The Universe: Size, Shape, and Fate

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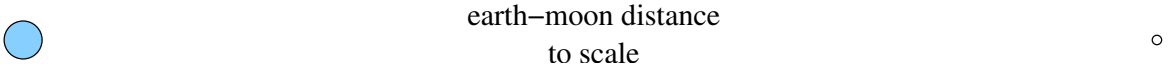
1 The Scale of the Universe

Our universe extends staggeringly far beyond our own earthly environment. Trying to grasp the size in any meaningful way is bound to make your brain hurt. We can make analogies to at least understand a few of the relevant scales, but this can't give us a complete picture all in one go. In the end, we must settle for an understanding of large numbers, aided by the tool of scientific notation. Modern astrophysicists don't walk around with a deeply developed intuition for the vast scale of the universe—it's too much for the human brain. But these scientists *do* walk around with a grasp of the relevant numbers involved. As an example, here are some of the numbers I carry in my head to understand the universe's size:

- A lecture hall is approximately 10 meters across, and light travels across it in about 30 nanoseconds. We will be using light, which travels at 300,000,000 meters per second to quantify distances.
- The earth is 6378 km in radius, and light would travel seven times around the earth in one second if it could travel in a circle like this.
- The moon is about one-quarter the diameter of the earth, and is 1.25 light-seconds away—corresponding to about 30 earth diameters.



- The sun is 109 times the diameter of the earth, and about 8 light-minutes away (this is 1 "Astronomical Unit," or A.U., and is about 150 million km).
- Jupiter is about 40 light-minutes from the sun (5 A.U.).
- Pluto is about 40 A.U. from the sun, or about 5.5 light-hours out.
- The next star is 4.5 light-years away—take a moment to appreciate this big jump!
- The center of the Milky Way (our galaxy) is about 25,000 light-years away. A galaxy is a gravitationally bound collection of stars: islands of stars—many of which make up the universe.
- Large galaxies like our own are about 100,000 light-years across.
- The nearest external large galaxy is the Andromeda galaxy—about 2 million light-years away (20 galaxy diameters).
- The nearest large cluster of galaxies (Virgo Cluster) is about 50 million light-years away.
- The edge of the *visible* universe is about 13.7 billion light years away.

As you can see, the range of scales is too huge to be described all at once by a single measure. We went from small fractions of a *light-second* (light crosses the lecture hall in 0.00000003 seconds, and can cross the U.S. in about 0.01 seconds) to huge quantities (billions!) of *light-years*. In total, going from the lecture hall to the size of the visible Universe takes us through 25 orders-of-magnitude (factors of ten). At best our puny brains are capable of comprehending maybe 8 orders-of-magnitude directly (1 mm grain of sand to 100 km scale visible from mountain-tops). Outside this direct experience, we rely on the numbers to convey the relative scales.

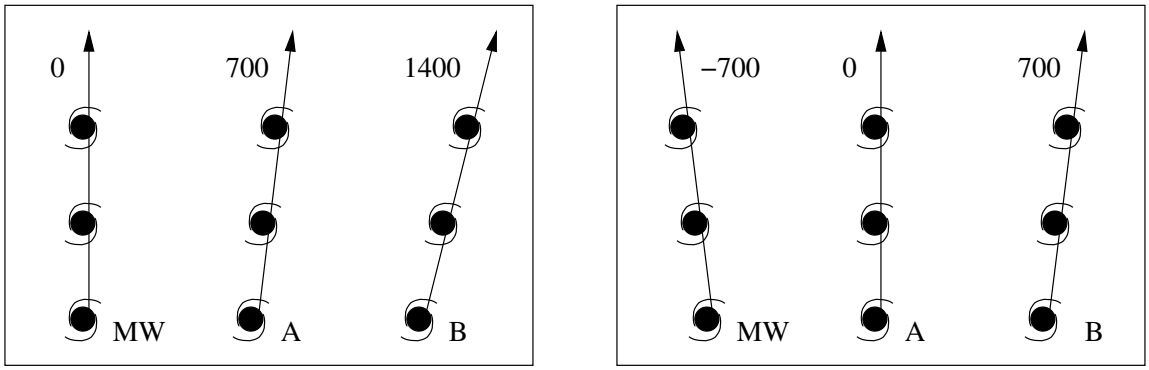
2 What Do We Know About the Beginning?

What we see when we look into the universe today is the illusion that all galaxies are hurtling away from our own, as if we were sitting at the center of some momentous explosion. The farther the galaxy, the faster its apparent recession from us. This effect is seen in the wavelengths (colors) of light from distant galaxies. Wavelengths from receeding galaxies are shifted toward the red ("redshifted") by a precisely measureable amount—analogous to the Doppler shift we hear in the pitch of an ambulance racing past. The farther the galaxy, the greater the redshift, and thus the faster it is moving away. As an aside, this expansion rate is characterized by the Hubble Constant, 70 km/s/Mpc. These strange units mean for every megaparsec (Mpc, or 3.26 million light-years) we go away, galaxies are receding by another 70 kilometers per second.

