THE BIRTH OF THE EARTH

A *Wanderlied* Through Space, Time, and the Human Imagination

David E. Fisher
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A *Wanderlied* Through Space, Time, and the Human Imagination

DAVID E. FISHER

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This book is Smyth-sewn.

For Hans Frese
Professor of German,
Trinity College, 1952/3

and

for my parents
Henry R. and Grace S. Fisher

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WHAT TOMAS SAID IN A PUB

I saw God! Do you doubt it?
Do you dare to doubt it?
I saw the Almighty Man! His hand
Was resting on a mountain! And
He looked upon the World, and all about it:
I saw Him plainer than you see me now
—You mustn't doubt it!

He was not satisfied!
His look was all dissatisfied!
His beard swung on a wind, far out of sight,
Behind the world's curve! And there was light
Most fearful from His forehead! And He sighed—
—That star went always wrong, and from the start
I was dissatisfied!—

He lifted up His hand!
I say He heaved a dreadful hand
Over the spinning earth! Then I said,—Stay,
You must not strike it, God! I'm in the way!
And I will never move from where I stand!—
He said,—Dear child, I feared that you were dead.—
. . . And stayed his hand.

—James Stephens (1880–1950).

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INTRODUCTION

Stories told of the history of science all too often portray a smoothly rolling film sequence of discovery, refutation, modification, and final verification. Someone conceives of a scenario to explain a concept such as our existence, and others find faults with it; point by point the arguments are attacked and experimentally or theoretically they are demolished, modified, or established. The scientific process thus described is a lovely fairy tale, but in my own experience I have found it to be usually more random and chaotic, explicable as much in terms of fashion and passion as in those of logic and measurement. Points of argument are often ignored, points of view skirted around; various counterarguments are presented simultaneously so that future impetus is split into skewed directions, nevermore to meet again; theories as well as experimental data are forgotten, resurrected, rediscovered, reforgotten; they are proven wrong one year, accepted the next, discarded without argument the third. And somehow, out of all this chaos, we slowly learn. It is not a calm, reasoned, logical learning experience: but it's not only the best we have, it's the only game in town.

The historian of science as well as of other torturous human paths cannot tell a story without inserting a thread through the holes to hold it together, to make a pleasing or at least an organized quilt out of the various ill-fitting patches. To tell it as it truly occurred would be bewildering, but to tell it as a coherent story is often untrue. So a compromise must be reached, in which we pick and choose among the refuse of history to find a scheme which approximates both the truth and a story with a beginning, a middle, and an end, and finally then we say, "This is the way it happened."

Right, then. This is the way it happened.

CHAPTER ONE

IN THE BEGINNING

In the Beginning God created the Heavens and the Earth.
Well, not exactly.

THAT FIRST SENTENCE represents an astonishing leap of human imagination. It replaced a universe of chaos with one of order. The universe—and the day-to-day fortunes of humanity—were no longer at the mercy of the whimsies of innumberable gods known and unknown, but were created by and subject to the one overriding purpose and stern discipline of a just (if occasional vengeful) God. The sun did not rise in the morning, bringing the light and warmth necessary for our survival because the god Shamash felt like driving his chariot across the sky, but because the sun was created by the Lord aeons ago precisely to bring us light by day; it existed for that purpose and would never stop, would never fail to appear. It was no longer necessary to worry each night whether Shamash might change his mind the next morning and fail to appear; there was no need to cut out the gizzards of chickens or the hearts of virgins and spread them on altars to induce Ushas to bring the dawn or Enki to send the fish for supper or Immer to water the fields with rain: the universe had an order, a discipline, a purpose, and so did we. That first sentence established the foundation of an understandable universe and became the basis of a system of moral and religious values that has lasted thousands of years and, though observed more in the breach than in the practice, still underlies the fabric of our civilization.

The second sentence is even more astonishing. It became possible to formulate it only in the second half of this present century: incredibly, we can now say with the utmost certainty something about the creation of our world. We know quite clearly that the Earth was not created *in the Beginning* at all: many billions of years actually elapsed between the creation of the first heavens and that of the Earth, many stars were born and passed into oblivion before ever the Earth was even a mote of dust in its Creator's eye, to coin a symbolic phrase.

