Roy Sablosky
1119 37th Street
Sacramento CA 95816
roy.sablosky *at* sablosky.com

Newton and the Next Million Years

How seventeenth-century science changed cosmology forever

Roy Sablosky

> As for the earth … we strive to make it like the celestial bodies, and, as it were, place it in heaven, from which your philosophers have banned it.
>
> —Galileo Galilei (1632)

WHETHER AN APPLE actually conked him on the noggin is not nearly as interesting as the question of what was on Isaac Newton's mind that day, and where those thoughts would eventually lead him—and all of us. His work was at the leading edge of the new scientific understanding that blossomed in the seventeenth century, profoundly altering our relationship to the natural world.

We don't often hear about Newtonian mechanics these days, except in the context of its "replacement" by the Einsteinian paradigm. In their own time, however, Newton's findings were much more revolutionary. One of the problems we face in trying to understand his achievement is that Newton's central insight, which in the 1600s was a stunning leap of imagination, seems, for us here in the twenty-first century, just plain obvious. If I told my nine-year-old that the force holding the moon in its orbit is the same force that pulls an apple toward the ground, she would be like, “Dad, I know that!” But Newton’s discovery is one of the *reasons* people came to feel this way. Back then, “Why does the moon go around the earth?”—a question people had been asking basically forever—was still a real head-scratcher. Newton answered this question, and in so doing, changed the world.

It’s not only that a quantitative theory of gravitation enabled us to aim rockets at the moon (and at each other). We also used it to discover Uranus, Neptune, Pluto, and the asteroid belt, but that’s still not it. In demonstrating that stellar gravity is exactly the same thing as terrestrial gravity, Newton breached the ancient wall separating Earth from Heaven. To put it another way: he parted the veil, that the face of Nature might be kissed.

You see, from the earliest days, it was assumed that the terrestrial and celestial spheres were disjoint and incommensurate. They were completely different places, governed by completely different laws. On Earth, for example, things always fell down; in the sky, they stayed up. This ontological dualism was a cornerstone of ancient cosmology. Aristotle, whose writings were canonical to western academic thought for two thousand years, considered it essential to a proper understanding of the universe.

No one will ever be more wrong.

When spectrographic measurements in the 1800s proved that our sun is a star, and that all the stars are made out of the same chemical elements that the earth is—and that humans are—the revelation was complete. There is no essential difference between Heaven and Earth. The starry world is neither inaccessible, nor incomprehensible, nor fundamentally superior to our own. Heaven is not *out there*, it’s right here. It’s where we live.

This change in perspective is so radical, so far-reaching, and so *positive* that we can, without exaggeration, divide all of human history into two phases: the million years preceding 1600, and the *next* million years.

Of course, Newton was not working in a vacuum. It is human nature to latch on to personalities, to make heroes, despite our knowledge that reality is always more complicated than that. Newton benefited from the findings of many of his contemporaries. The theory of universal gravitation was part of a larger trend: the birth and maturation of what he called *experimental philosophy* and what we now call science. Had he not found the key, someone else would have… eventually. Nevertheless, as it happened, he got there way before anyone else, and took care of the problem more thoroughly than almost anyone else possibly could. He found the key, and opened the door, and we all walked into a different world.

The apple question, briefly dispatched

~::~

There has been some news about the proverbial apple as recently as 1998. Newton more than once described himself as having the pivotal insight "in the garden" while watching an apple fall. Near Woolsthorpe Manor's back door, there is exactly one, very old apple tree. It was blown down in a storm in the 1800s; part of the trunk lies horizontally on the ground, but it survives to this day. R.G. Keesing quite literally tripped over it during his investigation into the history of the "Newton's apple trees" planted elsewhere in England as memorials (Keesing 1998). He had experts at Oxford University sample the trees' DNA (!) and it appears that some of them, but not all, are descended from the one at Woolsthorpe. On the other hand, he gathered substantial evidence that this particular apple tree, still growing by the manor house, could very well be *the tree* from which *the* *apple* really did fall, catching young Isaac's eye as he wrestled with his thorny, self-assigned problems in orbital mechanics.

