Epilogue: The Morning After 400 Years of Data and Science in Practice

TwnPks_RkGdn_left_med.jpg

We have seen the progress of science from the Middle Ages to its present tentative inferences on planetary habitability. We have gone from burning Bruno to the stake to landing probes on Mars. During this time, scientists sought generalizations from observations and made hypotheses based on these generalities. They then used logic (including mathematics) to make testable predictions from the hypotheses.

The actual practice is more complicated. Working scientists really generalize and predict at the same time. Even in the time of Galileo, scientists possessed reams of data. They need to do triage on their data to proceed.

(1) Many data are probably right and can be explained by existing theory. This is the stuff of routine science. Many scientists spend their careers making reliable observations. They and their colleagues interpret these data.

(2) Data that are probably wrong need no explanation. Such data need to be recognized as such before they become a big waste of time.

(3) Some data are probably right, but cannot be explained by current hypotheses. Here is where scientists achieve fame and glory. One acts at first on hunches, while avoiding issues that are too complicated. One proceeds either from recognizing a target of opportunity or an inconsistency in the currently accepted hypotheses. Einstein did the first in that he recognized the need to include gravity in the theory of relativity that had just proved useful for explaining the behavior of light. He partly proceeded from observations of the orbit of Mercury and a hunch that one could explain them by modifying Newton's laws of gravity.

Hunches often do not pan out. That is, the hunch hypothesis fails to explain even the data for which it was concocted. Then, it may never see the light of print. Scientists do not like to spend lots of time reading about what doesn't work. Graduate students learn early to avoid writing voluminous tracts on their missteps. I have brought in a limited number of dead ends into this book to illustrate how science works.

Sometimes, a hypothesis explains the observations for which it was formulated. If it is a major modification of existing wisdom, it is likely to attract attention. In the case of general relativity, light no longer traveled in straight lines. Scientists are human. They do not quickly abandon concepts that they have just taken a lot of effort to learn. (I had the advantage that I had not yet spent a lot of time accumulating excess baggage when I encountered plate tectonics as a young student in 1967.) It is work to understand a new hypothesis, especially a highly mathematical one like general relativity.

An individual scientist must act on gut feelings. The twin pillars of science, logic and observations, provide feeble help at this turning point of careers. (Otherwise, the issue would already be resolved.) Fish or cut bait? Should I stop everything or go about my business as usual? Are the data on which the hypothesis is based likely to be correct? In part, can I trust the source of the data? Does the hypothesis make sense? Do I see other observations that may bear on the hypothesis? And finally, do I have the knowledge and tools to do something useful?

Scientists concerned with the hypothesis sort themselves out into pros and cons. Proponents seek additional observations to explain. They make reputations if the hypothesis is successful with the added observation. (This is how I got my career started with plate tectonics.) If not, they become disillusioned. At the end of a failed hypothesis, only a hardcore of true believers remains after all others have consigned it to a dustbin. Conversely, the opponents seek cases where it seems likely to fail. (This is what I did with mantle plumes in the 1980s.) They become well-respected proponents when the hypothesis passes these tests. The hypothesis then becomes established, that is, tentatively considered correct. The final holdouts against the hypothesis succumb to old age.

It may seem inelegant to proceed from hunches. Yet, the waste of time chasing dead ends pays off. On the personal level, universities and research organizations expect results. A scientist who remains silent until any hypothesis has passed the test of time will be content with a teaching position at a small college. On a societal level, too much conservatism is a recipe for staying in the Stone Age. One can always urge delay in that better equipment or data will be available in 10 years. Following this advice foreordains that no equipment or data will ever be forthcoming.

Being wrong is no big sin in science. Any productive middle-age scientist has been wrong several times. (I have my share.) Scientists regard "perfectionist" as an insult. Well-posed wrong ideas like the Sun going around the Earth, fixed continents, and even a 6,000-year-old Earth led to measurements and progress. Problems arose when dogmatism had real secular power. Religious authorities imposed geocentric astronomy for centuries. Young-Earth Creationists impose laws and textbooks on K-12 instruction in the United States, but research science remains out of their grasp. Geological authorities in the old Soviet Union stifled plate tectonics for decades. However, scientists not in the tentacles of their branch were unaffected. The Politburo did not concern itself with this technical matter.

