CHAPTER 5

THE RUNAWAY UNIVERSE

It is mere rubbish, thinking at present of the origin of life; one might as well think of the origin of matter.

—CHARLES DARWIN

What Michael Turner and I argued in 1995 was heretical in the extreme. Based on little more than theoretical prejudice, we presumed the universe was flat. (I should stress once again here that a "flat" three-dimensional universe is not flat like a two-dimensional pancake is flat, but is rather the three-dimensional space that all of us intuitively picture, in which light rays travel in straight lines. This is to be contrasted with the much harder to picture curved three-dimensional spaces in which light rays, which trace the underlying curvature of space, do not travel in straight lines.) Then we inferred that all available cosmological data at the time were consistent with a flat universe only if about 30 percent of the total energy resided in some form of "dark matter," as observations seemed to indicate existed around galaxies and clusters, but much more strangely than even this, that the remaining 70 percent of the total energy in the universe resided not in any form of matter, but rather in empty space itself.

Our idea was crazy by any standards. In order to result in a value for the cosmological constant consistent with our claim, the estimated value for this quantity described in the last chapter would have to be reduced somehow by 120 orders of magnitude and still not be precisely zero. This would involve the most severe fine-tuning of any physical quantity known in nature, without the slightest idea how to adjust it.

This was one of the reasons that, as I lectured at various universities about the quandary of a flat universe, I evoked mostly smiles and no more. I don't think many people took our proposal seriously, and I am not even sure Turner and I did. Our point in raising eyebrows with our paper was to illustrate graphically a fact that was beginning to dawn not just on us, but also on several of our theorist colleagues around the world: something looked wrong with the by-then "standard" picture of our universe, in which almost all the energy required by general relativity to produce a flat universe today was assumed to reside in exotic dark matter (with a pinch of baryons—i.e., us Earthlings, stars, visible galaxies—to salt the mix).

A colleague recently reminded me that for the two years following our modest proposal, it was referenced only a handful of times in subsequent papers, and apparently all but one or two of these were in papers written by Turner or me! As perplexing as our universe is, the bulk of the scientific community believed it couldn't be as crazy as Turner and I suggested it was.

The simplest alternative way out of the contradictions was the possibility that the universe wasn't flat but open (one in which parallel light rays today would curve apart if we traced their trajectory backward. This was of course before the cosmic microwave background measurements made it clear that this option was not viable.) However, even this possibility had its own problems, though the situation there remained far from clear as well.

Any high school physics student will happily tell you that gravity sucks—that is, it is universally attractive. Of course, like so many things in science, we now recognize that we have to expand our horizons because nature is more imaginative than we are. If for the moment we assume that the attractive nature of gravity implies that the expansion of the universe has been slowing down, recall that we get an upper limit on the age of the universe by assuming that the velocity of a galaxy located at a certain distance from us has been constant since the Big Bang. This is because, if the universe has been decelerating, then the galaxy was once moving away faster from us than it is now, and therefore it would have taken less time to get to its current position than if it had always been moving at its current speed. In an open universe dominated by matter, the deceleration of the universe would be slower than in a flat universe, and therefore the inferred age of the universe would be greater than it would be for a flat universe dominated by matter, for the same current measured expansion rate. It would in fact be much closer to the value we estimate by assuming a constant rate of expansion over cosmic time.

Remember that a non-zero energy of empty space would produce a cosmological constant—like gravitational repulsion—implying that the expansion of the universe would instead speed up over cosmic time, and therefore galaxies would previously have been moving apart more slowly than they are today. This would imply that it would have taken even longer to get to their present distance than it would for a constant expansion. Indeed, for a given measurement of the Hubble constant today, the longest possible lifetime of our universe (about 20 billion years) is obtained by including the possibility of a cosmological constant along with the measured amount of visible and dark matter, if we are free to adjust its value along with the density of matter in the universe today.