The inverse-square law

~::~

Newton was 24. He had been attending Cambridge University, but the school had closed due to a local outbreak of the plague and he was back at his family's estate in Lincolnshire (200 miles to the north; the nearest big city is Nottingham). He had put aside his other studies (officially, he was a law major) and was relentlessly pursuing problems in experimental philosophy. On that day in the spring of 1666, he was thinking about gravity, had an amazing new idea about it, and found a pretty good experimental test for this new hypothesis just by thinking.

Newton's inspiration was to wonder whether gravity, the nominal cause of an apple's fall to earth, might also be identified as the cause of the moon's orbit around the earth.

The first step in constructing a test of this proposition is the *inverse-square law*: that the force of gravity weakens in proportion to the square of your distance from planet Earth. In 1666 this was only a hypothesis, but Newton had two good reasons to suspect that it was true.

The first reason has to do with what contemporary cosmologists call the "isotropy of 3-dimensional space," but it can be made intuitive with a simple visualization. Imagine gravity's pull as a finite number of straight lines radiating from Earth like the quills of a sea urchin. Let's say that each of these lines attracts, toward Earth (with some constant force, *not* depending on the distance), anything it touches. As a body moves away from Earth, fewer lines touch it. In fact, when it's three times further away, there are only one-ninth as many contacts: the attraction is reduced to a ninth of its previous strength. Five times as far, one twenty-fifth the attraction, and so on. As the "sphere of influence" expands, the "influence" itself is spread out (and weakened) to an extent proportional to the square of the distance. In this intuitive model, the inverse-square relation is a straightforward result of the ratio between the radius of a sphere and its surface area, a proportion that was known even back in the time of Euclid.

The other good reason for the inverse-square hypothesis had to do with Johannes Kepler's laws of planetary motion. In 1609, Kepler had found that the orbits of all the planets could be described mathematically as ellipses. He had been in possession of the most accurate body of astronomical observations in history, collected over many decades by the brilliant astronomer Tycho Brahe. Kepler was a Copernican: he believed that all the planets orbited the sun. And, like Copernicus, he was burdened by the Aristotelian assumption that planetary orbits, being *celestial* in nature, had to be perfect circles. He struggled for years to fit Tycho's data—thousands of pages of numbers, recording the exact (apparent) positions of the planets at specific times—to a series of concentric circles around the sun. These unbelievably laborious calculations never quite panned out. Finally, forced to admit that the numbers just really didn't fit into circles, he tried ellipses. The fit to ellipses was *excellent*—comparable, in fact, to the limits of error in Tycho's observations. Kepler was amazed, and dismayed. *They should have been circles.* The celestial harmony he had hoped to find did exist—but not in the form he had wanted. In the face of this painful contradiction between his most cherished beliefs and the observed facts of nature, Kepler displayed the hallmark of a true scientist: he put his beliefs temporarily aside, and *published the verifiable facts* that he had discovered.

These took the form of two "laws" of planetary motion:

1. Planetary orbits are elliptical, with the sun at one focus.
2. A radius drawn from the sun to the planet will sweep out equal areas in equal times.

(We pass over the second law because it later turned out to be mathematically equivalent to the *third* law, which will be introduced momentarily.) Taken together, these two formulae enabled the prediction of planetary orbits to a greater precision than either the Ptolemaic or the Copernican system. Both of those had of course been based on intricately compounded arrangements of circles. Kepler's findings explained *the successes and the failures* of the earlier systems: Ptolemy's famous "epicycles"—and Copernicus had had to use similar tricks—essentially served to make all those dozens of circles add up to something like ellipses.

The first two laws described orbits individually. Kepler's third law related the different planetary orbits to each other. Elegance and simplicity were, he was still certain, qualities proper to God's majestic creation. On later reflection, he could see that the adjustment from circles to ellipses, far from violating his belief in "celestial harmony," had actually redeemed it. The quest for the third law was extremely difficult; he worked on it, historians say, for 17 years. Finally, he came up with this:

3. The square of a planet's orbital period is proportional to the cube of its orbital radius: $T^2 = Kr^3$ (where r is the radius, T is the period, and K is a constant value, *the same for all planets*).

