Introduction

What is Astronomy?

1

astronomy

The science that deals with the material universe beyond the earth's atmosphere.

If you were to walk down a busy street and ask every third person what astronomy is, I suspect most of the answers would have something to do with "looking up at the stars," or "looking through telescopes," or something along those lines. But what is astronomy, really? Is astronomy all about "looking up at the stars"? Let's see what my dictionary has to say about it:

> **astronomy**: the science that deals with the material universe beyond the earth's atmosphere. (*The Random House Dictionary of the English Language, College Edition,* Random House / New York (1969).

Now, that's not a bad starting place. They should really have said "physical universe," since light is not "material" and astronomers clearly deal with light. Also, the phrase "beyond the earth's atmosphere" is a bit too limiting, since I know astronomers who study the Earth itself. But it's a good starting place. Let's explore the definition a little further by asking what it is that astronomers actually look at.

First of all, anything away from Earth—anything that is "out there"—is a fair topic for astronomy. Mars, for instance. Or the Sun, or the Moon. Any of the stars or galaxies that we can see with our telescopes. Those are the topics that are referred to by the dictionary definition. But as I just mentioned, Earth itself can also be a topic for astronomy. Earth is after all one of the planets that orbit the Sun. To some extent, astronomy is defined not so much by *what* you look at, as by *how* you look at things, or *why* you look at them. You might be looking at Earth rocks—doing geology—but if you are looking at them to learn how Earth compares to the other planets in the solar system, then you're also doing astronomy.

What about looking up at the sky at night—constellations, and all of that? Isn't "star gazing" a part of astronomy too? The night sky *is* part of astronomy—but only a part of it, and a relatively small part at that. If you glance through the table of contents you'll see that most of this book has less to do with how things look in the night sky, and more to do with what those things actually are. What *is* a star? How is it different than a planet? What makes one star different than another, or Earth different than Uranus? What is a galaxy? A quasar? A pulsar? A black hole? What is the Universe? And is there life anywhere else but here? These are the kinds of questions that are really at the heart of astronomy.

Astronomy is often confused with *astrology*, so we need to address that right up front. This is a book on *astronomy*, not astrology—and the two topics are much more different than their similar names might suggest. Astronomy is generally considered to be a science, whereas astrology is not. What's the difference? What makes one field of study a "science," and another not? These are very tricky questions, questions that have been debated for centuries. I would never presume to have the once-and-for-all answers; but before we begin our exploration of the Universe, it would be worthwhile to take a look at some of the important points that are involved in trying to answer such questions, as well as some of the terminology that is used.

1.1 Knowing, Believing, and Falsifiability

falsifiable

A falsifiable claim is one that could be shown to be false, if it were false.

First off, it's important to recognize that "knowing" is very different than "believing." We are all allowed to believe pretty much anything we want to. Some beliefs are considered "normal," because they are shared by many; others may be considered strange, or even irrational. But for the most part our beliefs are our own business.

Knowing, on the other hand, carries more weight. You can *believe* that Beethoven was the greatest composer that ever lived, or that chocolate is the best flavor of ice cream, or that space aliens built Stonehenge; but to claim that you *know* these things, as facts, would be something very different. Clearly, science claims to be in the business of knowing rather than believing. When scientists tell us that the Earth's crust is broken into plates that shift around and cause earthquakes, or that there is a black hole in the center of our galaxy, they are not merely telling us what they *believe;* they are telling us what they *know,* or at least what they think they know based on the current information that they have.

One thing that sets knowledge apart from belief, is that claims about knowledge are generally *testable.* This simply means that you can do some kind of test to see if the claim is true, since you can't know something unless it is true. You can't "know" that Martin Van Buren was the 9th president of the United States, because he wasn't (he was the 8th). You might *think* that he was, or *believe* that he was; but you can't *know* it. Sometimes the test is somewhat indirect. The only way to test, or check whether or not the 8th president of the United States was Mr. Van Buren is to look it up in some reliable reference. You can't find it out directly. This is often the case with scientific claims as well. You can do a test to confirm that the mass of an electron is what scientists claim it to be; but a test like that would not be as direct as weighing the electron on your bathroom scale.

The ability to test a claim is often referred to as *falsifiability.* If a claim can be "falsified," it just means that it would be possible, at least in principle, to show that the claim is false, *if* the claim is false. For example, let's say your claim is that gold is more dense than water. Of course, gold is more dense than water, so your claim is not a false claim. Nevertheless, the claim is **falsifiable**. Why? Because you can test it by putting a solid block of gold in water, and checking to see if it floats. If the claim were false, if gold was actually *less* dense than water, then the gold block would float, and you would have discovered that the claim is false. So the claim is *falsifiable,* even though it isn't actually false. Note that last point well, by the way. Just because a claim is *falsifiable,* that doesn't mean it is *false.* True claims can be falsifiable. Does that make sense?

Claims that are not falsifiable—that is, claims that cannot be tested—are usually considered to be unscientific. For example, what if I tell you that I can make it rain whenever I want to? This is not a scientific claim, because it cannot be tested, or falsified. Why not? Because whatever happens—whether it rains or not—I can always say "Yep! That's what I meant it to do!" There is no way to prove me wrong, so my claim cannot be falsified.

Note that just because a claim is unscientific that does not mean that it is nonsense, or useless, or meaningless. It simply means that it is not *scientific.* Claims about art, music, morality, ethics, religion, and countless other areas of human experience are often not falsifiable, and hence are not scientific; but that certainly does not mean they are unimportant! Scientific knowledge is not the only knowledge out there!

1.2 Deduction, Induction, and "Inference to the Best Explanation"

Scientific claims are generally testable, or falsifiable; but beyond that, the question of what constitutes scientific knowledge is an enormous one, and involves far more than we can go into here. However, there are three ways in which we can "know" that are worth knowing about, as they are especially important for science generally, and astronomy particularly. In all three cases, we start with some statements or events, and then ask what we can legitimately conclude or *infer* from those statements or events. Let's take them one at a time.

1.2a Deduction

deductive inference
An inference that absolutely must be true, if the premises on which it is based are true.