In 1996, I worked with Brian Chaboyer and our collaborators Pierre Demarque at Yale and postdoc Peter Kernan at Case Western Reserve to put a lower limit on the age of these stars to be about 12 billion years. We did this by modeling the evolution of millions of different stars on high-speed computers and comparing their colors and brightness with actual stars observed in globular clusters in our galaxy, which were long thought to be among the oldest objects in the galaxy. Assuming about a billion years for our galaxy to form, this lower limit effectively ruled out a flat universe dominated by matter and favored one with a cosmological constant (one of the factors that had weighed on the conclusions in my earlier paper with Turner), while an open universe teetered on the hairy edge of viability.

However, the ages of the oldest stars involve inferences based on observations at the edge of the then current sensitivity and, in

1997, new observational data forced us to revise our estimates downward by about 2 billion years, leading to a somewhat younger universe. So the situation became much murkier, and all three cosmologies once again appeared viable, sending many of us back to the drawing board.

All of this changed in 1998, coincidentally the same year that the BOOMERANG experiment demonstrated that the universe is flat.

In the intervening seventy years since Edwin Hubble measured the expansion rate of the universe, astronomers had worked harder and harder to pin down its value. Recall that in the 1990s they had finally found a "standard candle"—that is, an object whose intrinsic luminosity observers felt they could independently ascertain, so that, when they measured its apparent luminosity, they could then infer its distance. The standard candle seemed to be reliable and was one that could be observed across the depths of space and time.

A certain type of exploding star called Type Ia supernova had recently been demonstrated to exhibit a relationship between brightness and longevity. Measuring how long a given Type Ia supernova remained bright required, for the first time, taking into account time dilation effects due to the expansion of the universe, which imply that the measured lifetime of such a supernova is actually longer than its actual lifetime in its rest frame. Nonetheless, we could infer the absolute brightness and measure its apparent brightness with telescopes and ultimately determine the distance to the host galaxy in which the supernova had exploded. Measuring the redshift of the galaxy at the same time allowed us to determine velocity. Combining the two allows us to measure, with increasing accuracy, the expansion rate of the universe.

Because supernovae are so bright, they provide not only a great tool to measure the Hubble constant, they also allow observers to look back to distances that are a significant fraction of the total age of the universe.

This offered a new and exciting possibility, which observers viewed as a much more exciting quarry: measuring how Hubble's constant changes over cosmic time.

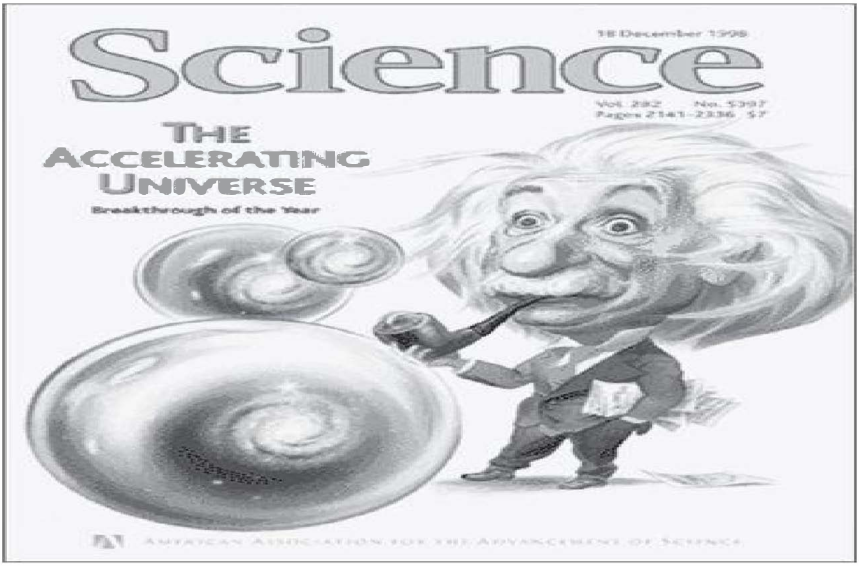
Measuring how a constant is changing sounds like an oxymoron, and it would be except for the fact that we humans live such brief lives, at least on a cosmic scale. On a human timescale the expansion rate of the universe is indeed constant. However, as I have just described, the expansion rate of the universe will change over cosmic time due to the effects of gravity.