There are two illusory aspects to this astounding observation (first recognized in the 1920's). The first is that though we appear to be at the center of the expansion, we are not. Every galaxy would make the same claim. Think about it this way. We look at galaxy A 10 Mpc away, receding at 700 km/s. Straight beyond galaxy A is galaxy B, 20 Mpc away, receding at 1400 km/s (Figure 1). Imagine standing on a planet around a star in galaxy A. In one direction, you can look back and see our galaxy, the Milky Way. On the opposite side of the sky you see galaxy B. Both are 10 Mpc away, and both appear to move *away* from you at 700km/s. So on galaxy A, it also appears that all galaxies recede from *you*. Two good analogies help illustrate this concept. For the first, imagine galaxies drawn on the surface of a balloon, and the balloon being blown up. As the "fabric" of the balloon stretches, galaxies move farther away. The farther, the faster. To each, it appears to be at the center of the expansion. But there *is* no center (here we confine our thoughts to the surface of the balloon—unaware of the three-dimensional center of the spherical balloon *we* can see). The second analogy is that of a baking raisin bread. Now imagine the raisins to be galaxies, and the bread is space itself. Again, each raisin sees all others moving away from it, and the farther the raisin, the faster it appears to move away. But there really is no center (forget that the bread has edges, or that it's in your oven).

The second correction to the statement that "we see galaxies receding with an ever-increasing velocity as we go farther" is subtle. But the correct picture is not that galaxies are whizzing out into a pre-existing, empty space. The right way to look at it is that space itself is being created/expanded between the galaxies. The galaxies are simply along for the ride, being carried in the expanding space. Here, the raisin bread analogy is particularly useful. The raisins (galaxies) are not zooming through the bread (space), but rather the bread (space) itself is expanding. This picture ultimately agrees better with observation, and is consistent with the predictions of general relativity. Space itself is being "created" as the universe expands.

It doesn't take a great leap of imagination to consider that if space is expanding in all directions, it used to be smaller. Galaxies used to be closer. How far do we carry this back? We can make the bold statement that maybe we should carry it to the extreme—to a time when the whole universe was smaller than a grain of sand. This seemingly preposterous extrapolation is, surprisingly, supported by observations. If the universe were once this small, it would also have been so very hot that even protons and neutrons would have been evaporated into quarks. If we play this game—knowing what we do about particle physics from our accelerator experiments—we can **predict** the relative abundance of the light elements that would have frozen out of this quark soup as the universe expanded and cooled. This simple (in concept) game actually gets the story **right**! It predicts the abundances of hydrogen, helium, lithium, etc. that we see in the primordial gas clouds that still surround us. Other predictions likewise work with this scenario (cosmic



From Milky Way (MW) perspective

From galaxy A perspective

Figure 1: The same motions of the Milky Way, and two galaxies labled A and B. The frame on the left shows both galaxies receeding from MW, B traveling faster than A. From the perspective of galaxy A, both B and MW move away at the same speed.

microwave background radiation, ages of oldest stars). This model of the beginning of our universe is called the Big Bang model, and has gained nearly universal (forgive the pun!) acceptance among scientists.

3 How Big is the Universe, Really?

This simple question has a somewhat complicated answer that may involve new ways of thinking, but we'll try to get to the bottom of the issue. To start, I note that the universe is largely made up of space. By space I mean vacuum—emptiness—nothing. Though we have galaxies of stars littering our skies, even these have lots of empty space in them. On the whole, if you smeared out all the atoms in the universe uniformly, you would end up with less than one hydrogen atom per cubic meter. That's sparse! Even in our locally dense galaxy (most of the universe is space *between* the galaxies), stars are like grains of sand several miles apart!

Since the universe is mostly empty space, it is appropriate to talk about the nature and extent of the universe in terms of the nature and extent of space itself. Here is where things start to get weird. We all picture space as being three-dimensional and *flat*. By flat, we mean Euclidean. By Euclidean, we mean that all the properties of geometry we learned about in high school apply. These are statements like: parallel lines remain parallel forever; the angles in a triangle add to 180°; space is infinite in extent. Such statements appear to be valid in our daily experience.

This picture of flat space formed the backdrop of physics throughout the Newtonian era. Einstein changed this when he suggested two radical ideas:

1. Time must be included in our description of space into a unified concept of *spacetime*. Time and space mean different things for observers moving with respect to each other, becoming inextricably mixed. This is the subject of special relativity.

2. Spacetime may be *curved*—there is no requirement for flatness. What's more, the presence of *mass* curves spacetime. This is the subject of general relativity.