What if I told you that all of the trees in my yard are pine trees; and what if you already knew that all pine trees have green needles? You could then conclude that all of the trees in my yard have green needles. Notice that I never *said* that the trees in my yard have green needles, but you *know* that they do from the information you have been given. Why? Because *if* it is true that all of the trees in my yard are pine trees, and *if* it is also true that all pine trees have green needles, then it *must* be true that the trees in my yard have green needles! They have to! It's unavoidable, guaranteed!

This is the essence of deduction, or a **deductive inference**. A deductive inference is one that absolutely must be true, provided only that the initial statements (known as *premises*) are true. Of course, if one or more of the initial statements turns out to be false, then all bets are off. If there is actually an oak tree somewhere in my yard, then the inference that all of the trees in my yard have green needles would be false. But if the initial statements are true, then the conclusion or inference must be true.

Deduction is very important in mathematics, since most mathematical knowledge is based on definitions that necessarily lead to definite conclusions. Given what you mean by the number "2," and given what you mean by the number "4," and given what you mean by the process of "addition," it follows necessarily that $2 + 2 = 4$. It has to! However, deduction does not actually play a very big role in the physical sciences. Why not? Because deductive inferences are not subject to experimental tests. If someone told you "Hey! I just took two socks out of my drawer, and then I took out two more socks, and now I have five socks! So $2 + 2$ doesn't equal 4, it equals 5!" you wouldn't say, "Wow! Really? That's amazing! We'd better check the multiplication table too! Maybe that's wrong!" You'd say, "Nonsense. You miscounted." The truth of a deductive inference is guaranteed from the start, and doesn't depend on tests, or experiments, or experience; and that's why scientists rarely use deductive reasoning as the basis of their knowledge of the world.

1.2b Induction

inductive inference
An inference that is based on previous experiences or examples of a similar nature.

Induction, inductive reasoning, or an **inductive inference** is often referred to as "more of the same." It is a type of reasoning or inference that we use constantly in our daily lives. If you order pancakes at a diner because you like pancakes, you're actually using inductive reasoning. Your decision is based on the fact that you have had pancakes before, and every time you've had them you have liked them. You therefore conclude, or infer, that you will like them if you have them again. That's induction. "It was that way before, so it will be that way again."

Induction is central to science, as much as it is to our daily lives. Why do we expect gravity to be attractive tomorrow? *Because gravity has always been attractive before.* Why do we expect this oak tree to develop acorns when it matures? *Because every other oak tree has developed acorns when it matured.* Why do we expect this star to have hydrogen absorption lines in its spectrum? *Because every other star has hydrogen absorption lines in its spectrum.* Inductive reasoning is the basis of much of our scientific knowledge.

Note that inductive inferences are *not* guaranteed in the way that deductive inferences are; and in that sense they are not as strong or reliable as deductive inferences. After all, just because you have always liked pancakes before, it does not follow necessarily that you have to like them today. They may be terrible pancakes; or you may suddenly decide that you don't like pancakes anymore. Likewise scientific claims based on induction are not guaranteed. Just because every other star has had hydrogen absorption lines in its spectrum, it doesn't follow necessarily that this next star *must* have hydrogen absorption lines in its spectrum. Maybe this star will represent a breakthrough in science! Perhaps it is a previously unobserved type of star, one that nobody ever expected. Even gravity could change. Maybe gravity will continue to be attractive until 11:30 in the morning on January 3, 2023, and then it will suddenly become repulsive and everything on the Earth will be ejected out into space. It could happen! Until January 3, 2023, at 11:30 AM, we won't know. We might have a theory that says that gravity does not change with time; but that theory is itself based on inductive reasoning, so its truth or validity cannot be known for certain either.

This is part of the reason why scientific "facts" are always changing so much. Something that we think is true today, may turn out to be only partially true, or even completely false, when new information comes in tomorrow. Anything learned through induction ("It's always been that way") could change ("It's not that way any more!")

1.2c Inference to the Best Explanation

inference to the best explanation

An inference that provides the best explanation of some event, based on a suitable definition of 'best.'

Imagine that you left a plate of cookies sitting on your kitchen table. A few minutes later you return to the kitchen and the cookies are gone. You notice that your dog, whom is big enough to reach the table, is curled up in her bed, licking her lips, and there are crumbs on her bed and on her nose. You would probably conclude that your dog at the cookies, right? Well, that's a perfect example of **inference to the best explanation**. You have *inferred* that the dog ate the cookies. Why? Because that's the *best explanation* for the fact that the cookies are gone!

Notice that this is not a case of deduction. If this were a deductive inference, the conclusion would be absolutely guaranteed; and if the conclusion were guaranteed, then it would be the only *possible* conclusion. But it's not! Someone could have broken into your kitchen when you were in the other room, eaten the cookies, sprinkled some crumbs around the dog to make it look like she had eaten them, and then left. Or a hungry alien could have materialized in your kitchen, done the deed, and then beamed back to its spaceship! These are obviously very unlikely explanations, but they are possible; and as long as there exists any other possible explanation, then the conclusion that your dog ate the cookies is not guaranteed. It may be the best explanation, but it's not the *only possible* explanation. Notice also that this is not a case of induction. Induction would imply that this same thing had happened over and over again. Every time you left cookies on the table in the past, the dog has eaten them; so you infer that the dog has eaten them again. Of course, that situation might occur, but that's not the scenario I'm describing here.

Like induction, *inference to the best explanation* is also central to how scientific knowledge is acquired. In February of 2016 a joint team of scientists from Caltech and MIT announced the first detection of a phenomenon known as *gravity waves;* and based on the details of what they detected, they claimed that the gravitational waves had been generated when two black holes, one with a mass equivalent to 29 times the mass of our Sun and the other 36 times the mass of our Sun, collided at a location in space some 1.3 billion light–years away. Now, nobody *saw* those black holes collide, in the way that you might see two people collide on the sidewalk if they're not watching where they're going. All they *saw* was that their detectors jiggled in a particular way. But they *infer* that the jiggling was caused by two black holes bumping into each other 1.3 billion light–years away because *that is the best explanation.* No other explanation can account for why their detectors jiggled in that very particular way.

1.3 Scientific Descriptions

When scientists come up with a description or an explanation of something in the natural world, they generally refer to it either as an *hypothesis,* a *theory,* or sometimes a *law.* These terms are used throughout science, and they are often misunderstood. Let's start with the first two.