There are three cardinal sins for scientists, in no particular order. The first is to produce worthless data, that is, data that are much less precise and accurate than purported. This results in getting one's experimental findings ignored. Faking data terminates one's career when caught. It goes on infrequently. It is far easier to produce routine but sloppy data on an issue of little consequence. Fake data on an overriding issue invites notoriety, attempts at duplication, and exposure. Recent scandals involved very important, but extremely difficult to reproduce data including stem cell work and the discovery of a new heavy element. Moreover, duplication (and hence the potential for exposure) gets done often as a first step to extend less notable findings. The second sin is not bothering to find out what is already known. Scientists collaborate with those in related fields because there is too much for anyone to learn. At the other end, well-known scientists continually receive tracts from amateur “nuts.” These end up either in a nut file, computer trash, or the recycle bin. The scientific community takes notice when a previously respected scientist goes off half-cocked into theorizing outside his field of expertise. The third sin is to ride a dead horse. Scientists remember from their youth distinguished older scientists ending their careers as holdouts. Both holdouts and nuts selectively cite only the evidence that fits their viewpoints. Milder forms of evidence selection occur even when a scientist is trying to be careful. It is hard to simultaneously exclude data that are likely to be wrong and to include all available evidence. I have erred in both ways.

Being logical

Logic separates science from pseudoscience. The field of mathematics has been onerous since the time of the Greeks. Graduate students in physics spend years learning higher mathematics. Many scientists devote careers to improving computational methods. There are calculations, like the accretion of planets that are at or beyond the limit of the largest computers. We cannot calculate what a string of DNA and the protein it codes will do macroscopically in an organism and we certainly cannot design (animate in its old sense) a creature from a Dr. Suess book from scratch.

The astrobiologist is faced with a mixture of hard data and theory, like the evolution of stars, and qualitative data, like geological observations of planetary surfaces. She lacks highly desirable data on extrasolar planets and even on the details of Mars and Europa. She must use the hard data to sort out the soft. Then she will proceed from hunches. Astrobiology is still a field with no confirmed astrobiota to study. We need to admit this ignorance.

Testable and compromising positions. Astrobiologists have to be particularly careful about testability. Their science forensically interprets circumstantial evidence in the geological and cosmic records. Formidable logistics limit immediate tests. Like all healthy sciences, it has a litany of hypotheses to test, a dumpster full of failed hypotheses, and a repertoire of repeatable observations and experiments. Yet pseudoscientists simultaneously exempt their pet theories from these trifling inconveniences and hold conventional science to the impossible standard of omnipotence. "You did not show to my satisfaction that goblins do not live in the center of the Earth. This means that Goblin Theory is a viable alternative science. Conventional science does not know everything. Seismologists even failed to predict the earthquake that occurred right here last week. Thus these spirits of the vasty deep must cause earthquakes." Proponents of untestable and off-base hypotheses often appeal to compromise and fair play. Thus the Orwellian terms for quackery: "alternative medicine," implying a dichotomy and equality with medical science and "integrative medicine," implying that equality has already been established. Actually anyone can come up with a myriad of alternative ludicrous cures. All can predict earthquakes or summon goblins from the bowels of the Earth. But will they come?

Six months after the *Porcupine Dialogue* in Chapter 4, Lithophilo and Rustico have nice photos of porcupines mating always in an ordinary mammalian manner. Faced with an increasingly untenable position, Eudoxio retreats to a compromise that is immune to refutation by further observation. Porcupines sometimes mate like other mammals, but they need help to get ready from Arachne always when no one is looking. He is begging the issue, a hallmark of holdouts for a dying hypothesis as well as outright pseudoscientists. I remember many holdouts and off-base arguments on the more recent controversies about plate tectonics and asteroid impacts, but none to the point of total untestability. Much earlier, two distinguished mainly empirical scientists replaced moribund testable hypotheses with untestable ones.

