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Daughter Moon

"I'm bursting with delight at my work of the last few days," wrote George Darwin to his father, Charles Darwin, on April 25, 1876. "I've been thinking day and night over Evans's suggested problem about the alteration in the axis of the earth. After long thought I have got through the hardest part and I think I see exactly what is the mathematical problem involved. . . . I'm rather counting my chickens before they're hatched, but I'm regular [*sic*] bursting with ideas on the subject."

Little did he realize it, but George Darwin had just stumbled on his life's work. His feverish ideas of that April would turn into a series of papers about Earth's rotation, about the tidal interactions between Earth and the Moon, and finally about the distant past of Earth and the Moon. Although a few people had jotted down some ideas about the Moon's origin, no one that we know of before Darwin really thought of it as a separate problem from the formation of the rest of the planets. And certainly no one subjected his or her ideas to the intense mathematical analysis, running to thousands of pages of calculations, that Darwin ultimately did. If Galileo and Kepler brought the Moon down to Earth (Galileo through his telescope and Kepler through his imagination), then Darwin was the man who brought its past into the present.

Britain's First Family of Science

Few people were ever brought up in a time or milieu more conducive to learning than George Darwin. Born in 1845 in Down, County Kent, England, he was fourteen years old when his father's monumental work *The Origin of Species* was published. His father enrolled him in a new style of public school, one where the sciences were emphasized as much as philosophy, religion, and the classics. Charles

Darwin never pushed his five sons, but he did support any interests that arose naturally. When the young George became fascinated by optics, Charles bought him a set of lenses. Charles also taught him the line from Anthony Trollope that became George's personal motto: "It's dogged as does it."

Sundays were a highlight of life at Down. Charles Darwin did not go out very often in later life; instead, friends and fellow scientists came to visit him. The long hours of conversation on the scientific and political topics of the day made for "the most agreeable society I have ever known," wrote George. His father was seldom eloquent ("I do not know that I have ever heard anyone whose sentences so often contained some infraction of grammatical rule," George recalled), yet always to the point.

With such a childhood environment, it is not surprising that all of Darwin's sons grew up to have impressive careers. The oldest, William, became a banker. Francis, the third son, followed in his father's footsteps and became a naturalist, and ultimately—like both Charles and George—a knight of the British Commonwealth. Leonard, the fourth, followed Charles in a sadder way. He became a leading eugenicist, trying to use the principles of evolution to prove the superiority of certain classes or races over others. It was a respectable theory at the time that became infinitely less respectable after World War II. Horace, the fifth and last son, founded the Cambridge Scientific Instruments Company, for many years a leading supplier of laboratory apparatus, and served briefly as mayor of Cambridge.

George was not an overnight success. He went to Cambridge University and graduated in 1868, taking second place in the university's vaunted mathematics competition, the Tripos. But after that, he vacillated, dithered, and struggled with poor health, which would become a lifelong annoyance to him. He studied for the bar but did not go into a law practice; he tried his hand at sociology, statistics, and economics but failed to accomplish anything of note.

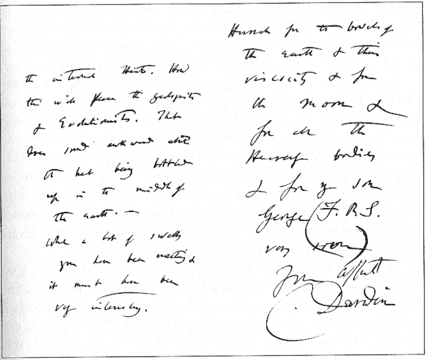
Then, toward the end of 1875, he struck gold. One of the biggest geological puzzles of that time was—and still is—the cause of ice ages. A fashionable theory, generally advocated by biologists who knew little about physics, attributed them to shifts in Earth's axis. In other words, Earth's poles had moved around over millennia, causing glaciers to appear in places that don't have them anymore. One scientist had suggested that this movement could have been caused by the rising of new continents out of the sea. Darwin didn't believe it, and in April 1876, the time of the creative frenzy he described to his father, he sat down to prove it.