1.3a Hypotheses and Theories

There are actually two differences between an *hypothesis* and a *theory,* two different ways in which the two terms are used. One way is that *theories* have more support behind them than *hypotheses;* the other is that *theories* tend to be bigger than *hypotheses.*

An **hypothesis** is basically an educated guess; and it is an educated guess about something comparatively small and specific. In 1964 Jocelyn Bell discovered a star that was flashing—getting brighter and dimmer, brighter and dimmer—roughly once each second. After this discovery the idea was put forward that this flashing star, which is now known as a *pulsar,* might be a spinning neutron star. We'll talk about neutron stars and pulsars later on in Chapter 6, but their story provides an excellent example of an hypothesis. A spinning neutron star was not the only possible explanation for what Jocelyn Bell had found. There were those at the time who considered it possible that this flashing star was actually a signal from an advanced alien civilization, that was announcing its presence in much the same way that we use flashing lights to call attention to something. Hence, the alien signal explanation was another hypothesis.

hypothesis
An explanation or idea that has not yet been empirically tested to any significant extent. Also, an hypothesis generally has a smaller application or scope than a theory.

theory
An explanation or principle that has considerable experimental support behind it. Also, a theory generally has a broader application or scope than an hypothesis.

Of course, both of these hypotheses are falsifiable claims. For example, one might reason that if this flashing star were a spinning neutron star, it ought to have a certain size and mass. Hence, a measure of the star's size or mass would constitute a test of that hypothesis. Alternatively, if it was an alien signal, one might expect the flashing to change, or to stop at some point; so monitoring the flashing to see if it varied might constitute a test of that second hypothesis.

So what is a **theory**? Well, the word "theory" tends to be used in two different ways. As I mentioned above, if a particular hypothesis passes enough tests, then it "graduates" in a certain sense, and becomes a theory. For example, hundreds of pulsars are now known to exist, and their masses and sizes are all consistent with spinning neutron stars; whereas in none of them has the flashing ever changed or stopped. This is one reason why the spinning neutron star hypothesis has caught on, whereas the alien signal hypothesis has not. Because so many tests have now been made, one would not refer to the spinning neutron star model as an hypothesis anymore; we would call it our current *theory* of what pulsars are.

The other difference between hypotheses and theories is that theories tend to be bigger than hypotheses; they tend to refer to larger, more sweeping phenomena. For example, if you have a new idea about how gravity works, scientists would probably not refer to your idea as an *hypothesis* about gravity. Gravity is such a vast, enormous thing, governing not only countless phenomena here on Earth, but also the structure and evolution of the entire Universe, that they would probably refer to it right from the start as your *theory* of gravity—even if your idea had not yet been tested at all.

Don't be too concerned with this distinction between *hypotheses* and *theories.* I'm not sure all scientists would agree on the point! It's just good to have a basic idea of how the terms are used, and to recognize that they are not generally synonymous. They refer to different things, even if it isn't always clear how to draw the line between them.

1.3b Laws and "Proof"

At what point can one legitimately claim that a theory has been proven to be correct? It's an important question, and the answer may surprise you. Are you ready? Here it is:

Never.

"Never? Not *ever?"* Nope, not really. A theory can never be "proven" correct. Why not? Well, the "technical" answer is because scientific theories are not based on deduction; and it is only in deduction that one can *prove* that something is true. In deduction, the truth of the initial statements guarantees, or *proves* the truth of the conclusion or inference. But remember, with inductive inferences, or inferences to the best explanation, there is *always* another possibility, another possible explanation, so there is no way to *prove* that the conclusion must be true. Mathematicians can prove their theorems, but scientists can never prove their theories. This does *not* mean that scientific knowledge is unreliable, or uncertain, or optional. Nothing of the kind! Only that it is never *certain*. But then, *no* knowledge is ever certain, scientific or otherwise! It's not *certain* that you're reading this book right now. You may have been hypnotized into *thinking* that you are, when in fact you are sitting outside in the rain!

With regard to science, what generally happens is that when scientists have gathered enough evidence in support of some idea, they will begin to assume that it *is* true, and will act as if it is true. This is perfectly right and reasonable. How many times would you need to put your hand into a candle flame before concluding that fire is hot? Nevertheless, such assumptions can lead scientists to become overconfident. As just one example, by the end of the 19th century virtually every practicing physicist would have said that light is a wave of electromagnetic energy. Both theory and numerous experiments all pointed to this conclusion. Yet it turned out to be wrong, and was eventually supplanted by a very different picture of light that emerged in the 1920s from what is now known as quantum mechanics.

So if you can never prove that a theory is correct, what is a *law?* Well, the fact is that the word "law" really has no place in science. I'm not saying it isn't used, because it is. I'm only saying that it shouldn't be. What happens in practice is that when a theory has been around for a long time, and it has passed many, many, many tests, people sometimes start calling it a "law." This is actually a bad thing to do, because of course the very word "law" suggests that the theory is fixed and unchangeable. But as I have been emphasizing, just because a theory passes lots of tests, it *doesn't* mean that it must be true.

History gives us a wonderful example of the confusion that can emerge when we start using the word "law" in a scientific context. The first theory of gravity was developed by Isaac Newton in the 1600s. It worked really well until the late 1800s, when astronomers found that it kept giving incorrect information when they tried to use it to estimate where the planet Mercury ought to be. This difficulty remained until 1915, when Einstein presented an entirely new and different theory of gravity. Einstein's theory was able to correctly describe Mercury's orbit, as well as everything else that Newton's theory had described so well—which was basically every other known gravitational phenomenon, from the motion of the other planets and moons, to baseballs and falling apples. Naturally, the scientific community quickly adopted Einstein's new theory as the correct description of gravity. But the interesting point is that, even today, more than a century after this transition occurred, Newton's description of gravity is still referred to as Newton's *law* of gravity, whereas Einstein's description is referred to as the general *theory* of relativity.

I do want to emphasize once more that the uncertain nature of scientific knowledge does *not* mean that scientific theories are somehow weak, or that we can just reject a theory simply because we don't happen to agree with it. When people say "Oh, that's only a theory!" they are really indicating that they don't understand how science works. *Everything is "only" theory! The claim that you are reading this book is "only" a theory! But that doesn't mean that we can dismiss it!* In science, theories are well tested, well supported, and very thoroughly thought out. They are our "best explanations" of the various phenomena of nature, and they cannot be rejected lightly.