In the late 1500s, Tycho Brahe, the Danish naked eye astronomer, had amassed a wealth of observations. The Sun-centered Copernican system seemed to make analysis simpler, but Tycho was unwilling to have the Earth move. He proposed that all the planets except the Earth (and Moon) orbited the Sun. The Sun and the rest of the planets then orbited the Earth as a unit. This rendered his hypothesis untestable at the time, as observations of the positions of the planets on the background of the stars were the same as in the Copernican system. So was the crescent of Venus seen by Galileo.

What Tycho did was mathematically transform the Copernican coordinate system so that the Earth is fixed. It is OK in one sense to do this. In modern physics, coordinate systems are arbitrary and for our convenience. For example, the optical astronomer makes calculations with Newtonian gravity (or general relativity) as discussed on Chapter 3. She centers her coordinate system on the center of mass of the solar system near the center of the Sun. This keeps the physics simple and predictive. At the end, she transforms her results into the Earth-floored frame of her telescope. She knows there is nothing special about this place, which is why Tycho's compromise is wanting. She could have used anywhere around the solar system, practically an interplanetary space probe beyond Pluto or a lander on Mars. Tycho's compromise would have been quickly forgotten had the Churchmen prosecuting Galileo not taken it seriously.

Ironically, Tycho's system proved both testable and wanting. He did not anticipate the development of physics by Galileo and Newton that has continued to the present. Countless observations, including the aberration of starlight, show that the Earth really orbits the Sun. The effects of the Earth's rotation on winds and ocean currents are a major part of modern mathematical meteorology (Chapter 11).

“To ourselves .... new paganism .... omphalos."

-- James Joyce, *Ulysssses*, 1922

The second great compromise, *Omphalos* by Philip Henry Gosse (1810-1888), has a more medieval aroma. Just what does this Greek word mean. Change the "f" sound to a "b" and modify the vowels and we have the Latin "umbilicus." Drop the leading vowel, insert a vowel between "m" and the "b", and fiddle with the pronunciation we have the English "navel." Yes the belly button, a serious and irresolvable matter for Scholastics in the Middle Ages. Adam and Eve were not born of woman, did they have belly button that revealed an event that never occurred? Artists sometimes dodged the issue by placing a fig leaf there as well as in the usual spots. (Such Puritanism persisted in the 1960s when censors restricted the dress of the lead character in the TV show *I Dream of Genie*.)

In 1857, Gosse was a respected naturalist and a keen observer. By then, the great antiquity of the Earth was a given even among scientists who supported events of biological creation. Gosse saw that all evidence points to an ancient Earth and provided an excellent summary in his book. Troubled, he saw that Adam would need far more anatomy than his navel to be viable.

Indeed Adam's whole body reveals growth that never occurred. This need for viable anatomy applies to any organism made from scratch, a "creature" in the original theological meaning of the word. To use a modern word, the whole ecology has to be present so that the new creatures did not immediately starve. The air has water vapor and rain clouds so they do not die of thirst. Gosse went on for over 200 pages providing numerous examples. In for a penny in for a pound, he proposed that the apparent great antiquity of the Earth was just an illusion. 6000 years ago, the Almighty created the Earth with both viable creatures showing growth that never occurred and a geological record giving a history that never happened. He was dead serious that he had solved a vexing problem once and for all.

Darwin published *The Origin of Species* within the decade. Omphalos ired the scientists opposing Darwin who were quite reluctant to relegate their work in geology and paleontology to mere studies of illusions. The old-earth catastrophists had real evidence, for example, the mass extinction at the end of the Cretaceous Period (66 million years ago on the modern time scale, now attributed to the natural cause of asteroid impact). For the most part, Gosse has never enamored religious Creationists who do not like having to explain why their benevolent deity made the geological record other than just to trick us.

Omphalos is great for poking fun. Gosse's own examples invite horselaughs. Coprolites (fossil dinosaur manure) came from ponderous breasts that never lived to defecate and contain scale fragments from fish that never swam. Light arrives from distant stars that never existed. I add the modern topic that the craters of the Moon record the impact of nonexistent asteroids.