The astronomers reasoned that if they could measure the velocity and distance of supernovae located far away—across the far reaches of the visible universe—then they could measure the rate at which the expansion of the universe was slowing down (since everyone assumed the universe was acting sensibly, and the dominant gravitational force in the universe was attractive). This in turn they hoped would reveal whether the universe was open, closed, or flat, because the rate of slowing as a function of time is different for each geometry.

In 1996, I was spending six weeks visiting Lawrence Berkeley Laboratory, lecturing on cosmology and discussing various science projects with my colleagues there. I gave a talk about our claim that empty space might have energy, and afterward, Saul Perlmutter, a young physicist who was working on detecting distant supernovae, came up to me and said, "We will prove you wrong!"

Saul was referring to the following aspect of our suggestion of a flat universe, 70 percent of the energy of which should be contained in empty space. Recall that such energy would produce a cosmological constant, leading to a repulsive force that would then exist throughout all of space and that would dominate the expansion of the universe, causing its expansion to *speed up,* not slow down.

As I have described, if the expansion of the universe was speeding up over cosmic time, then the universe would be older today than we would otherwise infer had the expansion been slowing down. This would then imply that the look-back in time to galaxies with a given redshift would be longer than it would otherwise be. In turn, if they have been receding from us for a longer time, this would imply that the light from them originated from farther away. The supernovae in galaxies at some given measured redshift would then appear fainter to us than if the light originated closer. Schematically, if one was measuring velocity versus distance, the slope of the curve for relatively nearby galaxies would allow us to determine the expansion rate today, and then whether the curve bent upward or downward for distant supernovae would tell us whether the universe was speeding up or slowing down over cosmic time.



Two years after our meeting, Saul and his collaborators, part of an international team called the Supernova Cosmology Project, published a paper based on early preliminary data that indeed suggested we were wrong. (Actually, they did not argue that Turner and I were wrong, since they, along with most of the other observers, really didn't give much credence to our proposal.) Their data suggested that the distance-versus-redshift plot curved downward, and thus that an upper limit on the energy of empty space had to be well below what would have been required to make a significant contribution to the total energy today.

However, as often happens, the first data that come in might not be representative of all the data—either you are simply statistically unlucky, or unexpected systematic errors might affect the data, which are not manifest until you have a much bigger sample. This was the case with data that the Supernova

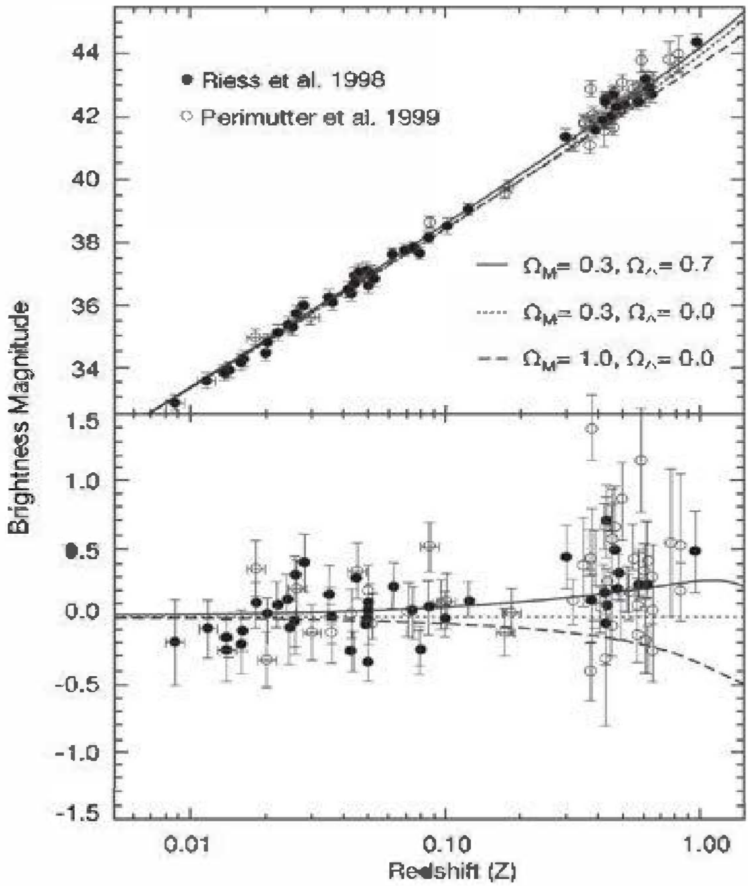
Cosmology Project published, and so the conclusions were incorrect.