~::~

Now, Kepler's laws differ from Newton's later results in a very important way: they are empirical rather than kinematical. That is, they accurately *describe* the observed paths of the planets, without providing a mechanism to explain *why* they follow these particular paths. So fifty years later, astronomers and mathematicians were looking at Kepler's published observations and saying: Yes, I can see that over time, each planet follows a curve almost perfectly identical to that of a mathematically plotted ellipse (the first law). I sure wish they had been circles, but there it is and you can't argue with the facts. And I can even see—now that I've mastered the new "calculus of infinitesimals"—that lines drawn from the sun to a given planet at equal intervals of time divide the region inside the orbit into sections of equal area (the second law). And finally, orbital period and radius are related as square to cube, or area to volume (the third law). Agreement of all three laws with observation is quite astonishingly exact. *Now* what I want to know is, *given* that the planets move through the time and space of the solar system along curves of this particular shape, what are the *forces* acting on them, to *cause* them to do so?

Using powerful, brand-new mathematical techniques, Newton (and a few others) discovered that Kepler's laws were consistent with an *attractive force* governed by an *inverse-square law*. In other words: **if** each planet is attracted toward the sun by a force which varies inversely as the square of the distance, **then** each planet will trace out, over time, a path which obeys all three of Kepler's laws.

An important element of this hypothesis was that the force had to be *centripetal* ("seeking the center"), in contrast to the *centrifugal* force ("fleeing the center") we are used to imagining when, for example, a stone is whirled around in a slingshot before being let go. Centrifugal force, about which many of us learned in grade school, does not, in general, exist. In an explosion, there are centrifugal forces. In slingshots, and in planetary orbits, not.

Let's take up our slingshot and give it a spin. As the stone whirls around, there are two forces balancing each other. One is the centripetal force of the leather thong, which keeps the stone in its little orbit by pulling the stone straight toward the stick to which the thong is attached. Plainly, the instantaneous direction of this force is illustrated by the thong itself. The other force derives from the stone's *momentum*. When it's let go, one might at first think that the stone would fly off in a centrifugal direction. On a second look, this turns out to be not quite right. The "arrow" of the stone's momentum—the direction it would go if it were released at that instant—points, not in the direction of the thong, but always at a right angle to it (tangent to the circle it's swinging around in). The stone is pulling outward, but not "straight" outward. Compared to the centripetal direction of the thong, the stone's momentum is always pointing "sideways"—that's why it's going in a circle! This dynamic arrangement had long defied mathematical treatment, until it finally yielded to the application of the *calculus* developed independently by both Newton and Leibnitz in the 1600s.

On that day in 1666, Newton spent some time pondering the simple fact that gravity evidently reaches straight out from the center of the Earth. A stone dropped from a high cliff falls *straight down*, rather than, for example, at some angle that depends on the size or shape of the mountain. Gravity was evidently *centripetal*—just like the mysterious force that might explain Kepler's laws.

The math question

~::~

Why are mathematical models so central to modern science? This is a deeply controversial issue.

To understand the world on its own terms, rather than on human terms, the fundamental, universal technique is measurement. And measurement yields numerical results. That's part of the answer.

For example, let's say we want to know how long a year is. We count the days, from equinox to equinox for example, and we get 365. You might say that's how long the year is for people; that's how people experience it. Whereas, if the behavior of the solar system is our primary concern, and human beings' experience of that behavior secondary, and we watch very carefully, we can make the measurement much more exact. A year is 365.2422 days long (on average; the actual length varies because of gravitational interactions with the other planets). This number is, in effect, the period of Earth's orbit around the sun, divided by the period of Earth's rotation on its own axis. It has nothing to do with people.

It's not that there's anything wrong with human beings, or with being human. Love, art, philosophy, sex, rock 'n' roll—these are all human activities and I probably speak for the majority of scientists when I say I'm in favor of them. Science itself is perhaps the most quintessentially human pursuit. It's just that, in science we're trying to understand fundamental, universal truths that apply to all of nature, always and everywhere. From that perspective, human experiences such as "It gets dark when the sun sets," and "You can never see the other face of the moon," and "That group of stars reminds me of a swan," are simply too parochial to be useful.