Is nothing sacred? Apparently not. These concepts truly re-shaped the way physicists think about space. Not surprisingly, the description of the nature of the universe (the size and shape of space) is profoundly impacted by this paradigm.

In addition to local spacetime curvature due to masses (stars, galaxies) within the universe, there may be a global curvature that apples to the whole of the universe. It is next-to-impossible to imagine in your head what it would mean for all of three-dimensional space (actually, 4-dimensional spacetime) to be curved.

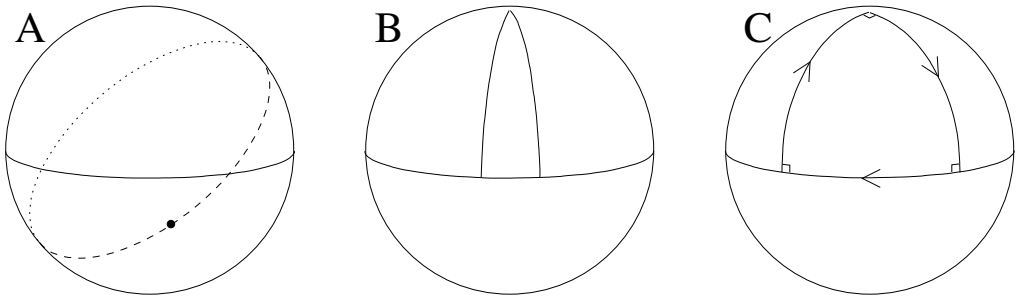


Figure 2: Ant experiments on a sphere: A) the straightest line possible—a great circle—comes back on itself; B) Initially parallel tracks eventually converge; C) A straight line triangle on a sphere has angles that add to more than 180°, in this case 270°.

Curved into what? But we have some lower-dimensional analogies to help us appreciate what this might look like.

3.1 A Two-dimensional Analog

Imagine you are an ant living on a basketball. You can only move around on the surface, so that you essentially live in a two-dimensional space. Another way to say this is simply that the basketball surface (texture notwithstanding) is a two-dimensional surface existing in our three-dimensional space. This third dimension allows us to see what the ant cannot. If the ant makes a smelly deposit on the surface and runs away in horror, it will ultimately come back on the surprise, though never deviating from a straight line. We call this straight line a great circle (see Figure 2A), because to our three-dimensional eyes, we can see that the path of the ant through three-dimensional space is a circle (like an equator). To the ant, the line was straight as could be. No matter what direction the ant chose to run in, the result would be the same as long as the ant kept to a straight line. So this space is finite: it does not go on forever.

The next experiment the ant attempts is to walk parallel to another ant. They both start out side-by-side on the basketball's "equator," and agree to walk "north." Once they decide this, they start out walking parallel in the north direction, but agree not to look at each other—just their compasses. Some time later, they bump into each other. Each suspects the other of deviating, while knowing that they themselves did not. In fact, neither deviated from a straight line (Figure 2B). But Euclid's relationships don't hold on this curved space. Parallel straight lines will always converge on a sphere. In this case, the convergence would be at the "north pole." (Take a look at how the lines of longitude converge at the north pole of a globe, despite starting out parallel at the equator and each representing perfectly "straight" great-circle paths.)

The last experiment the frustrated ant tries is to verify that the three angles inside a triangle add to 180°. The ant starts at the north pole, walks in a straight line south to the equator, turns right (90°) to follow the equator, walks a quarter of the way around the equator, then turns right again (90°) to head back to the north pole. On reaching the north pole, the ant finds that the angle that its current path makes to the original path from the pole is 90°, so that the three interior angles of this "straight-line" triangle add to 270°—much bigger than the expected result (Figure 2C).

The lesson is that the rules of Euclidean geometry don't hold on curved spaces. The analogy to our universe is as follows. If our universe has so-called positive curvature, then any straight line ultimately comes back on itself, parallel lines ultimately converge, and angles within a triangle add to something greater than 180°. Now it should be pointed out that had the ant on the basketball performed the triangle (or parallel line) experiment over a very small and confined region of the basketball, Euclidean geometry would have appeared to work to a high degree of precision. By analogy, the earth looks pretty *flat* over small distances.