Another international supernova search project, called the High-Z Supernova Search Team, led by Brian Schmidt at Mount Stromlo Observatory in Australia, was carrying out a program with the same goal, and they began to obtain different results. Brian recently told me that when their first significant High-Z Supernova determination came in, suggesting an accelerating universe with significant vacuum energy, they were turned down for telescope time and informed by a journal that they must be wrong because the Supernova Cosmology Project had already determined that the universe was indeed flat, and dominated by matter.

The detailed history of the competition between these two groups will undoubtedly be replayed many times, especially after they share the Nobel Prize, which they undoubtedly will.[*] This is not the place to worry about priority. Suffice it to say that by early 1998, Schmidt's group published a paper demonstrating that the universe appeared to be accelerating. About six months later, Perlmutter's group announced similar results and published a paper confirming the High-Z Supernova result, in effect acknowledging their earlier error—and lending more credence to a universe dominated by the energy of empty space or, as it is now more commonly called, dark energy.

The speed with which these results were adopted by the scientific community—even though they required a wholesale revision of the entire accepted picture of the universe—provides an interesting study in scientific sociology. Almost overnight, there appeared to be universal acceptance of the results, even though, as Carl Sagan has emphasized, "Extraordinary claims require extraordinary evidence." This was certainly an extraordinary claim if ever one was.

I was shocked when, in December 1998, *Science* magazine called the discovery of an accelerating universe the Scientific Breakthrough of the Year, producing a remarkable cover with a drawing of a shocked Einstein.