The more serious problem is that no geological (or really any) observation can ever bear on the hypothesis. As Gosse saw, there is nothing special about 6000 years except in the Hebrew Bible. One could equally well claim that Creation occurred 8 minutes and 37 seconds ago so my memory of the work taken to write this book and your memory of reading the previous chapters are just illusions. This is true whether you pick up the book in 2010 or 52250. Foraying into modern physics, Creation occurred just 8 minutes and 37 seconds after the Big Bang.

Attention to Omphalos lingers because it is the type example of a special-pleading hypothesis that can never be tested and nor potentially refuted by observations. It is a wondrous journey into sophistry. It brings chuckles from scientists and philosophers whenever anyone is ignorant enough to bring it up as serious science. Gosse's tendency to make analogy between legal proceedings and scientific reasoning with the Bible elevated to eyewitness accounts and the geological record relegated to mere circumstantial evidence, however, remains a tactic of Creationists. It falls flat in the modern courtroom. Circumstantial DNA is far more reliable that live eyewitnesses.

Technology versus insight, a retrospective. Now back from how not to do science to how science got done. Astrobiologists are technologically limited. They have just barely detected earthlike planets around other stars. We have no samples of Europa and none of the subsurface water on Mars. They are also limited by insight but they don't know it, except as a generality. To know a specific lack of insight is to think of it. Let's see which of the major discoveries of the last 400 years did not require high tech. That is, which ones could have been done with equipment in hand in 1600 or even classical Greece?

There is, of course, a two-way link between the ancients' lack of instruments and their aversion to measuring things. With rare exceptions, like Archimedes, they did not behave like Galileo with the telescope. They had no precise data that required improved mathematics to compare with precise hypotheses. Instead, they regarded mathematics as a pure field and as a way of "saving" physical phenomena. Archimedes and Galileo used primitive calculus, but it took until Kepler and Newton for math beyond geometry to come to the forefront. I address what could have been done with insight and the equipment at hand, going through the observational fields in the order I presented them.

One does not need a telescope to get at the vastness of space. One can get the distance to nearby stars with a candle as an intermediary as we did in the do-it-yourself project. One can get the disk angle of planets and their variation with orbital position using lunar occultations. This takes many years of observations, but constrains the disk angles of stars in the process. The hardest measurement is the AU, the distance from the Earth to the Sun. One does need a telescope here and must either wait for a transit of

Venus or have very good clocks. One obviously needs a telescope to work out beyond the stars that we can see with the naked eye.

Darwin required no equipment to show that geological time is at least hundreds of million years. He needed only to measure current rates and extrapolate them into the past. Fossils are exposed for all to see. The basic method is that of Herodotus, with a penchant for measuring what one sees. Radioactive dating requires high tech. Photographic film is nice for discovering radioactivity in the first place. High tech astronomy gave the first useful information on cosmic time.

The dogmatism of Ptolemy kept astronomers from discovering the proper motion of stars, as did his fake data. Halley quickly established the phenomenon when he compared modern and ancient star charts. Any penchant for measuring and trusting few hundred-year-old data would have done this much earlier. Beyond that, one needs heavy physics and math to figure out how stars work.

The literate ancients, as well as unlettered peoples, knew empirically how weather is where they live. The instruments to weigh air and to detect air pressure are simple. The failure of a vacuum pump was all that was needed to get things started. The culprit here is the lack of a simple practical innovation with regard to pumps. The progress of chemistry until the early 1800s required only balances and glassware. Beyond that, heavy physics and chemistry come into play in relating planetary surface temperature to atmospheric structure and the luminosity of stars.

Any systematic collection of geological data would have sufficed to get tectonics to the point at the time of Darwin. Being able to see much of the world was nice, but the basic points are evident in Western Europe, Central America, South America, China, and the Middle East. Wegener's initial continental drift hypothesis came mostly from global information that was available by 1860. The modern theory of plate tectonics was driven by high tech data collection by marine scientists and seismologists. It needed only a few years of reliable earthquake data and marine magnetic field measurements. Geodynamics with strenuous physics (including my work) came in only after empirical evidence clinched the issue.