The evidence for this comes from several different lines of scientific enquiry, from nuclear physics and geology as well as astronomy, and all the evidence fits together to form a proof beyond all reasonable doubt. We know, to begin with, that the universe we live in was created in a fantasic explosion we call the Big Bang. We don't know what happened or existed before this event, whether other universes existed in an unending chain beyond the beginning of time and whether the process will continue infinitely far into the future, or whether our present universe is the sum total of existence. Our imaginations boggle and collapse under the weight of such heavy questions. But we do know that our present universe was created in that moment of the Bang: we see the evidence of that event in the nearly homogeneous background radiation that now pervades the universe, the slowly dying relic of that first radiation flash. We see the evidence also in the motions of the galaxies, which are still being blown away from us and from each other with the force of that initial explosion. This latter observation, that of the motion of the galaxies, was the first hint we ever had of the overall structure of the universe. It depends on measurements of the spectra of wave lengths of light emitted by hot gases.

It was discovered early in this century that when a gas is heated to incandescence the light it emits consists of a series of discrete wavelengths which are typical of the type of gas; in fact, the spectrum of wavelenghts provides a spectroscopic fingerprint by which the identity of the gas is revealed. In this way astronomers analyzed the light coming to us from the stars in our galaxy, and found that all the stars were composed overwhelmingly of hydrogen. When they looked at the spectra of light coming from other galaxies, however, it was subtly different: it showed the characteristic relative spectrum of hydrogen, but the absolute values were always shifted to higher wavelenghts. This became explicable in terms of Einstein's General Theory of Relativity and an experimental observation known as the Doppler Shift.

In 1917, even before his theory of general relativity had been proven correct, Einstein attempted to apply it to the entire universe. He managed to find a unique solution to the relativistic equations which specified a homogeneous universe with no motion, space curved and without limit, yet finite, and with time uniform but infinite. He was mildly disturbed when the Dutch mathematician Willem deSitter found another solution in which the universe was empty but had the peculiar quality that if any small amounts of matter were introduced into it they flew apart spontaneously and continued to recede into infinity. Since, however, our universe was demonstrably not empty, it was possible to dismiss the DeSitter solution as irrelevant.

Nothing, however, is irrelevant to mathematicians, and by 1924 the Russian mathematician Alexander Friedmann had discovered a whole spectrum of possible solutions in which matter, which here was as natural a component as in the Einstein universe, spontaneously flew apart as in the deSitter universe. This model was extrapolated backward in time by the Belgian Abbe Georges Lemaitre, to a point of infinite density at zero time known as a "singularity." This word is used to denote a situation that is physically impossible—that is, impossible within our laws of physics. It arises mathematically as a function that is not well-behaved: noncontinuous, with a noncontinuous derivative.* An example might be something like a radar plot of a jet airplane's trail from Miami to New York which instantaneously becomes zero over Richmond and then just as abruptly reverts to its proper value again. This would be impossible as a plot of a real airplane in our real world; if it showed up this way on a radar screen the operator would conclude that the system was malfunctioning. And that is what Einstein and many others thought at first when the Friedmann/Lemaitre solutions to the relativistic equations showed a singularity at the beginning of time.

*To be more precise, if $f(z) = u(x,y) + iv(x,y)$ and if u and v and their partial derivatives with respect to x and y are continuous and satisfy the Cauchy-Riemann conditions

$$\partial u/\partial x = \partial v/\partial y \text{ and } \partial v/\partial x = -\partial u/\partial y$$

in a given region, then $f(z)$ is said to be *analytic*. A *singularity* is a point at which $f(z)$ is *not* analytic. "Real" functions are analytic everywhere under conditions we consider normal in our universe.

The flinging apart of matter in these solutions was also disturbing; it meant that the universe could not exist as a stable, static system. Rather it had to be continually expanding. (Actually, as I mentioned, the Friedmann solutions are an entire family of possibilities, including the possibility of contraction as well as expansion; but certainly a static, nonmoving, time-independent universe is not one of them.)