1.4 The Scientific Method

Science textbooks often make much of what is referred to as the "scientific method." Although I have no wish to cast aspersions on the authors of those books, I myself will downplay the scientific method a bit. Philosophers, particularly philosophers of science, often have a better grip on what it is the scientists actually do than scientists themselves have; and philosophers of science have known forever that there is no one method that all scientists use in all situations. Lots of methods have been used over the centuries, methods that often seem in direct conflict with each other; and if history teaches us anything, it is that scientists do pretty much whatever they need to do to get the job done.

scientific method
A series of basic steps that often guide scientific research.

Nevertheless, it is perfectly legitimate to recognize that scientists *in general* tend to follow certain broadly defined steps that work well in many situations, across scientific disciplines; and it is worthwhile to give at least some kind of structure to what those steps are. Here then is one description of what could reasonably be called a **scientific method**, what it is that one does if one is approaching nature as a scientist:

1. **Observe** That is, look closely at some aspect or phenomenon of nature. If appropriate, make any necessary measurements as carefully as possible.
2. **Make an hypothesis** As was described above, an hypothesis is basically an educated guess as to why the things you have observed are as they are, and why the phenomena occur as they do. Try to suggest a cause for every effect.
3. **Check** To check, or test to see if your "guess" is correct, you predict something that has *not* yet been observed. You basically say, "If my hypothesis is correct, then if I do X, I would expect Y to happen." You then perform the test and record carefully what happens.
4. **Analyze and interpret** Take a good, hard, *unbiased* look at the results of your test and see what you can learn. The more you can set aside your own expectations, wishes, opinions, and feelings, the more you'll be approaching the situation as a scientist would.

Let's look at an example of how this method works by imagining that you have in your hand a rubber ball, and that you want to find out what happens when you let go of it.

First of all, you *observe* that when you let go of the ball it falls to the ground. You might choose to make some measurements, such as how long it takes the ball to reach the floor, but that needn't concern us here.

Your next step is to come up with an *hypothesis* about what is causing the ball to fall when you let go of it. Let's say you notice that the ball is blue. This might lead to your first hypothesis:

First hypothesis: *The ball falls because it is blue; that is, blue things fall.*

Okay. Now that you have your hypothesis you can set about trying to *check* it, or *test* it. Such a test might look something like this: You take another ball, a red one, and before you drop it you make a prediction based on your hypothesis. Your hypothesis is that the original ball falls because it is blue; hence, you predict that the new ball, since it is *not* blue, should *not* fall. You then perform the test by letting go of the red ball; and of course it falls. In this case, the last step, the *analysis*, is particularly straightforward. Both balls fell in apparently the same way; hence, the color of an object can have little if anything to do with why things fall. Your first hypothesis is not correct. You have to go back to the drawing board and start again. You need a new hypothesis.

You notice now that both balls are the same shape, and wonder if perhaps this has something to do with why they fall. You formulate your second hypothesis based on this:

Second hypothesis: *The ball falls because it is round; that is, round things fall.*

You could then test this as you did your first hypothesis. To do so you would have to drop something that *isn't* round. Your prediction would then be that the *not* round object would *not* fall. Of course, you would find that roundness has no more to do with why things fall than color.

In this way you might try several hypotheses. But let's suppose that eventually you stumble on an idea that is nearer the truth, and form an hypothesis accordingly:

Eventual hypothesis: *The ball falls because it is near the Earth; that is, things fall because the Earth draws nearby things toward it.*

Now, to test this hypothesis directly would be very tricky. You would have to take some object, like the ball you dropped in the first place, and go way out into space with it, far from the Earth, and let go of it out there. Your hypothesis would lead you to predict that, since the Earth is no longer nearby, the ball would not "fall" in any direction, it would just stay put. Of course, if you could perform this test, it would confirm your hypothesis. You are definitely on the right track!

In order to have a genuine theory of gravity, one that is worthy of serious consideration, you would need to pack a lot more into your hypothesis than simply "things fall because the Earth draws them towards it." But with work, and thought, and lots of testing, you could do it—and that is of course what Isaac Newton, and later Albert Einstein did.

1.5 Communicating Scientific Ideas (Or Anything Else)

"Doing" science is one thing. But if you do anything worthwhile as a scientist—or anywhere else in life, for that matter—at some point you will want to communicate your ideas to others. In that regard, it would be useful to point out three broad categories of statements: statements of fact, statements of opinion, and—for lack of a better way of putting it—statements of nonsense.

Let's image you and I are chatting one day, and I say "You know, I just read in National Geographic that chocolate ice cream is the most popular flavor of ice cream in the United States." This is a statement of fact. Notice that the statement does *not* have to be true to be a statement of fact. It might actually be false. Maybe vanilla is actually the most popular flavor in this country, and the article was based on false information. That doesn't matter. It's a statement of fact because it is *about* factual information. And because it is a statement of fact, it must be either true or false. There is a most popular flavor of ice cream in this country, and that flavor may or may not be chocolate. Notice also that the statement is about two things: ice cream, and the United States. If it's true, then it tells you something about chocolate ice cream, and it tells you something about the people of the United States. It does not tell you anything about me—except that I read National Geographic.

What if you disagreed with me? What would that mean? Since the statement has nothing to do with how you or I feel about chocolate ice cream, the only thing you could disagree with is the claim itself. Perhaps you read in another magazine that chocolate ice cream *used* to be the most popular flavor, but now Pecan Praline is. Notice that in such a case you would *not* be disagreeing with me; you would be disagreeing with National Geographic magazine. This means that there would no basis for any kind of argument between you and me, although we might get into a discussion about which magazine was most likely to have the more accurate information.

Let's now imagine that, after having exhausted the fascinating topic of which flavor of ice cream is the most popular, you say to me "You know, my favorite flavor is mint chip. I love that stuff!" This is a statement of opinion. Notice that this statement is not actually about ice cream; it's about you. It tells me something about you, but it doesn't tell me anything about mint chip ice cream—except that you like it. Notice that if I disagree with you here, it just means that I prefer some other ice cream, like Neapolitan. And again, there is no basis for an argument between us. You like mint chip. I like Neapolitan. I have learned something about you. You have learned something about me. But there is nothing to argue about.