Aristotle got to the point of limited natural selection and evolution. It helped that Darwin and Wallace saw the world, but an ancient penchant for gathering biological and fossil data would have got the basic information for gross evolution. Beyond that the evolution of microbes, DNA, and biochemistry are high tech. An ancient could not have got much beyond showing that the scum in hot springs is alive. A little thought and measurement on why heat purifies might have led to pasteurization and germ theory, but at least a crude microscope would have been necessary to get the idea taken seriously.

After this, we are pretty much into the realm of high tech and serious math and physics with asteroid impacts, planet formation, and the conditions on other planets. We are also into observations that cannot be made without tentatively accepting that that much of science works. We would still know very little about the other solar planets without the space program. Planetary scientists are familiar enough with the Earth and basic science that the lag between new information and explanation is sometimes days.

Technology and logistics: the planet of the octopi

The actual historical development of astrobiology and modern science began with questions about the vastness of space, like whether the Sun is a star. The question of other inhabited worlds intrigued the populace. Let's see what would have happened if deep-sea octopi had developed science.

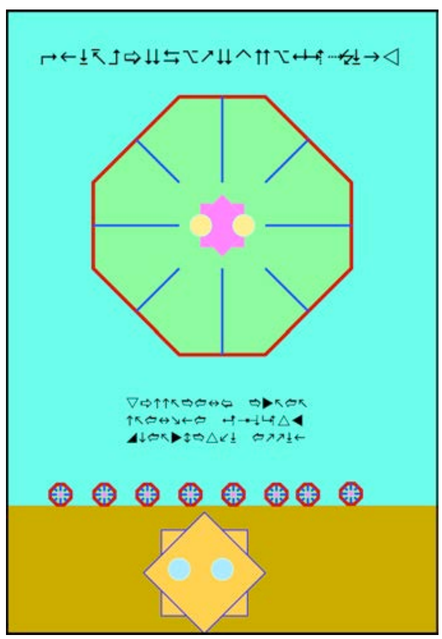
Our octopi live at depths below two kilometers in the ocean. Their metabolism evolved for this and does not tolerate the lower pressures in the shallow ocean. Neither can they tolerate warm surface water. They live in the dark depths of the sea where the temperature stays constant. Their eyes, however, are sensitive to feeble amounts of light from their bioluminescence. The octopi communicate by complicated bioluminescent signals and clicking sounds at larger distances.

The octopi first tame giant squid. Octopus communities are in constant danger from the squid. A bright octopus realizes that giant squid come from squid eggs. They gather squid eggs and guard them like they do with their own eggs. They raise the squid with their own young. The squid are initially only a little tame, but unintentional selective breeding selects the tamer varieties. Soon tame squid guard every octopus village. The innovation spreads worldwide in prehistoric times.

Technology and herding begin with the sea cucumbers (actually animals) that eat organic matter in the mud at the bottom of the ocean. They are easy to manage with the help of herd squid.

The octopi need rock shelters to keep their eggs and the tame squid eggs. They build these by moving rocks short distances in areas of outcrop near the ridge axes. They overcome this limitation by transporting rocks to sediment-covered areas of the seafloor. The squid are some help in moving rocks, but king crabs are better and also good to eat.

The octopi domesticate king crabs and breed them for bottom transport. These innovations let the octopi spread out and colonize the bottom of the whole ocean. The octopi have no need for housing to keep warm because the water is always at the same temperature, but big egg-growing structures are nice for vanity. They require social cooperation that keeps population in check. The octopi have no interest in war, especially since this is the one activity where the squid do not cooperate. (OK it is a bit of a utopia, but I am into science and technology, not octopus wars.) Writing develops from the bioluminescent signals used for talking. The octopi first use it to mark egg shelters. It soon becomes a standard means of communication. They scratch crab shells, shed frequently, with rock pens.