Many of our early observations of the universe were made under the misapprehension that the whole universe was made especially for us by some deity. In the 1600s it was possible to begin to outgrow this. Much later, Darwin would write in *The Origin of Species* (1859):

> Were the beautiful volute and cone shells of the Eocene epoch, and the gracefully sculptured ammonites of the Secondary period, created that man might ages afterwards admire them in his cabinet? Few objects are more beautiful than the minute siliceous cases of the diatomaceæ: were these created that they might be admired and examined under the higher powers of the microscope?

This thought would not have been possible before the revolution that is our present topic.

So here's another part of the puzzle. In studying the structure and behavior of the universe with this new, self-effacing, deeply humble approach, scientists have been astonished, repeatedly, to find that when measurement is precise enough, the observed phenomena can often be described by comparatively simple mathematical rules. (Newtonian mechanics is the classic example.) *Why this should be so*, however, remains a mystery. Eugene Wigner, writing in 1960, called it "the unreasonable effectiveness of mathematics in the natural sciences."

Is nature inherently mathematical? (What would that mean, exactly?) Or, we can ask: is mathematics a kind of nature? That is, are mathematical laws in some sense laws of nature as well? This of course was Plato's view, but it has little currency among philosophers today.

There is a broad sense in which it could be said that scientists *choose* problems to solve that *can* be treated mathematically, as opposed to problems that can't. Richard Feynman once said, "There's a reason physicists are so successful with what they do, and that is, they study the hydrogen atom and the helium ion and then they stop." But this is not for some trivial reason, for example that scientists like playing with numbers, and they try to make the universe fit into their favorite games. Not at all. Nature dictates the mathematics, not the other way round. For some reason, when scientists try to "read the book of nature," they usually find that math helps—that, as Galileo first remarked, the book is *written in a mathematical language*. Therefore, those problems that are not susceptible to mathematical treatment are, in general, regarded as (temporarily) unsolvable and are left to the philosophers—until someone can find a quantitative approach.

In *Where Mathematics Comes From*, linguist George Lakoff and psychologist Rafael Núñez argue that the human brain uses the same deep mechanisms for its understanding of the physical world and for abstract, symbolic reasoning—that both, ultimately, are understood in terms of our physical experience of being in a human body.

Whatever the connection may be, it is certainly true that since Galileo much of our understanding of the world has been mathematical in character. However, the thing to remember for our present purposes is that Newton's work on gravity was not mathematics per se, but physics. He was not looking for beautiful equations; he was looking for useful explanations.

Now it all comes together

~::~

Now comes the real moment of inspiration, and we don't know exactly how it went. One can find many different narratives purporting to describe Newton's thoughts that day. This is due to his life-long tendency not to share his results—a reticence verging on paranoia. Newton's *Principia* contained an exhaustive and detailed treatment of Universal Gravitation, but was not written until twenty years later. Exactly what he did in 1666—*before* he had seen the important mathematical contributions (gracefully acknowledged in the *Principia*) of Huygens, Wren, and Wallis—was never revealed.

We do have the following, in Newton's own words (quoted in Ferris 1988):

> In those days I was in the prime of my age for invention & minded Mathematics & Philosophy more than at any time since.... I began to think of gravity extending to the orb of the Moon & ... from Kepler's rule of the periodical times of the planets being in sesquialterate proportion of their distances from the center of their Orbs, I deduced that the forces which keep the planets in their Orbs must

> [be] reciprocally as the squares of their distances from the centers about which they revolve: & thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the Earth, & found them answer pretty nearly.

However, this is lacking in detail, and furthermore, it was dictated many decades after the actual event. In effect, we know what kind of pie he baked, but not the recipe.

The following is adapted from the description in Timothy Ferris's peerless history of cosmology, *Coming of Age in the Milky Way*. It may well be quite close to Newton's actual thoughts.

~::~

Throw an apple across the yard. Its path corresponds to a mathematical curve: a parabola. (This was first demonstrated by Galileo.) Now imagine throwing it so fast that it doesn't fall in the yard, but travels halfway around the Earth. Is this still a parabola? Probably not.