Darwin considered an extreme scenario: How far would the pole shift if a continent a quarter the size of the Northern Hemisphere suddenly emerged from the ocean? He worked out that each foot of rise would move the pole by fifteen yards, so even a rise of ten thousand feet—the height of the Tibetan Plateau, highest on Earth—would move the pole by only one and a half degrees. There was no way this theory could explain ice ages. Darwin wrote a paper on the subject and, feeling "like a pea meeting a cannonball," discussed it with Britain's leading physicist, Sir William Thomson (later Lord Kelvin). Thomson praised the paper, and Darwin was on his way to a new career. With that, Thomson became a lifelong friend.

Meanwhile, the ideas continued to bubble forth from Darwin's pen. If a change of axis couldn't explain ice ages, perhaps a change in the obliquity of Earth's rotation could. This would be different from the other theory: The North and South Poles would remain in the same geographic locations on Earth, but the tilt of the axis of rotation with respect to the ecliptic plane would change. The Earth's present twenty-three-degree tilt has a powerful effect on climate; it is responsible for the seasons, and it delineates the Arctic and Antarctic Circles. George Darwin's idea was that tides—not tides in the ocean, but distortions in the entire shape of Earth—had caused the tilt to grow.

By 1878 George had written a paper proving his thesis about the tides, and his stock was rapidly on the rise. On October 29 of that year his father wrote him a letter awash in paternal pride: "My dear old George, I have been quite delighted with your letter and read it all with eagerness. . . . Hurrah for the bowels of the earth and their viscosity and for the moon and for all the heavenly bodies and my son George (F.R.S. very soon)." As he wrote these words, Charles Darwin's usual cramped handwriting grew larger and larger and darker and darker, and the last three words were a great, ungainly scrawl of emotion.

Charles forecasted his son's triumph correctly. (He may have had inside information.) George was indeed made a Fellow of the Royal Society (F.R.S.) in 1879, which, for a British scientist, was the equivalent of earning a union card. Four years later he became a professor


the internal heat. How this will please the geologists & Evolutionists. That [illegible] it has been bubbled up in the middle of the earth.— What a lot of swells you have been meeting & it must have been very interesting.

Hurrah for the bowels of the earth & their viscosity & for the Moon & for the Heavenly bodies & for my son George (F.R.S. very soon) Yours affect C. Darwin

When George Darwin's first papers on tidal friction came out, his father, the world-famous naturalist Charles Darwin, could scarcely contain his pride. "Hurrah for the bowels of the earth and their viscosity and for the moon and for all the heavenly bodies and for my son George (F. R. S. very soon)," he wrote in this letter from October 29, 1878. *Courtesy of Cambridge University Library.*

of astronomy at Cambridge University, where he would spend the rest of his life. By then, unfortunately, Charles was no longer alive to cheer him on; the elder Darwin had died in 1882.

The Fission Theory

Darwin's theory of the origin of the Moon grew out of his work on the tides; he first began to work on it in about 1878, and he continued to add details throughout his life. It is a theory worthy of the son of the great evolutionist, because it is very much an *evolutionary* theory of the Moon—and Darwin himself thought of it in those terms.

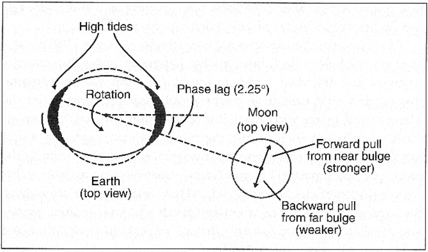
Darwin began by investigating the tidal forces of the Moon on Earth, which he had already shown would lead to a gradual increase in the tilt of Earth's axis. Everybody knows that the Moon creates tides in the oceans, but the same forces also must create bulges in the solid body of Earth, though they are not as noticeable as the ocean tides. If Earth had a molten beginning, as all astronomers thought at the time, then the tides might have been even stronger at that stage.