Now let's imagine our conversation is joined by a third person, who loudly proclaims "Pistachio is the only ice cream worth eating!" Think about that statement for a moment. Is it a statement of fact, or opinion? You and I both recognize that, of course, this person is only stating their opinion. And yet, they have presented their opinion *as if it is a fact.* They haven't said "My favorite ice cream is pistachio," or "I *think* pistachio is the only ice cream worth eating." They have simply said "This is the way it is! Period!" In other words, their statement isn't really about them, as it would be if it were stated as an opinion. It's about ice cream. It's about pistachio ice cream, as well as all other flavors. It tells us that pistachio ice cream is worth eating, and that chocolate, mint chip, and Neapolitan are not worth eating.

Notice how things are now set up for an argument. You love mint chip, and I love neapolitan—and this third person has just told us that those flavors aren't worth eating. They're garbage. What does that say about you and I? That we are people who think that ice cream tastes good when, in fact, it isn't worth eating; that we can't tell the difference between good ice cream and bad ice cream; that we have no taste in food; and on and on.

The trouble with this last statement is that *it doesn't actually say anything!* It attempts to state an opinion as if it is fact, and you can't do that. Opinions *aren't* facts, and if you try to turn an opinion into a fact, you just end up with nonsense. So the lesson for communicating science—and anything else!—is to endeavor to be as aware as we can of our own opinions, and keep them separate from factual information.

1.6 Astronomy and Astrology

So what about astrology? Most astronomers, as well as scientists generally, do not consider astrology to be a science, and they tend to have a pretty dim view of it. The dim view stems from the fact that astrologers often claim that astrology is a science, and they want to be treated accordingly; whereas most scientists feel that astrology does not deserve the credibility that goes along with being a science.

Astrology is based on a sweeping hypothesis that is supposed to clarify the causes for lots and lots of things that happen in our lives. Here essentially is the hypothesis:

> **The Astrology Hypothesis:** *The location of the Earth in its orbit on the day a person is born determines, at least in part, not only many of the things that will happen to that person during theirlifetime, but also the very nature of that person.*

With this hypothesis astrology makes specific predictions about things that have not yet happened. You can read these predictions in pretty much any newspaper, and on lots of websites—in short, any source that publishes a "daily horoscope." So far, so good.

The trouble is, that after establishing its hypothesis astrology doesn't play by the rules. Scientific claims are supposed to be falsifiable; whereas many of the claims of astrology are not. For instance, according to one astrological web site that I visited just before writing this paragraph, if you are born early in January then you like music and you have a dark sense of humor. Now, it may be perfectly true that people born in early January *do* like music, and they *do* have a dark sense of humor, but how could you possibly test that? I mean, just think about it. What test could you use to find out if someone has a "dark sense of humor"? Is there even a definition of "dark sense of humor"? And show me someone who *doesn't* like music!

Also, astrologers don't tend to follow any kind of method that is remotely scientific, in the sense we discussed in Section 1.4. Granted, scientists don't always agree on the "right" method themselves; but they do expect *some* kind of method. For example, although astrologers do have the Astrology Hypothesis, and they do use this hypothesis to make predictions about events and conditions in the world, they don't follow up on those predictions to see if they ring true. They don't *check*. And most importantly, they don't go back and throw out the original hypothesis if the tests do not support it.

For these reasons and others, most scientists object pretty strongly to astrology. It claims to be a science, but it isn't. It doesn't play by the rules.

1.7 Science, Art, Religion, and Other Ways of Knowing

Science differs from other human endeavors, like the arts, philosophy, or religion, not so much in *what* it studies, but in *how* it studies things. An artist for example may know every bit as much about native plants and trees as a biologist, but what the artist *does* with that knowledge will be very different than what the biologist does with it. Whereas the artist will use knowledge to *interpret* nature, and speak to the human soul, the scientist's job is specifically *not* to interpret nature, but rather to understand the various causes and effects that are seen in nature, and eventually to report that knowledge and understanding with as little personal bias or opinion and as much clarity as possible.

It is important to realize that the scientific method is not the only way of learning things; and scientific knowledge is not the only knowledge that is valid or worthwhile. Every poet *knows* which word is needed to complete their poem. Every musician *knows* which note or chord is required at each point in their composition. And yet neither of these is scientific knowledge. There is no way the scientific method could have told Emily Dickinson which word to use in a given poem; and yet she *knew*. No amount of scientific knowledge could have enabled Beethoven to know which notes were needed in his symphonies; and yet, he *knew*.

I won't tell you that you shouldn't believe in astrology, anymore than I would tell you not to believe in art, music, or religion. But I will urge you very, very, *very* strongly to *always* have a reason for believing something. Whether it is science, or religion, or astrology, make sure you know what your reasons are. Ask yourself: "Why should I believe this?" If your answer is, "Because the supporting factual evidence is overwhelming," great! If your answer is, "Because my heart tells me it's true," that's great too! If your answer is "Because I read it on the internet, and everything that appears on the internet must be true," then you might want to look a little more closely at your reasons for believing things. But the most important thing is to always be sure that the reason is there.

1.8 A Brief Introduction to the Universe

Imagine you go to visit a distant cousin whom you've never met. You go to their house, and while chatting with them you discover something extraordinary. Despite the fact that they are older than you are, this relative has never once been out of their house. In fact they've hardly ever even looked outside. They have only taken a casual glance out the window from time to time as they go about their life.

"Haven't you ever wondered who lives next door?" you ask. "Or what the downtown is like? There are other cities out there too, and countryside, and oceans. Haven't you ever wanted to know what's out there?" Your cousin just shrugs and says, "I guess I never really thought about it."

Well, the fact is if you've never taken the time to really look up at the sky, if you've never learned what a star is, or what the Milky Way Galaxy is all about, you're kind of like that distant cousin of yours. You see, the Earth is like your house; and it's got a really great view of the Universe! But what's the point of having such a great view of the Universe if you never bother to look at it or learn anything about it? Although only a few astronauts have been fortunate enough to leave the house and stand for a while on the front steps, astronomers have learned a lot about our neighborhood, and other neighborhoods as well. It's worth finding out what they've discovered!