These two problems suddenly became the solution known as the Einstein-Friedmann universe when it was realized what they mean: that the universe began as a singularity, in a state which does not correspond to any aspect of physical reality today, a state of infinite compression and density which *in the Beginning* exploded and sent all the matter in the universe spinning outwards. Today that matter, in the form of galaxies, is still spinning out, expanding, receding from itself.

We see this expansion of the universe in the Doppler Effect. The shift in wavelength of the lines of the hydrogen spectrum is due to the motion of the light source—the distant galaxies. When an object emitting light waves is moving toward the observer, the wavelength of the light appears to him to be shortened; when the object is moving away, the wavelength appears lengthened. This effect was first discovered by the Austrian scientist Christian Johann Doppler, who thought that observations of starlight would show random motions of the stars: some moving toward us, some away from us. Within our galaxy, such motions are so small as to be all but indiscernible, but the light from other galaxies all show a shift to longer wavelengths: every galaxy is moving away from us and away from each other. Not only that, but the further ones are receding at faster velocities, proportionally to their distances. This is precisely the effect to be seen as the aftermath of an explosion, and so the observations together with the theory tell us clearly the story of the Big Bang.

They tell us more: they tell us *when* it happened. Simply by taking the measured distances of the various galaxies together with their measured velocities, we can tell how long it took them to get where they are; the calculation is simply the inverse of determining how far an airplane has traveled, from a knowledge of its take-off time and its speed. Unfortunately, it's not quite so simple: there are large errors in our measurement of the distance of the galaxies. But taking these into account, we can place the time of the Big Bang at certainly within 12 to 40 billion years ago, and probably within 15 to 20 billion. In other words, the universe began at least 12 billion years ago.

That's the evidence from astronomy. Nuclear physics tells us much the same thing. We know today that of all the different elements present on earth only hydrogen and helium were created during the Big Bang. The other elements—including oxygen, silicon, iron, uranium, and all the various elements which form our planet and our bodies—were created by nuclear reactions occurring in the interiors of stars scattered through the galaxy during the billions of years before the sun and earth were formed.

The realization of these processes began in the war year 1944 when Fred Hoyle (then a young scientist working on radar for the British Royal Navy, now Sir Fred Hoyle of Cambridge and California and Wales, arguably the greatest astrophysicist of his generation), took time out from a visit to the U.S. Naval radar installations at San Diego to visit nearby CalTech and talk about nuclear reactions. The source of energy in stars like the sun had only recently been understood: in 1929 the Danzigian nuclear physicist Fritz Houtermans and the British astronomer Robert Atkinson applied the Russian George Gamow's theory of artificial radioactivity to thermonuclear reactions and concluded that such reactions could produce the solar energy, and one decade later the then German, now American physicist Hans Bethe worked out the details of the particular reactions taking place at the extremely high temperatures in stellar cores. The basis for this is the conversion of four hydrogen nuclei into one helium. The mass of the helium is slightly less than that of the four hydrogens, and the mass difference is converted into energy according to $E = mc^2$.

Hoyle was intrigued not only with the energy production, but with the fact that one chemical element was converted into another: alchemy had been removed from the realm of medieval fantasy and had been transplanted whole and hearty into the center of stars. He began to think about what further nuclear reactions might take place later in the star's lifetime, converting helium successively into heavier elements. But he got sidetracked on other problems, and it was Ed Salpeter of Cornell who discovered that helium could be thermonuclearly fused into carbon by the nearly simultaneously coming together of three helium nuclei. Hoyle immediately jumped back into the problem, calculating further that carbon would fuse with another helium nucleus to produce oxygen. In fact, he found that this process would be even too effective, removing all the carbon as soon as it was formed. The result would be a universe without carbon, and that doesn't happen to be the universe we live in.

The only way to save the situation and preserve a universe built by stellar nucleosynthesis was if the production of carbon was more effective than Salpeter had originally calculated. After fiddling with the mathematics a bit, Hoyle found that the process would be possible if the carbon nucleus had a metastable state at a particular energy level, 7.65 Mev, which would have the effect of drawing its formation reaction forward.