We know that the universe is very large—because we see new and different stuff in every direction for a long way. So in our tiny local region, things look pretty flat. But is the large-scale universe curved? This

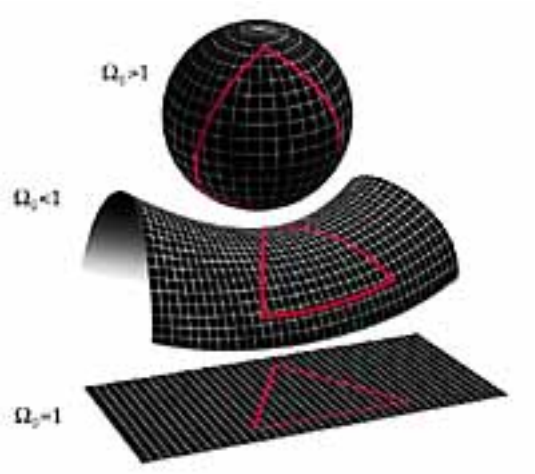


Figure 3: Possible geometries of the universe, in two-dimensional analog.

has been an open question in cosmology, and we're finally gaining some resolution.

3.2 Types of Curved Universes

To motivate more concretely the notion that the universe is curved, I mentioned above that Einstein's theory of general relativity produces spacetime curvature—in fact, it produces *positive* curvature—like that of a closed sphere. So the question of "how much curvature" boils down to "how much matter is there in the universe?" We know that the universe is expanding, based on galaxy redshifts. Since matter is gravitationally *attracted* to itself, the presence of matter in the universe may be sufficient to slow—even halt and reverse—this expansion. In other words, the presence of mass applies brakes to the expansion. But is there enough matter present to halt the expansion? Enough to reverse it? In a universe that contains only gravitating matter and empty space, the question of the fate of the universe and the type of curvature are intimately related.

A universe with more than enough matter in it to halt the expansion has enough matter to make it *positively* curved on the whole. This type of universe would wrap back onto itself. Like the ant traveling in a straight line and coming back to the same spot, so we would come back to earth if we flew a straight line in a rocket for a very, very long time. Other properties of positive curvature would also be present: parallel lines would eventually converge, and triangle angles would add to greater than 180° (the larger the triangle, the greater the deviation—like on the surface of the basketball). Besides these geometrical properties, this "closed" universe would ultimately turn back on itself and experience a Big Crunch when it all came back together. Figure 3 shows the possible geometries, with the closed geometry on top.

On the other extreme, if the amount of matter in the universe is insufficient to halt the expansion, the resulting geometry has a net *negative* curvature. This is harder to visualize, but the properties are that it goes on indefinitely (you would *not* wrap back on yourself if traveling in this space), parallel lines now *diverge*, and triangle angles add to *less* than 180°. The best visualization I can offer here is that of a Pringle's potato chip: saddle-shaped. This kind of surface has all the right geometrical properties, if for instance an ant were to do similar experiments to what it did on the sphere. The only catch is that you have to imagine a Pringle of infinite extent (yum). The negatively curved universe is said to be "open," as it is infinite in extent, and will never re-collapse. It will continue to expand forever. The existence of matter may slow down (decelerate) this expansion, but it will never be enough to stop it.

Precariously balanced between these two extremes is a *flat* universe. A flat universe has just the right amount of matter to exactly balance the expansion, so that ultimately the universe's expansion will exactly stop (as time marches toward infinity). In this case, there is no net curvature, and Euclidean geometry holds across the infinite extent of the universe. Though seemingly impossibly tuned to have just the right amount

of matter (not a teaspoon more or less), this has been a favorite of theoretical cosmologists because they think this condition would have been automatically satisfied the *way* the universe started.

If the universe is *close* to being flat, but not precisely so, then it has some net curvature, but this curvature may be hardly noticeable. This is analogous to saying that the effects of earth's curved surface are not very noticeable over small scales (like on a soccer field), while the soccer ball is very noticeably curved. In other words, a universe that is positively curved, but very large, will appear pretty flat on the small part we can see. It is very difficult to unambiguously tell the difference between these scenarios through our observations of the universe—though we have been surprisingly successful at setting limits on this curvature using the CMB.

3.3 Geometry Summarized

If the universe is composed *only* of gravitating matter and the empty space in between, then the *geometry* of space—positive curvature, flat, or negative curvature—is intimately connected with the *amount* of matter in the universe. This is also then connected with its fate. A nice verbal relationship exists to sum this up: a positive-curvature universe is said to be closed (finite) and is both finite in spatial extent (wraps back onto itself) and in the time domain (will ultimately re-collapse). A negatively curved universe is said to be open, and extends infinitely in both time and space. The flat case is a special, limiting case of the open scenario—it too is infinite in extent and will go on forever in time, but only just so.