Figure 1.1 The Hubble "Deep Field"
Each smudge of light in this photograph is a distant galaxy. The red and blue regions indicate the presence of what astronomers call dark matter, an unknown substance that does not appear in our telescopes, but which can be identified from its gravitational effects.
NASA and the Space Telescope Science Institute

So what is the Universe? What is it like, this "neighborhood" you've been living in all these years? That's our main task in this book—to introduce you to the Universe. As a preliminary, we're going to start with a brief tour, a trip through the cosmos; and what better way for that tour to begin than with the most familiar object in the sky: the Sun.

1.8a Our Front Yard: The Sun and the Solar System

The Sun is actually a star. It happens to be a lot closer than the stars you see at night, so it looks a lot brighter than they do. But otherwise it's pretty similar to most of them. Like all stars, it is made mostly of hydrogen and helium. Its temperature is about average for a star: 10,000 °F on its surface, increasing to perhaps 25 million °F in the center. In size it seems huge to us—you could fit more than a million Earth's inside of it! But as stars go it's only about average there too. Also like every other star the Sun generates energy by converting its own matter or mass into pure energy or light. Every second of every day the Sun converts some four-and-a-half million tons of itself into sunlight. *Four-and-a-half million tons!* Think about that! It's been doing this for a good 5 billion years already, and should continue for another 5 billion years. The Sun is what you might call "middle aged" for a star of its size.

The Sun is also the central object in what we call our *solar system*. The root of the word "solar" is "Sol," which is what ancient peoples called the Sun. "Solar system" means literally "system of Sol." The solar system includes all of the objects that are in orbit around the Sun, or that are in orbit around things that are in orbit around the Sun.

Now, one of the difficulties in trying to introduce people to the Universe for the first time is the sheer scale of everything. The Universe is *so big*, that it can be really difficult to grasp. One way I've found that seems to help is to tour the Universe as if you were traveling along with a beam of light. So let's do that. And since we're starting with the Sun, we'll follow a beam of sunlight as it leaves the Sun's surface and travels first through the solar system, and then out to the stars and beyond.

First of all, you need to know that all light travels at a very definite speed through the emptiness of space, a very fast speed. In fact, the speed of light is the fastest speed that is allowed in our Universe. It is usually abbreviated with the letter *c*, and has this value:

$$
\begin{aligned}
c &= 300{,}000 \; km/s \\
&= 186{,}000 \; miles/s \\
&= 670{,}000{,}000 \; miles/hour
\end{aligned}
$$

This means that light travels a distance of 300,000 kilometers (km) in one second (*km/s* means "kilometers per second"), or equivalently 186,000 miles in one second, or if you prefer 670,000,000 miles in one hour. That's 670 *million* mph! That's fast! Since this speed has such a well known value, astronomers actually use it to measure distances. We'll see how this works at the same time that we take our tour of the Universe.

The first object we'll come across as we follow the sunlight away from the Sun is the planet Mercury, the closest planet to the Sun. Mercury's average distance from the Sun is 60 million km (37 million miles), which means that the sunlight that leaves the Sun in the direction of Mercury will take 3 minutes and 20 seconds to get there. This means you could either say, "Mercury is 60 million km from the Sun," or you could say, "Mercury is just over three *light-minutes* from the Sun." One *light-minute* is a measure of *distance*. It is the distance that light travels in one minute, and Mercury is about three times this distance from the Sun. Although you won't hear them talking about "light-minutes" very often, astronomers do prefer to measure distances according to how far light will travel in a given amount of time. I can't really say why they prefer to do this; but I think once you've gotten used to it, you'll agree that it is a pretty good way to do things. Let's continue.

The next thing that sunlight encounters after passing Mercury is the planet Venus. Venus is a little less than twice as far from the Sun as Mercury is: 105 million km. At this distance light would take 5 minutes and 49 seconds, or 5.8 minutes, to get there from the Sun's surface. So if you like you could say that Venus is 5.8 light-minutes from the Sun.

After Venus comes our own planet Earth, the third planet out from the Sun, at a distance of 8.3 light-minutes (150 million km); and then Mars, which is 12.5 light minutes from the Sun, or 225 million km.

Mercury, Venus, Earth and Mars are sometimes called the "inner planets," since they are the closest to the Sun. They are more formally known as the *terrestrial planets*, which means literally "Earth-like planets." They are called "Earth-like" mainly because they all have essentially the same composition and interior structure. That is, they're all made of pretty much the same stuff: rocks and metals. Also, they are all similar in size. Earth is the largest of the terrestrial planets, but it's only about twice the size (diameter) of the smallest one, Mercury.

Although they are similar in many ways, the surface conditions on the terrestrial planets vary dramatically. Mars did once have liquid water on its surface, but it is now cold and barren, with an atmosphere far too thin to support life as we know it. Venus on the other hand has so much atmosphere that the sheer weight of it would crush you; and this thick blanket of atmosphere maintains the surface temperature at a toasty 850 °F. Mercury has no atmosphere at all, and with no blanket to trap the heat its surface temperature plunges from a daytime high of 800 °F to a low of –280 °F at night. To a vacationing tourist, these planets are anything but "Earth-like"!

As we follow the sunlight out beyond the orbit of Mars we encounter something known as the *asteroid belt*. If you saw the second Star Wars movie made by George Lucas' team, "The Empire Strikes Back," you'll remember the scene where Han Solo has to fly the *Millennium Falcon* through the perilous asteroid field, dodging back and forth and up and down with lightning reflexes to avoid the giant space boulders hurtling everywhere. Of course, that scene took place "long, long ago, in a galaxy far, far away," so it was never intended to depict anything in our own solar system. Nevertheless, it does portray most people's general impression of what our own asteroid belt must be like.

Alas, reality is somewhat less dramatic. The Star Wars asteroids themselves do look very much like our own, which are essentially boulders tumbling through space. What doesn't carry over to our own solar system is just how close together the asteroids are. The asteroids in the asteroid belt are typically more than a million miles apart. Far from having to dodge with lightning reflexes to avoid them, anyone flying through the asteroid belt would be lucky to even see one! It's always a little disappointing when fiction turns out to be stranger than fact. I'm glad to tell you that from what I've seen of the Universe it's more often the other way around.