The consensus during those years was that although nuclear reactions in stars were the source of stellar energies, the universe had been created with all the variety of elements already present, or at least they had been created in the first few moments of the universe; the conversion of hydrogen into helium was thought to be the only significant alchemical reaction occurring today. Then in 1953, on another visit to CalTech, Hoyle discussed the problem of the creation of carbon with Willy Fowler, a nuclear physicist there. Hoyle insisted that the 7.65 Mev state of carbon-12 must exist. Previous experimental work had in fact found some doubtful evidence for such a state, but later and more careful research had not seen it at all. When Hoyle argued that he was convinced it was there and that the experiments should be redone even more carefully, Fowler's initial reaction was, he later recalled, "Go away, Hoyle, don't bother me." But Hoyle was a persuasive speaker and there were intelligent listeners at CalTech. A research group carried out the definitive experiment, in which the predicted state of carbon-12 was found precisely where Hoyle had predicted it must be, and Fowler became a believer.

A couple of years later he spent his sabbatical year at Cambridge, where he was waylaid by the husband and wife astronomy team of Geoffrey and Margaret Burbidge, who wanted the help of a nuclear physicist. Inspired by Fred Hoyle's work, they were investigating the possibility of element production in stars via neutron-induced reactions. Hoyle was also in residence in Cambridge, and the four of them worked together that year, often spending evenings over their calculations in the Burbidge's tiny flat on Botolph Lane, "a flat with a roof that leaked in the nearly incessant winter rain, and to which the only access was an unlit passage past innumerable outhouses and up a very narrow, winding staircase." When Fowler's sabbatical was done he arranged for the Burbidges to follow him back to California; in 1956 Fred Hoyle also accepted a professorship there, and the four of them produced the bible of nuclear astrophysics, "Synthesis of the Elements in Stars," known to succeeding generations of scientists colloquially as B^2FH, after the authors. In this paper they presented in whole cloth an understandable and workable system of a variety of nuclear reactions in different stellar conditions that would in toto produce the elements seen in the universe in their proper proportions. In 1983 Fowler was awarded a Nobel Prize for this work, invoking surprise in several quarters that the others were not similarly honored.

The models of stellar nucleosynthesis which began with the Fowler/Hoyle work tell us how the different isotopes of the various elements are created. One such pair consists of uranium-235 and uranium-238. We know that they must have been created in roughly equal abundances, yet the ratio of U-235/U-238 today on earth is only 0.0073. What happened to all the original U-235? Well, the answer is clear: U-235 is radioactive, with a half-life of 713 million years; every 713 million years, half the U-235 is transformed into other elements. U-238 is also radioactive but its half-life is much longer so that every 713 million years only 10 percent of it changes to other elements. Therefore the ratio U-235/U-238 is always decreasing at an easily measurable rate, and it is a simple matter to reverse the calculation and determine how long ago the ratio was unity; the answer is about 6 billion years ago. This tells us that the isotopes of uranium were created at *least* as long ago as that: the true age is actually longer since they (and all the elements) were created over a period of aeons of time in a succession of stars. The calculations become more complex and model-dependent, but using several pairs of radioactive isotopes of different elements the answer always comes out to be the same, giving a rough date of 12 billion years and a firm lower limit of 9 billion years. Since these elements were created in various stars within our galaxy, the result is an average age for the galaxy. This fits perfectly with our Big Bang model in which the universe itself is something more than 12 billion years old, most probably 15 to 20.

Now what about the age of the earth? The answer comes again from nuclear physics, this time combined with geology. Radioactive elements behave chemically just like normal stable elements. In particular, they combine naturally to become part of the minerals and rocks on earth. The difference is that, whether combined in a rock structure or not, wherever they are and in whatever form, they continually decay and change into other elements at an unalterable, predetermined rate. Obviously the ratio of a parent radioactive element to its daughter is a continually changing function of time. Simply by measuring this ratio one can determine the age of the rock, and the age of the earth is to a first approximation equal to that of the oldest rock measured. Better approximations can be obtained by particular methods on particular geological samples, as will be discussed in chapter 7. Many such measurements in the past fifty years have shown that rocks on earth commonly reach ages of millions, hundreds of millions, even billions of years, providing the first conclusive evidence against the seventeenth-century biblical-based estimates of some literal-minded Christian theologians, which gave results of a few thousand years—but the *oldest* age of any rock on earth is only a few billion years, less than half the 9 to 12 billion-year age of the galaxy.