Theoretically, a body—a cannonball, say—can be launched with such a velocity that it leaves Earth entirely and flies off into space. This would be more or less a straight line. Now, could there not be a slightly lesser velocity where the cannonball, instead of entirely escaping the influence of gravity, curves back toward the Earth, but "misses" it? And might it not then continue, for an arbitrarily long period, describing a perfect circle around the Earth? And in such a case, might this circular orbit not be solely attributable to *the influence of gravity*?

If gravity doesn't reach just to the tops of trees, or the tops of mountains, might it not extend to the orbit of the moon (and far beyond)? And in this case, could this not be *why the moon stays in its orbit*?

Imagine that Earth's gravity is a centripetal attraction governed by an inverse-square law, exactly like the *solar* force that seems to explain Kepler's *planetary* laws. Let's say that gravity is acting on the moon, constantly pulling it toward Earth. Were gravity suddenly to be turned off, the moon would continue in a straight line, tangent to its previous orbit (just as in the slingshot example earlier). Draw a line from where the moon *would* be after one second *without* gravity, to where it has "fallen" *because of* the influence of gravity. This would be how far gravity has pulled the moon in one second, and it can be roughly calculated if we know the size and period of the moon's orbit and if we are really good at geometry. It would seem to be about .0044 feet. Now an apple, in the same length of time, will fall 16 feet, and this is happening about 4,000 miles from the center of the Earth.

Why do we say "from the center of the Earth"? This is because in Newton's calculations, bodies were treated as "point sources" of attraction: as if all their mass were concentrated in their centers. This was a brilliant insight, and it makes a lot of sense if you picture the slingshot again: the center of revolution is effectively a point. Newton surmised that for bodies in general, especially spherical ones, the two cases were mathematically equivalent. Later, in writing the *Principia*, he managed to prove it. You actually *can* treat spherical bodies as point masses and still get the right answer, but in 1666, Newton was not entirely confident of this—which is possibly one of the reasons he didn't publish his results until much later.

Be that as it may, in 1666, having educated himself as to all the relevant science, and, where existing mathematical methods were inadequate, having developed the necessary apparatus from scratch—all in a few months—Newton had prepared the ground for an unprecedented thought experiment, the culmination of which went something like this.

In its first second of falling, an apple, roughly 4,000 miles from the center of the Earth, moves toward it about 16 feet. In the same interval, the moon moves *toward the Earth*, let's see, about .0044 feet. At 240,000 miles, the moon is about 60 times as far away as the apple, so the inverse-square law says it will experience 1/3,600 as much acceleration. 16 divided by 3,600 is .004444—that's pretty close! Therefore, the idea that gravity is centripetal, and that it varies inversely as the square of the distance—and that *the very same gravity* operates throughout the earthly and celestial spheres—*could be right*.

This was the first glimpse of a universal truth entirely unknown to the human race during its first million years.

Historical background

~::~

Let's take a moment to wind our history video *all* the way back to the beginning, the better to understand the context and significance of Newton's insight.

The first beings we would now call *human* lived roughly a million years ago. When those first hunters and gatherers, our ancestors, looked up at the night sky, they saw a multitude of exquisitely beautiful, impossibly brilliant pinpricks of light. Long before recorded history, human beings began charting these heavenly sparks and keeping track of their behavior. Through meticulous observation and record keeping, early astronomers learned, some thousands of years ago, to predict the phases of the moon, planetary conjunctions, and so on—even eclipses, which are really tricky to figure out.

From the very beginning, people must have had a lot of questions about the heavens. Unfortunately, they would have been unable to find anyone who could answer even the simplest ones. The remoteness of the starry world made it impossible to learn anything about the objects living there. Of what material, for example, are the stars composed? How big are they, and how far away? Why do a few of them move, while most don't? Why do they come in different colors? The white mist in the Milky Way—what's that made of? And perhaps the biggest, the most central mystery: why do the sun, the moon, and all the planets, and all the stars, circle the earth every day? None of these questions could be answered, nor was there any reason to believe that they would be answered in the future.