Continuing our journey outward we encounter the four jovian or "Jupiter-like" planets: Jupiter, Saturn, Uranus, and Neptune. Here in the outer solar system the planets are much farther apart. The distance between the orbits of Jupiter and Saturn is 10 times the distance between the orbits of Earth and Mars, and the other jovian planets are even farther apart. The jovian planets are about as different from the terrestrial planets as it is possible to be. Not only are the jovian planets much larger—you could fit 60 Earth's inside Uranus[1], and more than 1,000 Earth's inside Jupiter; they are also completely different kinds of objects. Whereas Mercury, Venus, Earth and Mars are all made of rock and metal, Jupiter and Saturn are made mostly of hydrogen, and Uranus and Neptune contain more water and methane than anything else. None of the jovian planets has a solid surface. If you tried to land on any of them it would be like trying to land on a cloud.

Another thing that makes the outer solar system different is the number of moons out here. Of the four terrestrial planets, only one—Earth—has a significant moon going around it; whereas there are six large moons in the outer solar system, two of

1 This statement is but one of many that make it clear why astronomy instructors generally prefer the pronunciation "YUR-a-nus" to the more common "yur-A-nus;" but you're welcome to use whichever you prefer.

light-year

A measure of distance equal to the distance that a beam of light would travel in one year's time.

which—Ganymede and Titan—are even larger than Mercury. At last count there are more than 200 moons, or natural satellites as astronomers often call them, orbiting the jovian planets.

When we reach Neptune we have reached the most distant planet from the Sun. Sunlight takes 4 hours and 9 minutes to reach Neptune, so we would say that it is just over 4 *light-hours* from the Sun. (Are you starting to get the idea of how to measure distances with light travel time?) But the solar system does not end there. Beyond Neptune, out to a distance of approximately 14 light-hours, there are literally billions of chunks of ice and rock tumbling around in a region known as the *Kuiper Belt* (pronounced "KY-per"). Most of these objects are known commonly as *comets*. Comets spend most of their time way out at the furthest reaches of the solar system. Occasionally one of them falls towards the Sun and makes a quick fly-by through the inner solar system. As it nears the Sun it begins to sublimate, a process very much like evaporation. When the comet sublimates a long tail is formed streaming out from it in the direction away from the Sun. It is this image of a comet that is probably most familiar to you, but you should keep in mind that it's a comparatively rare experience for the comet itself.

One very large chunk of ice and rock known to exist beyond Neptune deserves some individual attention. It is familiarly known as Pluto, and when it was discovered in 1930 it was claimed to be the ninth and most distant planet. It does have many characteristics one would associate with a planet. As I just mentioned, it's larger than almost everything else beyond Neptune, and it is clearly orbiting the Sun. It even has several moons going around it! However, its orbital path is strange, not like the other planets; and although it is larger than any known comet, it is very small for a planet. In fact, if it were in orbit around a planet, it wouldn't even be considered a large moon. Largely because of its small size, Pluto was removed from the list of planets by the International Astronomical Union in 2006. Since then, it—along with several other large but not large enough objects in the solar system—have been classified as *dwarf planets*.

As our sunlight continues beyond the Kuiper Belt it will encounter little else for awhile. But astronomers do believe that before the light leaves the solar system entirely it will come across a second vast collection of comets that live in a region known as the *Oort Cloud* (pronounced "ORT"). Unlike the Kuiper Belt, in which the comets orbit the Sun in more or less the same flat plane in which the planets, moons and asteroids orbit, the Oort Cloud forms a broad spherical shell that surrounds everything else in the solar system. There are at least as many comets out here as there are in the Kuiper Belt—perhaps many more; but they are much, much farther from the Sun. Our beam of sunlight would take as much as a *year* to reach the most distant ones. In other words, the Oort Cloud extends out to a distance of a **light-year**—the *distance* that light would travel in one year. Remember that light travels 186,000 miles every *second*. A light-year is a very, very long way—at least by human standards! (In more familiar units a light-year is about the same as six trillion, or 6,000,000,000,000 miles.)

As far as we know, the comets of the Oort Cloud mark the distant edge of our solar system, as they are the most distant objects to be significantly influenced by the Sun's gravity. After traveling for an entire year, our beam of sunlight will finally leave the solar system as we know it.

1.8b Our Home Town: The Milky Way Galaxy

What does our beam of light encounter when it leaves the solar system? In a word: nothing. The light has now reached the realm known as interstellar space, and for a long time it will encounter nothing but empty space. During the entire second year of its trip it won't encounter anything at all. Nor in its third year. The light will have to travel for more than four years before it reaches anything new. Four years and 88 days after leaving the Sun—at a distance of 4.24 light-years—the sunlight will finally reach the distance to the Sun's nearest neighbor, a small star, not very luminous, known here on Earth as Proxima Centauri. Proxima Centauri, whose name can be translated from Latin as "nearest [Proxima] star in the constellation of Centaurus [Centauri]," is known to have at least two planets in orbit around it, so it has its own planetary system, just as the Sun does.

Beyond Proxima Centauri the light beam will encounter lots more stars, and lots more empty space. Since stars are typically several light-years apart, it will take our beam of light several more years to reach the next star, another several more years to reach the star after that, and so on. What is happening is that our light beam is making its way through a vast collection of some 100 billion stars (that's 100,000,000,000) that make up our *Milky Way Galaxy*. The stars of our galaxy are spread out in a huge flat spiral pattern, known as the *disk* of the Galaxy, that is centered around a densely packed central region known as the *bulge*. In the very center of the bulge, in the region known as the *galactic center*, lies an incredible hole in space and time, an object known as a *black hole*. (More on black holes later!)

Our solar system, which is the merest speck in comparison to the vastness of the Galaxy, is situated in this disk, about a third of the way out from the center. Returning to our analogy from earlier on, if the Earth is our house and the solar system is our yard, then the Galaxy can be thought of as our home town. The galactic center is downtown. We live out in the suburbs.

Along with the stars, our galaxy also includes lots and lots of huge clouds of gas, known as *nebulae* (singular is "nebula"). Some of these are created when stars end their lives in cataclysmic explosions known as *supernovae*. Others are in the process of creating new stars. You've probably seen posters or calendars with photographs of some of the more spectacular nebulae. They are definitely some of Nature's most beautiful and dramatic artwork!