By measuring the isotopic composition of radiogenic and primordial lead averaged for the whole earth, it is possible to show that the earth is just about 4.5 billion years old. Incredibly enough, similar experiments on meteorites show the same result, which means that they and the earth were created together, within a possible error of only 100 million years.

Let's stretch the error estimates as much as we possibly can; still the earth is unquestionably less than 5 billion years old. And the galaxy is more than 9 billion years old, and the universe itself is more than 12 billion years old.

And so in the Beginning the heavens were created, but the earth came a long time later, many billions of years later. Many billions of stars lived and died, creating the elements that now form the earth and spitting them out into the vast interstellar spaces, before finally the clouds of dust and gas began to fall together to form our sun, our solar system, our earth, and ourselves.

The story of how that all happened is an incredible one, but just as incredible is the story of how we dug out the secrets of our own creation, piece by piece, and put them together. That's what this book is about.

SOURCES: Burbidge and Burbidge 1982; Hoffman 1972; Hoyle 1982; Lovell 1981

CHAPTER TWO

THE SPINNING EARTH

THE CONCEPT OF One God was the first major step man took in bringing order to the universe, in understanding that the world we live in—bewildering as it seems to be—is in fact governed by strict laws. The realization that such laws do exist and are discoverable, knowable, and independent of the moods of any Creator did not come for more than another two thousand years, not till the middle of the seventeenth century when Kepler propounded his laws of planetary motion and Newton explained them with his laws of gravity and inertia.

Today we take the laws of physics for granted. They have become part of our everyday lives and we neither wonder at them nor doubt them, nor do we realize that they are statements of ignorance as well as triumphs of the human intellect.

Perhaps the most basic of these, for example, is the law of conservation of mass-energy, which states that mass-energy can be neither created nor destroyed. Ignoring relativistic considerations which merge the previously separate categories of mass and energy in a manner now commonly accepted though difficult to understand, we speak of the conservation of mass or of energy. The statements are simple and intuitively obvious: matter does not disappear before our eyes nor does it come into being. Work must be expended in order to generate energy: there is no free lunch.

But why? Where is it written that this must be so? Why could not the universe exist with atoms spontaneously appearing and disappearing, and with energy freely available? In 1948, for example, the Steady State theory of the universe was proposed, incorporating the idea that atoms were continually created out of nothing. Nearly three decades later the theory was proved wrong, but it was new experimental data rather than the concept of atomic creations that did her in. In fact if the law of mass-energy conservation is truly a universal law for all time, then where did all the mass and energy in the universe come from?

We don't know the answers to these questions. Or rather, by the very definition of the meaning of a scientific law and the meaning of the word *why* the questions become internally contradictory, mutually exclusive. To ask why something is true is to ask that an explanation be derived from a simpler, more basic principle: Why is 2 + 2 equal to 4? Because 1 + 1 is equal to 2, and (1 + 1) + (1 + 1) equals 4. But what we *define* as scientific laws are ultimate and basic principles: if we could derive them, then the principles from which they were derived would replace them as our laws.

For example, what makes the earth go round?

When man first realized that the sun, moon, and stars rise and set every day and night in the same way, he asked why? And he answered with a set of mythological stories. Today we accept without question the dramatically unobvious notion that the rising and setting of the heavenly bodies is actually a manifestation of the fact that the earth is spinning on its axis, rendering the ancient explanations irrelevant and unnecessary. But we may now quite reasonably ask instead, why should the earth spin? The biblical interpretation that it does so in order that the sun might bring us alternating day and night is no longer satisfying, since that answer rests on the assumption that the universe was created for our convenience; this notion was acceptable when we thought of the universe in an Aristotelian sense, with the earth at the center of it all, but it became obviously ludicrous when we realized the immensity of the real universe and the insignificant location in it of the solar system we inhabit, and indeed of our own location in this one particular solar system. We are a natural part of the universe, but certainly not its center nor its *raison d'etre*.