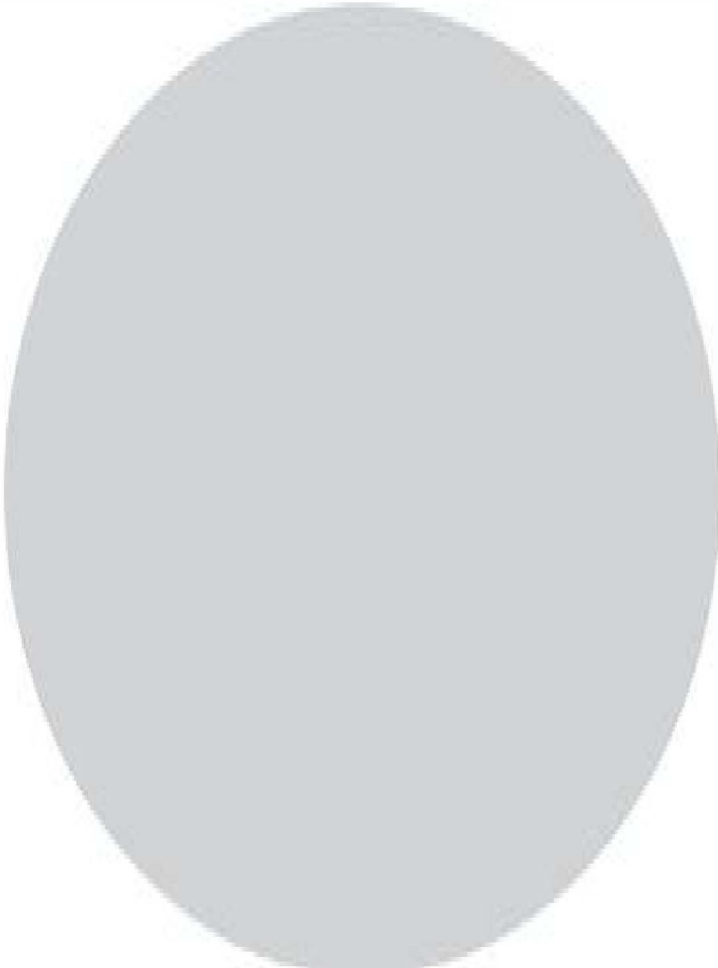


I wasn't shocked because I thought that the result wasn't worthy of a cover. Quite the contrary. If true, it was one of the most important astronomical discoveries of our time, but the data at the time were merely strongly suggestive. They required such a change in our picture of the universe that I felt that we should all be more certain that other possible causes of the effects observed by the teams could be ruled out definitively before everyone jumped on the cosmological constant bandwagon. As I told at least one journalist at the time, "The first time I didn't believe in a cosmological constant was when observers claimed to discover it."

My somewhat facetious reaction may seem strange, given that I had been promoting the possibility in one form or another for perhaps a decade. As a theorist, I feel that speculation is fine, especially if it promotes new avenues for experiment. But I believe in being as conservative as possible when examining real data, perhaps because I reached scientific maturity during a period when so many new and exciting but tentative claims in my own field of particle physics turned out to be spurious. Discoveries ranging from a claimed new fifth force in nature to the discovery of new elementary particles to the supposed observation that our universe is rotating as a whole have come and gone with much hoopla.

The biggest concern at the time regarding the claimed discovery of an accelerating universe was that distant supernovae may appear dimmer than they would otherwise be expected to be, not because of an accelerated expansion, but merely because either (a) they *are* dimmer, or (b) perhaps some intergalactic or galactic dust present at early times partially obscures them.

In the intervening decade, it has nevertheless turned out that the evidence for acceleration has become overwhelming, almost unimpeachable. First, many more supernovae at high redshift have been measured. From these, a combined analysis of the supernovae from the two groups done within a year of the original publication yielded the following plot:



As a guide to the eye, to help you see whether the distance-versus-redshift curve bends upward or downward, the observers have drawn a dotted straight line in the upper half of the plot from the bottom left to the top right corner that goes through the data that represent nearby supernovae. The slope of this line tells us the expansion rate today. Then, in the lower half of the figure they have made that same straight line horizontal, to guide the eye. If the universe were decelerating, as had been expected in 1998, the distant supernovae at a redshift (z) close to 1 would fall below the straight line. But as you can see, most of them fall above the straight line. This is due to either one of two reasons:

1. the data are wrong, or
2. the expansion of the universe *is* accelerating.

If we take, for the moment, the second alternative and ask, "How much energy would we have to put in empty space in order to produce the observed acceleration?" the answer we come up with is remarkable. The solid curve, which fits the data best, corresponds to a flat universe, with 30 percent of the energy in matter and 70 percent in empty space. This is, remarkably, precisely what is needed in order to make a flat universe consistent with the fact that only 30 percent of the required mass exists in and around galaxies and clusters. An apparent concordance has been achieved.

Nevertheless, because the claim that 99 percent of the universe is invisible (1 percent visible matter embedded in a sea of dark matter surrounded by energy in empty space) fits into the category of an extraordinary claim, we should seriously consider the first of the two possibilities I mention above: namely, that the data are wrong. In the intervening decade, all the rest of the data from cosmology has continued to solidify the general concordance picture of a cockamamie, flat universe in which the dominant energy resides in empty space and in which everything we can see accounts for less than 1 percent of the total energy, with the matter we can't see being composed mostly of some yet unknown, new type of elementary particles.