4 The Universe As We See It

In an effort to determine the matter density of the universe, and thus its ultimate fate and geometry, astronomers for many years pursued a measurement of the deceleration of the matter in the universe. The logic was that if any matter existed at all (and clearly it does), the net gravitational effect between all bodies in the universe would apply the brakes to the expansion, slowing down its rate. The effect is relatively small, and it took a very long time to be able to make any measurement. Finally, in the late 1990's, two independent teams of physicists and astronomers had managed to make a measurement using the light from a special type of supernova (exploding star) thought to act as a "standard candle"—having the same intrinsic brightness no matter when and where in the universe it happened. The result they found was startling. The data that stared them in the face proclaimed that the universe is actually *accelerating* presently! It's as if the balloon is being blown up more rapidly today than yesterday. Nobody (well, practically nobody) had anticipated this possibility. But this provides an example of the triumph of measurement over theory. You can't argue with measurement. (Well, you can, actually, and should. You should make sure the measurement is valid and that you aren't being fooled by other effects that you have not yet considered. And believe me, this surprising data has been challenged extensively.) In a moment of severe whiplash in the astronophysical community, we suddenly had a huge mystery on our hands. If the universe is accelerating, what's pushing it apart? Why isn't gravity working like we thought it should?

These sorts of challenges crop up in science from time-to-time, forcing its practitioners to take a hard look at their fundamental assumptions. This is a very healthy process, and it gives me great hope in humanity that we, as humans, do not cling maniacally to a dearly held belief when new evidence points to the contrary. Lest you think that these revolutions "undo" any of the previous measurements and experience from the past, let me assure you that the entire body of measurement and observation stands. The revolution is on the side of theory, whose job it is to explain the collection of empirical data in a self-consistent way. These revolutions typically make it clear that we simply didn't have the full theoretical picture, or that we can't get away with an over-simplified view.

Around the same time as the discovery of the universe's acceleration, astrophysicists looking at the afterglow of the Big Bang (called the cosmic microwave background: CMB, or also the surface of last scattering) were intent on measuring the shape of our space. They could do this because they could predict in great detail what kinds of structures existed at this stage in the universe's development, when it was

only 380,000 years old. By structures I just mean temperature variations (departures from uniformity)—or "structure" in the density/temperature of the early plasma. They knew, in effect, how large the largest structures could have become in that time—in real units like meters! Given this, and also armed with the knowledge of how far the surface of last scattering is, the apparent angular size of these blobs on the sky then tells us what kind of geometry we live in. Are we drawing this long, skinny triangle on a positively-curved space, like a basketball, on a negative potato-chip, or in plain Euclidean flat space. The answer—much to the delight of many theorists—came out to be that space is flat. If we quantify this in terms of the amount of matter required to make for a flat universe, the answer came out to indicate the critical density within 2%. In other words, if the universe had too much stuff, it would have positive curvature. Too little stuff and it would have negative curvature. We appear to be in the "just right" scenario, to pretty high precision.

A third leg of evidence supported both by measuring masses of huge clusters of galaxies, and also from secondary "structure" in the CMB indicates that the universe only has 30% of the *gravitating* matter necessary to flatten the universe. How could this be consistent with the previous CMB finding that we were within 2% of the magic value? The answer is in the subtle use of the word "gravitating" above. It turns out that 70% of the total mass-energy (i.e., stuff) in the universe is of a non-gravitating form. We call this "dark energy" because we can't see it, it's not matter, and we frankly have no idea what the stuff is. But it's the stuff that is responsible for the acceleration of the universe—it's pushing us apart.

Thanks to astrophysical measurements, we now know exactly how much dark energy, dark matter, and ordinary matter exist in the universe. But we still don't know what any of the "dark" stuff actually is. Ideas abound, but no one pays close attention to ideas unless they suggest additional tests or measurements that can support or refute them.

5 What Does It All Mean?

This is mind-blowing stuff, to be sure. We're talking about the geometry of space, and suddenly we find out that it is indeed flat, but that there are constituents in the universe that we know very little about. It's confusing, and may sound even absurd (more like fantasy or science fiction than science). But scientists are serious about this. It's hard to drag along a skeptical bunch like scientists on a wild ride like this without an awful lot of experimental evidence. Many scientists are still uncomfortable with this surprising new landscape. But almost all acknowledge that we're faced with striking measurements that will likely radically change our fundamental understanding of what makes up the universe.

To talk concretely about the meaning of these observations, let me answer some common questions:

5.1 Is the universe infinite in extent?

If the geometry of the universe is indeed flat, as we measure it to be, then yes: the universe goes on forever. This doesn't mean that we can see the whole universe, though. We can only see about 13.7 billion light years away in any direction.

5.2 So the universe is finite if we can only see so far, right?

These are unrelated things. Because light travels at a finite speed (albeit fast), when we look far away, we look back in time. When we look 13.7 billion light years away, we see the universe as it existed near the time of its birth. There are no stars or galaxies there yet. A being sitting at that point in the present day would find themselves in a setting that looks much like the one around earth today. If they looked back toward earth, they would see our local environment as it was 13.7 billion years ago—long before the sun or even our galaxy formed. We would be the limit of their vision: the edge of their visible universe; their CMB. You could play this game forever: at each horizon edge, the universe looks normal, and there is a new horizon in all directions. Imagine the universe as a huge ocean. In the ocean, you can only see so far due to the cloudy water (maybe several tens of meters). It doesn't mean that stuff doesn't exist outside of the visible horizon.