We might improve on the biblical interpretation by realizing from observation that every other planet we see is also spinning; it would then be a reasonable step to conclude that it is a natural law of the universe that all planets spin. The earth is a planet, *ergo sum:* the question is answered.

This proposed law—that all planets spin—would reveal both knowl-

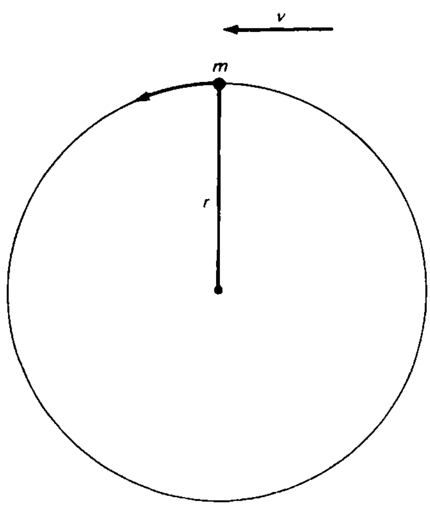

Figure 2.1.

edge and ignorance of the most profound sort. It would incorporate the empirical knowledge that all planets are spinning, and to have learned this—to have learned something of such basic significance about objects hundreds of millions of miles away, infinitely far away to us creatures locked on our own planet—is a magnificent accomplishment. And yet this law would also be a confession of ignorance, for it would reveal that we have no idea as to *why* they are spinning. We would be saying that we know they spin and that is the extent of our knowledge.

But in fact we know a bit more than this. We can indeed derive this "law of spinning planets" from a more basic law: the law of conservation of angular momentum, illustrated in figure 2.1.

Figure 2.1 shows a body of mass m moving around a center O in a circle of radius r with a velocity v. It represents any number of situations: if the line r is a string and the mass m is a stone and the center O is a person, it represents someone swinging a stone around his head on a string. If O is the sun and m is the earth, and the force holding m to O is gravity rather than a string, it represents the earth revolving around the sun. If O is the center of the earth and m any point on the surface of the earth, it represents the earth spinning on its axis.

All these situations have something in common: if no energy is added or subtracted from the system, the product of $m \times r \times v$ will remain constant. The product of these three numbers is named the *angular momentum*, and the previous sentence comprises the Law of Conservation of Angular Momentum. First we'll discuss it, then try to explain it.

If the string holding the stone is pulled in, the distance r gets smaller; then in order for the angular momentum to remain unchanged, either m or v must increase. Since mass conservation prevents the stone from getting bigger, the velocity must: the stone will whirl faster. Conversely, if some string is let out so that r increases, the stone will whirl more slowly. All this is without the person whirling the stone making any effort to spin it faster or slower.

The effect is seen commonly on television whenever figure skating on ice is shown. A skater goes into a whirl with arms outstretched, then pulls her arms in across her chest *and she spins faster*. This is because the radius around her spin axis, from the center of her body to her outstretched fingertips, decreases when her arms come in close; since her mass can't increase, her spin velocity must. To stop, she'll throw her arms wide again: the resulting increase in r makes her v decrease drastically and she can easily stop without falling over.

During the formation of the solar system, the earth as it formed acquired a certain amount of spin angular momentum both from the tumbling motion of its component parts and from late collisions with asteroidal-type objects, all of which will be discussed in detail later in this book. The point now is that once the earth acquires this angular momentum, it can't lose it—and so it keeps on spinning, aeon after aeon, until the last syllable of recorded time.*

So why does the earth spin? Why do all planets spin? Because during their formation they acquire some angular momentum, and because of the law of conservation of angular momentum they can't lose it, and so they spin.

But why must angular momentum be conserved? No one knows. The law is, at the present time, the ultimate expression of our most basic knowledge about rotating objects; we can neither derive it nor explain it

*In this discussion I have treated each planet as if it were isolated in space, ignoring higher-order coupling effects which would only cloud the basic concept of angular momentum.

by more basic principles. We have to be satisfied if we can explain the observed universe with a set of such basic principles. This is at the same time our glory and our limitation; we have discovered that the universe is an orderly one governed by law, but the ultimate reasons for these laws lie in that undiscovered country whose bourne none of us travelers have yet reached.

SOURCE: Morrison 1971