Still, many fascinating observations could be made. First, of course, the whole field of stars moved as a unit. Individual stars never moved with respect to each other—they just turned, all together, around the earth, exactly as if the sky were a huge revolving sphere, decorated with precious jewels (or pierced with tiny holes). Because of their brightness, a handful of people speculated that the stars were actually distant suns—but this seemed unlikely, because their tiny appearance would then imply that they were set at a truly inconceivable distance.

Poets, astrologers and philosophers composed countless tales, extracting cosmological allegories and morality plays from the evocative patterns festooning the tent of heaven. Some of these stories attained the status of myths; they could be passed down through hundreds of generations, because the constellations never changed. Strictly speaking, though, these were human stories—the twins, the swan, the Milky Way—they were not stories about the stars themselves.

Among the myriads of celestial beings, there were exactly seven that traveled, independently, among the fixed stars. These were the sun and moon, plus five very special objects which the Greeks called *planetes*: wanderers. Individually, we know them by their Roman names: Mercury, Venus, Mars, Jupiter, and Saturn. We know these names because the planets evoked wonderful stories of their own. Venus was associated with beauty, presumably because of its fabulous radiance in the dusk or dawn hours (often with a crescent moon nearby). Mercury was the fleet one—depicted with wings on his All-Stars—and so on. Again, none of these stories had much to do with the diverse and absolutely astonishing natures of the bodies that actually orbit our sun. They were yarns spun from the wool of human experience. They reflected human affairs and human concerns. They "explained" nature by giving it a human face.

We now know that those bright, "fixed points" in the night sky actually *are* distant suns, except for the ones that are entire galaxies: congregations of *billions* of suns. We live in such a galaxy, and the night sky's Milky Way is our view of it from out near the edge—a glimpse of the glittering skyline of the Big City from our rural hilltop 30,000 light-years away. We also know that though the constellations seem changeless in human experience, they are not actually permanent. A million years from now, none of the ones we recognize will still be visible. This is because they are actually three-dimensional arrangements of stars at various distances from us. We see them as if projected onto an imaginary surface, the *celestial sphere*. Only from our point of view in this particular solar neighborhood do they take the forms with which we are familiar. And since all the individual stars are actually moving through space in different directions—each pursuing in its own unique path through the infinitely complex gravitational contours of the galaxy—their accidental groupings, as seen from our neighborhood, are slowly, but constantly, changing. (A partial exception is the Pleiades, whose opalescent beauty derives in part from surrounding "molecular clouds" that reflect and tint the starlight before it heads out into space. Unlike most constellations, the Pleiades really is a cluster of stars. Bound to each other by mutual gravitation, the Seven Sisters are slowly changing partners in a kind of merry Maypole dance. They will still be clustered together—though in a different arrangement—even millions of years from now.)

It was simply impossible to know any of these things before the invention of the telescope. And so, for a million years, the celestial world consisted of the sun and the moon, and a stunning night-time panorama of magical colored sparks. Their movements could be predicted, sometimes—explained, never. Not until the seventeenth century did explanations begin to appear.

Contrary to some reports, *none of the beauty was lost* in the scientific revolution. The heavenly bodies are, and will always be, magnificent. In the seventeenth century we began to be able to see *what's really out there*—to see, in fact, just how beautiful they are.

In 1610, Galileo Galilei announced (in *Siderius Nuncius*, usually translated as *The Starry Messenger*):

> I have observed the nature and the material of the Milky Way. With the aid of the telescope this has been scrutinized so directly and with such ocular certainty that all the disputes which have vexed philosophers through so many ages have been resolved, and we are at last freed from wordy debates about it.

He had seen it with his own eyes: the Milky Way is made of *stars*.

Galileo did not invent the telescope, but in 1609, soon after he heard about it, he had managed to build one for himself. Where others were using their new instruments to observe ships far from port, or armies far from the castle walls, Galileo is the very first person we know of who turned his toward the night sky. Through his telescope, what had been only vague shadows on the moon were resolved into a landscape of mountains and valleys. The moon was a world, like Earth! This discovery so clearly contradicted the traditional conception of the heavens as being "perfect," that Galileo knew he was about to become famous. (Unlike Newton, he relished the possibility.)