5.3 If we can look 13.7 billion light years away, shouldn't we see the Big Bang?

Yes! And in fact, we do! Only light isn't free to travel through empty space until all the electrons are moved out of the way. So as the hot plasma emerging from the Big Bang cooled, ultimately things settled out enough so that electrons could pair up with Hydrogen and Helium nuclei, so that the plasma became neutral. Now light could stream freely across the universe. This is what we see in the CMB: it is the plasma afterglow of the Big Bang, seen about 380,000 years after the universe started—just cool enough to have become neutral. We see it in every direction 13.7 billion light years away as an almost perfectly uniform microwave glow. Truly amazing, really.

5.4 If we know the universe is flat to 2% precision, is there room for error?

Absolutely. All we are prepared to say for now is that over 13.7 billion light year scales, the universe looks pretty flat: it doesn't deviate by more than 2% from being flat. But, the possibility exists that the universe is still curved on much larger scales. It's just like the fact that the earth looks flat locally, over small scales, but is curved on the whole. The universe could be closed into a sphere, but on a much larger scale than what we can see. A 2% limit translates to a factor of 50 (it takes 50 2%'s to make 100%), so we could say that if the universe is finite, it must be at least 50 times bigger than our 13.7 billion light year horizon.

5.5 What is the ultimate fate of the universe?

Ten years ago, the answer would have simply been that it depends on how much matter is in the universe. If the universe had critical density, it would expand forever, but eventually come to a stop infinitely far out into the future. But it was already looking like there was too little matter to do this, so the universe would expand forever. Now things are more complicated. Even though we think the universe is flat, it has too little gravitating matter to halt the expansion, and moreover, seems to have a dark energy that is accelerating this expansion. Under this scenario, the universe will in essence blow itself apart. But it takes a long *time* (tens of billions of years), so don't pack your bags yet.

5.6 Things seem uncertain now in cosmology. Is the fate of the universe also uncertain?

For sure it is. Until we understand what this dark energy is, we won't be able to predict with any certainty how it will evolve as the universe ages. If things don't change, the above scenario will hold. It's our best guess in the absence of a complete understanding. But as a consequence of the recent series of fantastic measurements, we can say more now than ever before about what we *think* will happen.

5.7 What does this mean for humanity? Why should I care?

Good question! Who asked that? You may not care. You may not find this to be relevant to your life. That's one of the great things about our lives: we get to choose what we are interested in, and pursue it. But in general, humans have always been curious about origins. Though not every human will be interested in dinosaurs, as a whole we are certainly intrigued, and have learned much from studying them. Science is the process of looking to our surroundings to see what we can learn about how we got here. Recent astrophysical observations are painting a rich story that we simply can't ignore. Nor do we want to. How it will affect humanity in the very long term is an open question. Does it change the way you live your life or treat others if you know that the universe is a transient thing?—that it will one day expand itself to oblivion? Does it change the frequency of religious wars on this planet if in 500 years we all share a common creation story? At this point, this is more complicated than predicting the fate of the universe. Humans are frighteningly complex!

6 Life in the Universe

I am no expert on life in the universe. There is a new and growing field of science called astrobiology that delves into the requirements for life, and explores the extremities in which life on the earth has been able to thrive. This direction of exploration may then define for us how likely it is that life—however simple—could exist on other planets, in comets, etc. But we can at least explore an aspect of the question of additional life in the universe based on what we know about the universe.

Does life exist elsewhere in the universe? Let's play the numbers game. Our galaxy is composed of roughly 100 billion stars. How many of these stars have planets? We're finding that quite a few do! We already know of over 100 stars aside from our sun that have at least one planet. As of December 2005, the numbers are: 146 planetary systems; 170 planets; 18 multiple-planet systems (as many as 4 in some systems). At present, we can only detect large Jupiter-like planets in orbits that are relatively close to their stars: these produce the strongest tugs on the parent stars, which is what we measure. But it appears that a substantial fraction of stars—at least 5%—have planets. As our detection techniques improve, we may find many smaller planets and find that indeed *most* stars have planets. Right now, we would not be able to detect our own set of planets around another star using current techniques. Yet we know we are here. This means solar systems much like our own are still beyond our detection limits. Putting the number of stars in our galaxy together with an estimate that 10% of stars have earth-sized planets (just a guess), we get that 10 billion stars in our galaxy alone harbor earth-like planets. By earth-like, I just mean rocky planets with masses comparable to earth's mass.

Not all of these earth-like planets will be in the "habitable zone" where we see life in our solar system. Example: Venus is too hot, Mars is too cold, though both are "earth-like" by the definition above. Let's say only 1% of these earth-like planets happen to be in the "Goldilocks" just-right zone. Now we have as many as 100 million habitable planets in our galaxy.