Very roughly speaking—perhaps *too* roughly—the Moon makes Earth bulge in two places: the part directly beneath the Moon, and the part directly opposite the Moon. But because Earth rotates faster (once a day) than the Moon revolves around it (once a month), its rotation carries the bulges past where they would otherwise be. This has to do with the viscosity of Earth, as noted in Charles Darwin's letter to George; the rocks and oceans cannot relax immediately once they are past the region of greatest tidal force. One might compare Earth to a giant glob of silly putty, which only grudgingly changes its shape when you squeeze and knead it.

So we can visualize Earth as a spherical body with two bulges: one closer to and a little bit ahead of the Moon, the other farther from and a little behind the Moon. The Moon's gravity tends to pull the nearer bulge backward, because it is behind that bulge. For the same reason, the Moon pulls the more distant bulge forward. But because the gravitational force on the nearer bulge is stronger, the overall torque is backward, against the direction of Earth's rotation. The Moon is gradually slowing Earth's rotation, making the day get longer.

This much had already been figured out by Kant, although he waffled on it later in life. Like many other scientists, Kant believed that Earth had contracted as it cooled, and that the contraction would speed the day, thereby counteracting the tidal effect.

By Newton's first law ("Every action has an equal and opposite reaction"), if the Moon was pulling backward on the tidal bulges, those bulges must be pulling *forward* on the Moon. It would be natural to assume that this makes the Moon orbit Earth faster, but that would once again be a Keplerian/Cartesian mistake. Thinking again of the rock swinging around at the end of a rope, if the rock starts moving faster, it will tend to pull out on the rope. Unless you resist that force, the rock will move outward, and the radius of the circle it moves in will increase (assuming there's more rope). In space, of course, there is no rope holding Earth and the Moon together, so the Moon *does* move outward. The net effect of the tidal bulges is not to make the Moon go faster, but to make it retreat from Earth. As it



George Darwin's theory of tidal friction. Earth's rotation, which is faster than the Moon's orbital motion, carries Earth's tidal bulges around too fast for the Moon to keep up. As a result, the nearer high-tide bulge is slightly ahead of the Moon, and the farther one is slightly behind. However, the gravitational force from the nearer bulge is slightly stronger, so there is a net forward pull on the Moon (in addition to the much larger pull toward Earth's center, which is not shown here).

moves away, the month gets longer (because of Kepler's third law). Thus both the month and the day are getting longer. But the mathematics revealed that the day is lengthening more rapidly than the month is, so at some time in the far future it will catch up. At that time, Darwin worked out, the month and the day will both last fifty-five of our present days. Earth will always show the same face to the Moon, just as the Moon already shows the same face to Earth, and this arrangement will be stable for all time.

What if we run the movie backward? As we move backward in time, the Moon gets closer and closer to Earth. Both the day and the month get shorter and shorter, until the Moon is whizzing around Earth once every five hours and thirty-six minutes, and Earth is rotating at the same speed. At this point, the Moon's surface would loom over Earth, only five thousand miles away. To put it another way, a flight from Earth to the Moon would be shorter than a flight from London to San Francisco. But that is assuming that both bodies retained their present shapes. If they were molten, they would be hugely distorted by the immense tidal forces on them. The Moon would have a cigar shape, perhaps twice as long as it was wide. The two bodies would be practically touching one another.

At this point, the movie reel, frustratingly, runs out. The physics gives no valid clues for inferring what happened earlier, because the situation just described is also an equilibrium. But anyone watching this movie would have little doubt about what happened next: the Moon would merge with Earth. Of course, that's in the "backward" version of the movie. Running the movie forward again, we would see Earth flinging the Moon off into space. And that (minus the movie-projector imagery) is how George Darwin came to propose his fission theory of the Moon's birth. "These results point strongly to the conclusion that if the Moon and Earth were ever molten viscous masses, then they once formed parts of a common mass," he wrote in his seminal paper, published in 1879.