And he was just getting started. A few months later, he noticed three tiny stars, arranged in a perfectly straight line, very close to Jupiter—but they couldn't be stars, because stars don't move (compared to all the other stars). He could see them shifting, changing places, even in the course of a single night. Soon he was quite sure they were *orbiting Jupiter*—another blow for the traditional model, because in addition to being "perfect and unblemished," all the planets were supposed to be orbiting Earth. Galileo also observed the phases of Venus—it waxes and wanes like our moon does. This strongly suggested that Venus orbits the sun. Galileo insisted, perhaps disingenuously, that the phases of Venus proved once and for all that Copernicus was right. This was not strictly true, because other explanations were still conceivable. They did, however, prove that Ptolemy was wrong.

An odd thought suggests itself with regard to Galileo's telescope. With its modest magnification and its heavy chromatic aberration, it would have performed rather poorly if compared to a $75 pair of modern binoculars. This means that the marvelous things Galileo saw—which, as far as we know, *no one* had ever seen before—are *just barely* outside the capabilities of the naked (human) eye. Hawks and eagles have probably been watching them for eons, but of course these creatures have never recorded their sightings for the benefit of others.

~::~

Isaac Newton read Galileo about fifty years later, in his third year at Cambridge. By then the Copernican model of the solar system was already part of mainstream scientific thought. It had been convincingly demonstrated that of all the heavenly bodies, *only the moon* orbited the earth. All the planets—of which Earth was now one!—orbited the sun. The size and even the "weight" of our planet were approximately known, as was the distance from Earth to the moon.

Yet, the mysteries I listed at the beginning of this section were still mysteries, and in this regard cosmology at the beginning of the seventeenth century was closer to that of our remote ancestors, 40,000 generations ago, than to our own. Much had been learned of the *apparent movements* of the heavenly bodies, across earthly skies—virtually nothing of the *actual character* of those bodies.

During the seventeenth century—just a few hundred years ago—we began to dramatically expand our frame of reference: to look at celestial events in a celestial context. Instead of putting a human face on nature—thinking of the planets as *super-human* beings, for example—we were learning to put questions to nature in nature's own language. And because, for the first time in history, the questions were correctly posed, we could hear, plain as day, the answers coming back.

Wrinkles

~::~

Newton's theory of Universal Gravitation, after it was finally published, was considered exactly perfect for hundreds of years. "Nearer the Gods no mortal may approach," wrote the astronomer Edmund Halley (discoverer of the periodicity of the comet now bearing his name) in an *Ode to Newton*.

However, there were a few, shall we say, *wrinkles*. Some were known right away; others were discovered much later. One of them has to do with the gravitational attraction between objects that are not spherical. This is mathematically a very thorny problem. However, it is not *in principle* a problem for the theory. It just makes the calculations extremely tough.

Then there's the "many-body problem." The *Principia*'s examples mostly deal with only two objects at a time, but real situations always involve more than two things. The solution is to separate out the most significant interactions, treat them independently, and then add them up, hoping that the weaker effects didn't matter very much. It's approximate, but it basically works. For mathematical purists, it may be highly suspect—but what else are you going to do? Newton himself threw up his hands on this one (as quoted in Ferris 1988, p. 121):

> The orbit of any one planet depends on the combined motion of all the planets, not to mention the action of all these on each other. But to consider simultaneously all these causes of motion and to define these motions by exact laws allowing of convenient calculation exceeds, unless I am not mistaken, the force of the entire human intellect.

Did it invalidate the theory? No, because for most practical purposes it would still get you the numbers you needed, to whatever precision you needed.

The really devastating "wrinkle" was found by Albert Einstein, who in 1905 yanked on it hard enough to pull the entire Newtonian fabric away, revealing the exceptionally fine mahogany tabletop underneath, and without even spilling our soup. But that's a story for another evening.

The next million years

~::~

In evolving from human-centered to nature-centered explanations, seventeenth-century science discovered more than a new set of tools for the quantitative prediction of natural phenomena. The new explanations have had a profound effect on our sense of what it means to live in this world.