We don't know yet how rare life is. With only one planet to guide us, the estimates cover a huge range. But let's say for the sake of argument that the chances for life to form are a remote one-in-a-million given a habitable planet. Some would argue that it's closer to near certainty that life (we're talking single-cell organisms here) forms. But with the pessimistic long-shot odds of one in a million, that still gives 100 instances in our galaxy.

Now hold onto your seats. There are approximately 100 *billion* galaxies within our 13.7-billion-light-year horizon. So now we have 10 trillion instances of life in our universe given the harsh one-in-a-million odds. Hard to imagine this not panning out.

But wait, there's more. Our visible universe is but a small portion of the entire universe, as quantified in Section 5.4. We know the universe is *at least* 50 times the size of the visible universe within our horizon. But this is in linear size—radius, or diameter. In volume, the universe is then at least $50^3 = 125,000$ times larger in volume than our visible volume. Assuming physics looks the same outside our horizon, there are now about a quintillion, or 10^{18} instances of life in the entire universe, *as a lower limit*! Our estimates could be off here and there; they are very rough. But it is hard to reduce a number this big to zero (or one, since we're here, at least) by revising estimates of probabilities. The sheer size of our universe and the resulting number of stars and planets is so absolutely staggering so as to overcome the long odds for developing life.

One other aspect we haven't reflected on is the enormity of time over which life has to develop. We can't really easily grasp time periods longer than maybe 1,000 years. Yet it takes 1,000 of these periods to constitute one million years, which is still short on geological timescales. It would take 1,000 of these one-million-year periods to make one billion years. The universe is 13.7 billion years old, and we find fossil evidence of simple life on the 4.5-billion-year-old earth as far back as about 3.5 billion years. Interestingly, the earth was not very hospitable when it was young. It may have taken only (*only!!*) a few hundred million years for life to form once the earth was a calm and hospitable neighborhood. Even this geologically short period is sooooo long that it is truly impossible for our brains to take it in—much like how we started in comprehending the vast size of the universe.

Intelligent life is another beast altogether. It's a long road from simple organisms to pigs and things. But nature provides a self-ratcheting mechanism to constantly push the developmental arms race toward greater

complexity. I'm talking here about natural selection. But by now I have strayed far from physics, and should leave this topic for your continued ponderings.

7 Science, Religion, and Anthropic Ideas

Science often tackles the biggest questions—the questions humans have been asking since prehistoric times. Questions like: how did we get here? was there a beginning? will there be an end? are humans special? what is our place in the universe? for that matter, what *is* the universe? There are loads more, of course, but this set touches on the topics discussed in this paper. It's the chance to work on and think about these big questions that make science interesting and fun.

In prehistoric times—and even in *historic* times—we did not have the tools of science available to us the way we do today: no microscopes, telescopes, oscilloscopes, spectroscopes, stethoscopes. And other things besides 'scopes: radio-isotope dating, computational tools, precision electronic measurement tools, etc. So how did we answer these gripping questions before we had the tools to quantitatively explore? Religion. Almost every culture has an ancient creation story that tells not only how the world came to be, but how humans came to populate the world. Many also have stories about the end of existence. Most—but not all—place humans in a very special role: often the whole reason for the universe to be here in the first place.

This kind of reasoning can be called *anthropic*, or human-centric. It stands to reason that human thought should center on human existence. Pick up a random magazine sometime, like the generic magazines in airplane seat pockets. Notice how hard it is to find a page without a picture or drawing of a human. On those rare pages, the text almost certainly deals with people in some way. It's hard to get around–we're rooted in humanity.

Science *attempts* to break free of this potentially biased point of view. It does not explicitly forbid thought in this direction, but the preference is to keep our obvious self-interest out of the picture. Science goes where the measurements take it. Sometimes we don't like the answers, and have philosophical objections (quantum mechanics is a prime example). But we're stuck with the results of our experiments: reality does not always respect our sense of aesthetics.

7.1 Science and Religion at Odds?

Science often runs into conflict with religion. Science never sets out to invalidate a particular religious viewpoint. But arriving at different answers is the inevitable consequence of science's different approach to answering the big questions (i.e., via investigation, measurement, data analysis). Is one a better truth than the other? How do you judge this? They are just different. One is based on listening to the story the world itself tells, and the other is based on listening to stories that are generally attributed to a divine influence. A divine influence could always have created the world to tell a misleading or false story—maybe as a means to test our faith. But science operates outside of such concerns, only asking what secrets we can uncover from the world itself. It is *a* truth, if not *the* truth—and a remarkably consistent one thus far.