How long will it take our beam of sunlight to traverse the disk of the Galaxy? Well, it depends on which direction we choose to go. As I just mentioned, the Milky Way is in the shape of a more-or-less flat disk. That disk is some 1,000 – 3,000 light-years thick, depending on where you measure it, and roughly 150,000 light-years in diameter. Of course, the quickest way out of a disk is to go in a direction that is perpendicular to the disk—like going up or down out of a pancake. If we do that then our light beam will take something like 1,000 years to leave the disk. On the other hand, if you're not in a hurry and you want to take the scenic route, we could follow the beam of light as it travels through the disk, towards the bulge and the galactic center, and out the other end. If we do that, provided it misses the black hole at the center, our sunlight will emerge from the other end of the disk of our Galaxy some 101,000 years from now. (Why 101,000? Well, to get that number you have to do a little mathematics—but only a little! It goes like this: If the disk of our galaxy is 150,000 light-years in diameter, then the *radius* of the disk—the distance from the center out to the edge—is half of that, or 75,000 light-years. I mentioned a moment ago that we are about a third of the way out from the center. Specifically, the center of the Galaxy is about 26,000 light-years from where we are now. So our sunlight, if we follow it across the entire disk, will take 26,000 years to get to the center, and then another 75,000 years after that if it continues all the way out to the furthest edge. 26,000 + 75,000 = 101,000. Got it?)

Now think about that before reading on. Light, traveling at a speed of 186,000 miles every single second, would still take 150,000 years to go from one end of our Galaxy to the other. That's a long, long way! Which means that our Galaxy is a very, very, *very* big place!

1.8c Distant Lands: Galaxies and Quasars

As it leaves the Milky Way, our beam of light emerges into a vast expanse of emptiness that seems endless to the human mind. This is the realm of intergalactic space, the space between the galaxies. You see, our Milky Way is not the only galaxy. Not by any means! But the distances out here are truly immense. Our beam of light will be "on the road" for more than 2 million years before it reaches our nearest neighbor galaxy, the great galaxy in Andromeda.

The Andromeda Galaxy is also a spiral galaxy, a little larger than our own. You can see it with your naked eye, in fact, and it's a very beautiful thing to see. Faint, but beautiful. It also happens to be the only thing that you can see from the northern hemisphere that is *not* a part of our own galaxy.

As we continue to follow our light beam beyond the Andromeda Galaxy, we find that there are literally billions of other galaxies out here, most of which contain many billions of stars. Many of them are also spirals; others are known as *elliptical galaxies* because of their even, round, symmetrical shapes; still others, known as *irregular galaxies*, have no familiar shape at all, but are just big blobs. Also scattered about through intergalactic space are what might be called the "extreme galaxies"—Seyfert galaxies, radio galaxies, and quasars. These are objects whose light comes not from stars, but mostly from material falling into black holes so powerful they make the one that hides in the center of our galaxy look like a toy by comparison.

The most distant galaxies and quasars in the Universe are some 13 billion light-years away. In other words, the light we are now seeing from these objects has been traveling through space for 13 billion years. When that light was first created and began its journey, a journey that would ultimately end at the focal point of one of our telescopes, neither the Earth nor the Sun yet existed. In fact, that light had already completed more than half of its trip by the time the Sun had emitted its first light. When the last tyrannosaurus rex fell here on Earth some 65 million years ago, the light from the most distant quasars was more than 99% of the way here.

What this means, of course, is that the light we are seeing today from those distant objects was created when the Universe was a lot *younger* than it is today. Or to put it more bluntly, the Universe that we are looking at when we point a telescope at a far off quasar is a lot younger than the Universe we are living in here on Earth. Do you see why? If you look at a quasar that is 10 billion light-years away, then since the light from that quasar has taken 10 billion years to get here, the quasar that you are actually seeing in your telescope is a 10 billion year old quasar. That is, you're seeing the Universe as it was 10 billion years ago. You could say that the Universe "out there" is a lot younger than the Universe here where we live.

Now imagine that you look *beyond* the most distant galaxy with your telescope. What would you see? Well, you may not see anything, since there may not be anything to see. But the space you are looking into is even younger than where the galaxy is. The farther out into space you look, the farther back in time you are looking. As you look farther and farther out into space, you are seeing the Universe at earlier and earlier times, when it was younger and younger. So telescopes are almost like time machines. They don't allow us to travel back in time, but they do allow us to *see* back in time.

1.8d How Big Is the Universe?

If you've followed the reasoning of the last paragraphs, you will be able to answer for yourself one of the most popular questions people have about astronomy: How big is the Universe? Think about that question for a moment and see if you can glimpse the answer. Can you see first of all that the greatest distance we can see is not a limit of space, but of *time*? To ask, "How far can we see?" is to ask, "How far back in *time* can we see?"

Here's how the reasoning goes: When you look at a star that is 10 light-years away, you are seeing light that is 10 years old since the light has been traveling through space for 10 years to get here. Likewise, when you look at a star that is 1,000 light-years away, you are seeing light that is 1,000 years old. When you look at a quasar that is 10 billion light-years away, you are seeing light that is 10 billion years old.

Now imagine that you are looking at the most distant object that we can possibly see. In that case you are looking at light that is as old as light can possibly be. And that's where the real limit appears. You see, there is no limit to how *far* we can see, but there *is* a limit to how old light can be, since *light cannot be older than the Universe itself*. If the Universe is 14 billion years old, which is a pretty good estimate based on current information, then no light that is reaching our telescopes can be any more than 14 billion years old. To be older than that, the light would have had to have been created before the Universe was created. And that's impossible! But if light cannot be older than 14 billion years, then it cannot have been traveling through space for more than 14 billion years. *And that means that the greatest distance it could have traveled is 14 billion light-years.*

So the furthest distance we can see is not limited by our telescopes, it's limited by the age of the Universe itself. But have you noticed the really weird part of all of this? Ask yourself: What would we see if we could see out to a distance of 14 billion light-years? The answer is clear: We would see light that has been traveling through space for 14 billion years; which means we would see light that was created 14 billion years ago; which means we would see the light from the actual creation of the Universe. We would see the Universe being created, all around us! And that is exactly what we do see. We are surrounded by the creation of the Universe, and it's going on right now, even as you read this book. Now that's something to think about!

Key Terms

astronomy, pg. 1

deductive inference, pg. 3

falsifiable, pg. 2

hypothesis, pg. 5

inductive inference, pg. 3

inference to the best explanation, pg. 4

light-year, pg. 14

scientific method, pg. 7

theory, pg. 5