The cultural relativism prevailing in postmodern intellectual discourse might tempt us to concede, with a kind of false modesty, that our new understanding is not actually superior to the old one—only different. This would be incorrect. "Everything is relative," a popular sound bite referring to (and misquoting) Einstein's theory of relativity, entirely misses the point. Einstein did not say *everything* is relative, and in fact, not everything is relative. The new understanding that Newton helped inaugurate was not just different from what came before. It was truer.

Speaking of Einstein, some would claim (were they to read this article) that the theory of relativity represents *another* million-year cusp. I am proposing that the differences between Newton's world and our own are already so huge that relativity doesn't change the picture significantly.

Besides, we may not be able to experience the Einsteinian world-view until we have first internalized the Newtonian one. Take mornings, for example. Very rarely do we notice what Copernicus believed, and Newton made plausible—and what human beings have now seen through their own eyes, looking back from the moon: that we live on a *planet*. Every morning, we have an opportunity to observe the gentle eastward roll of our home world, and to behold again the fiery countenance of our closest star. Instead, we usually see what our ancestors did a million years ago: "the sunrise." (See Swimme 1996 for some helpful hints on this particular problem.)

We are learning, we humans—slowly, perhaps—by fits and starts, perhaps, but in any case the wall is down and it won't be rebuilt because we are better off without it. Perhaps in a few more generations we'll *grok* where we really live, when we look "up" at the starry sky or "down" at the living earth. We are fortunate to be here, at this time and place, surfing the density waves at the edge of the galaxy, on this rare and beautiful blue-green world—our eyes newly opened, and the next million years, just begun.

FOR FURTHER READING

Dawkins, Richard. 1998. *Unweaving the rainbow: science, delusion, and the appetite for wonder*. Boston: Houghton Mifflin.

Deutsch, David. 1997. *The fabric of reality: the science of parallel universes, and its implications*. New York: Allen Lane.

Drake, S. (ed.) 1990. *Discoveries and opinions of Galileo*. New York: Anchor.

Einstein, Albert. 1920. *The principle of relativity*. Translated by M. N. Saha and S. N. Bose. Calcutta: University of Calcutta.

Ferris, Timothy. 1988. *Coming of age in the Milky Way*. New York: Morrow.

Keesing, R. G. 1998. The history of Newton's apple tree. *Contemporary Physics* **39**:377-391

Lakoff, George and Rafael E. Núñez. 2000. *Where mathematics comes from: how the embodied mind brings mathematics into being*. New York: Basic Books.

Newton, Isaac. 1999. *The principia: mathematical principles of natural philosophy*. Translated by I. Bernard Cohen and Anne Whitman. Berkeley: UC Press.

O'Connor, J.J. and E.F. Robertson. *Newton*. Jan. 2000. U. of St Andrews, Scotland. 10 Oct. 2002. <http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Newton.html>

———. *Orbits*. Feb. 1996. U. of St Andrews, Scotland. 10 Oct. 2002. <http://www-gap.dcs.st-and.ac.uk/~history/HistTopics/Orbits.html>

Panek, Richard. 1998. *Seeing and believing: how the telescope opened our eyes and minds to the heavens*. New York: Viking.

Park, David Allen. 1997. *The fire within the eye: a historical essay on the nature and meaning of light*. Princeton: Princeton University Press.

Rubin, P. *Physics 131 lecture notes*. 24 Nov. 1998. University of Richmond [Virginia]. 10 Oct. 2002. <http://chemweb.richmond.edu/~rubin/pedagogy/131/131notes/Newton.html>

Ryan, C. (ed.) 1979. *Starry messenger: the best of Galileo*. New York: St. Martin's.

Swimme, Brian. 1996. *The hidden heart of the cosmos: humanity and the new story*. Maryknoll, NY : Orbis.

Westfall, Richard S. 1980. *Never at rest: a biography of Isaac Newton*. London: Cambridge University Press.

Wigner, Eugene. 1960. The unreasonable effectiveness of mathematics in the natural sciences. *Communications in Pure and Applied Mathematics* **13**, no. 1.

###