
white holes, 312, 338
white light, 41, 62, 68
white stars, 22, 68
Wide-Field Infrared Survey Explorer, 117
Wien, Wilhelm, 74-75

Wilkinson, Dave, 228-32, 235
Wilkinson Microwave Anisotropy Probe (WMAP), 13, 235-38, 240, 353, 373, 387, 391-92
Wilson, E. O., 19
Wilson, Robert, 71, 229-30, 373, 375, 415
Witten, Ed, 351
Wordsworth, William, 258
worldlines: astronaut time (AT) and, 276-82; black holes and, 309-13; depiction of, 272, 273, 281, 309, 323, 325, 328, 335, 368, 377, 378, 383; de Sitter space and, 378, 380, 382-85, 393-99, 405-6; inflation and, 378, 379-81; personal, 272-73; relativity and, 271-74, 278-86, 294-95, 297, 30913, 322-27, 334-35, 364, 365, 367-69, 378, 379-81, 427; symmetry and, 427; time travel and, 322-27, 334-35, 364-69
wormholes: black holes and, 311-12, 319-20; speed of light and, 341-43; time travel and, 327, 336, 341-44; traversable, 341

X-bosons, 402, 404
X-rays, 63, 65-68, 113-14, 263
Yahil, Amos, 243
Zeldovich, Hakov, 317
Zipf's law, 168-69
zodiac constellations, 32-33
Zubrin, Robert, 422-23
Zwicky, Fritz, 196, 243-44, 244
ZZ Ceti stars, 190