No religion tells the story of the Big Bang with the same details we've learned from looking at the universe. Nor does any religion (to my knowledge) spell out the process of natural selection by which it appears we evolved to be who and what we are. Quantum Mechanics and General Relativity likewise find no religious context. There are lots of interesting ideas in the world, but the ones that "stick" in science are the ones that explain experimental results, and produce new predictions that are subsequently verified by experiment. Many ideas in science have failed to stand up to this test, and they are chucked out like yesterday's Guardian, usually never to be revisited.

My personal view is that science and religion need not be in conflict. The recipe is simple: science does not intrude on the spiritual domain—never answering questions like: what does it mean to be human? how should we treat fellow humans? how can we celebrate our existence in this fantastically amazing and beautiful world? Likewise, religion does not intrude on the scientific domain, leaving aside details about the formation of the universe, evolution of species, etc. Science is generally much more convincing in these cases, being based on observation and measurement. As long as overlap exists, conflict will likely follow.

7.2 Limitations of Science

There are some very basic questions that science will probably never be able to answer. Questions like: what *is* mass/energy? what *is* space, really? what *is* time, and why is it so different from space? why only three dimensions of space? why do we have the set of particles that we do? Some of these questions may be too fundamental for science. Science is probably forever limited to a *description* of reality. It can explain why things behave the way they do, but not why the rules are what they are. There are two divergent lines of thought in the physics community when it comes to these issues. One is the thought that physics will ultimately be complete enough to unambiguously and uniquely explain the world. The accompanying statement is, "it could logically be no other way." The other point of view is that physics will remain descriptive, never nailing down why our universe is just as it is. The accompanying statement is, "it just happened this way, man."

String theory is currently the best hope for the former line of thought. Fueled by decades of reduction and unification within physics (culminating in the "Standard Model" of physics in the 1970's), a new line of physics inquiry showed promise to uniting gravity with the Standard Model, and perhaps even uniquely determining our physics (laws, particles, masses, etc.) so that we would see no other possible way things could be. This would be the ultimate triumph of physics, and a goal many physicists (including Einstein) have sought.

The other attitude strikes physicists as "giving up." Why stop trying to explain things now? Further insights may be forthcoming—look at how far we've come. But an interesting recent development—ironically, stemming from string theory—is shoving many physicists in this direction. Seeking a unique description of nature (meaning a single, unambiguous solution), string theorists stumbled on a fantastically large "Landscape" in which physics could exist. Each of the 10^{500} possible stable positions within this domain represent valid (internally consistent) laws of physics. Then why the heck did we end up in *our* type of universe? Why not one of the other possibilities?

This is where things get interesting: the vast majority of the other universes would destroy themselves almost instantly (too much mass density, too much dark energy leading to uncontrolled acceleration, etc.). Even those that don't self-destruct right away have properties unfriendly to life: they don't even form stars, or in many cases even atoms. Lots of things have to be just right to pick out a location in this Landscape that results in a habitable universe. The chances, in fact, are exceedingly remote that an arbitrary universe in this Landscape could form life.

Three ways to go with this thought. 1) Aha: God must have made it special for us. 2) Geez, lucky break on those stiff odds! 3) We couldn't live in most of those universes, so obviously our universe is going to satisfy the conditions. This last thought is another form of anthropic reasoning: things are the way they are because *we* are here. It sounds circular, but here's the catch: our universe may not be the only one. Whatever spawned our Big Bang may have happened loads of times in loads of places. It's not as crazy as it sounds: our best model for how the universe started (the inflation model) has much experimental support and naturally accommodates the multi-verse concept. In any case, if there is even one lucky universe in all this batch that can form life, that's the one we'll find ourselves in. It's a lot like the planets scenario. There may be many planets in this galaxy, but most are entirely unsuitable for life. It's no mistake we find ourselves on a habitable planet—it could not have gone any other way.

This is the ultimate Copernican revolution. 500 years ago, Earth was special: at the center of the whole universe (according to people from that time). Then Copernicus came along and put the sun at the center of the universe (1514). Next, our sun wasn't special: just another star in our galaxy (1800's). Then in the 1920's it was understood that our galaxy wasn't special: just another galaxy in the cosmos. Now perhaps our universe isn't special: just one of many disconnected instances.

The problem with all of this is that it falls outside the boundaries of science, spilling into philosophy. I could state that our universe is nothing special, and that we simply occupy the habitable type for anthropic reasons. But this is not a testable idea. It makes no predictions and is therefore not falsifiable. The closest we could come is gaining experimental confidence in the ideas of string theory, with these same ideas leading inevitably to a rich Landscape of possible physics realities. But we would still never know *why* our universe

ended up the way it did—why we occupy this habitable region of the Landscape. While anthropic selection is intriguing, and may even be right, at the end of the day all we can do is keep looking for clues and continue trying to understand this world we live in.