First, new data on stellar evolution have improved as new satellites have provided us with information on the elemental abundances in old stars. Using these, my colleague Chaboyer and I were able, in 2005, to demonstrate definitively that the uncertainties in the estimates of the age of the universe using these data were now small enough to rule out lifetimes younger than about 11 billion years. This was inconsistent with any universe in which empty space itself contained a significant amount of energy. Again, since we are not certain that this energy is due to a cosmological constant, it now goes by the simpler name "dark energy," in analogue to the moniker of "dark matter" that dominates galaxies.

This estimate for the age of our universe was vastly improved in about 2006 when new precision measurements of the cosmic microwave background using the WMAP satellite allowed observers to precisely measure the time since the Big Bang. We now know the age of the universe to four significant figures. It is 13.72 billion years old!

I would never have figured that, in my lifetime, we would obtain such accuracy. But now that we have it, we can confirm that there is no way that a universe with the measured expansion rate today could be this old without dark energy, and in particular, dark energy that behaves essentially like the energy represented by a cosmological constant would behave. In other words, it is energy that appears to remain constant over time.

In the next scientific breakthrough, observers were able to measure accurately how matter, in the form of galaxies, has clustered together over cosmic time. The result depends upon the expansion rate of the universe, as the attractive force pulling galaxies together has to compete with the cosmic expansion driving matter apart. The larger the value of the energy of empty space, the sooner it will come to dominate the energy of the universe, and the sooner the increasing expansion rate will eventually stop the gravitational collapse of matter on ever larger scales.

By measuring gravitational clustering, therefore, observers have been able to confirm, once again, that the only flat universe that is consistent with observed large-scale structure in the universe is one with approximately 70 percent dark energy and, once again, that dark energy behaves more or less like the energy represented by a cosmological constant.

Independent of these indirect probes of the expansion history of the universe, the supernova observers have done extensive tests of possibilities that could induce systematic errors in their analysis, including the possibility of increased dust at large distances that make supernovae look dimmer, and ruled them out one by one.

One of their most important tests involved searching back in time.

Earlier in the history of the universe, when what is now our currently observable region was much smaller in size, the density of matter was much greater. However, the energy density of empty space remains the same over time if it reflects a cosmological constant—or something like it. Thus, when the universe was less than about half its present size, the energy density of matter would have exceeded the energy density of empty space. For all times before this time matter, and not empty space, would have produced the dominant gravitational force acting on the expansion. As a result, the universe would have been decelerating.

In classical mechanics there is a name for the point at which a system changes its acceleration and, in particular, goes from decelerating to accelerating. It is called a "jerk." In 2003, I organized a conference at my university to examine the future of cosmology and invited one of the High-Z Supernova survey members, Adam Riess, who had told me he would have something exciting to report at the meeting. He did. The next day, the *New York Times,* which was reporting on the meeting, ran a photo of Adam accompanied by the headline "Cosmic Jerk Discovered." I have kept that photo and turn to it for amusement from time to time.

The detailed mapping of the expansion history of the universe, demonstrating that it shifted from a period of deceleration to acceleration, added substantial weight to the claim that the original observations, which implied the existence of dark energy, were in fact correct. With all of the other evidence now available, it is very difficult to imagine that, by adhering to this picture, somehow we are being led on a cosmic wild-goose chase. Like it or not, dark energy seems here to stay, or at least to stay until it changes in some way.

The origin and nature of dark energy is without a doubt the biggest mystery in fundamental physics today. We have no deep understanding of how it originates and why it takes the value it has. We therefore have no idea of why it has begun to dominate the expansion of the universe and only relatively recently, in the past 5 billion years or so, or whether that is a complete accident. It is natural to suspect that its nature is tied in some basic way to the origin of the universe. And all signs suggest that it will determine the future of the universe as well.