Turbidity currents, widespread flows of mud suspended in water, sometimes rush down the slopes of the seafloor. They are very destructive to the sea cucumbers and egg shelters and sometimes kill octopi who do not swim up quickly into calm clear water. The octopi know that the areas prone to turbidity currents are fertile for growing sea cucumbers and well worth the risk. Geometry evolves from restoring the sea cucumber farms where currents wiped out the markers. It becomes useful for building fancy egg shelters. The octopi at first count with their legs and then develop to base 8 arithmetic.

Trade develops between the ridge axis regions that supply rock and copper metal sometimes found along fault scarps and the deep plains of the ocean that supply sea cucumbers. King crabs and their shells are also valuable items.

The octopi discover that heated whale fat is buoyant when a carcass settles near a hydrothermal vent. The buoyancy is useful for moving rocks. They attempt to capture the hot fluid from the vents for buoyancy. This proves dangerous but they collect gasses in small quantities, including methane, hydrogen, and carbon dioxide. The carbon dioxide becomes a hydrate, a powdery solid, when cooled. If they can keep water out, the gas sinks rather than floats.

A hydrogen-methane mixture stays buoyant if kept dry. This helps moving rocks. The octopi place these buoyant gasses in bags made of whale hide. Gas and gasbags are valuable commodities. Methane hydrates are nice for transporting that gas without having it buoyant. The gas can be regenerated by heating and the octopi discover vast deposits of the hydrate on the seafloor.

It is obvious to all that the methane bags expand and contract as the octopi move up and down on the seafloor. This is a nuisance when they are trying to keep rock loads transported from the ridge to the deep plains neutrally buoyant. This observation leads to the concept of pressure and big trouble.

An octopus makes a simple graph of the volume of the gas versus depth below the ridge axis. There is a smooth relationship, nice for figuring out how much gas one will need to lift a rock. This innovation spreads worldwide.

Then an octopus named Jordan Brown (science fiction writers get into parallel worlds) plots the inverse of the volume, the density. It varies linearly with depth below the ridge axis. He extends the line upward. The density goes to zero two and a half kilometers above the ridge axis. He gets to thinking. He proposes that the rock part of the Earth is a sphere and the water is a thin shell. Water extends only a little ways up (2.5 kilometers from the ridge axis); beyond that there is a thin layer of gas and a void.

The octopi believe in various religions, but all agree that there are two gods. The Water God protects the octopi and occasionally sends down manna in the form of dead whale carcasses and tree trucks. These fertile oases provide tasty clams and small crabs along with various kinds of sea worms. The Water God gently stirs the water, which extends upward forever. The Rock God supplies rocks and hydrothermal vents at the ridge axes. Sometimes this God gets angry and the ground shakes. The rock extends down forever. The seafloor is a nearly flat surface for the octopi between the infinite regions controlled by their two Gods.

The spherical rocky part of the Earth does not stir up a lethal trouble. The octopi have sent mail by trained squid for a long time and some octopi have traveled moderate distances. Mail squid and mail pouches leave in one direction but sometimes return from the other. Cartographers can never seem to get the flat surface of the Earth right. The heresy that the Earth is a rocky spherical pebble in an infinite ocean dates from antiquity.

The finiteness of the ocean stirs up religious fervor. The Water God cannot be finite! Zealots chain Brown to a hydrothermal vent where he dies. The story spreads widely. The octopi are quite peaceful and a serious crime is big news everywhere. Executions are even rarer; this is the first in a century. In months, Brown’s village gets the story from several paths around the Earth on the seafloor with various improvements in the telling. The zealots ban the news and teaching that the Earth is round. This does not help, as everyone already knows the contrary.

The fervor ends when an octopus sends a whale-fat bag up on a rope made of crab sinew. It floats up until it reaches the sea surface right where Brown said it was. The invention becomes useful in that attaching a copper hook to the device catches fish. Copper is now in great demand; zealots are not.

The octopi now get into chemistry. They have a sense to detect electric currents in the water. They discover electricity while trying to perfect getting copper out of sulfides at the ridge axis. They soon have batteries that produce hydrogen gas and oxygen. They combine violently if sparked but the hydrogen is useful for getting copper, lead, tin, and zinc out of sulfides. Tin is rare, so they use brass made from copper and zinc. After some fatal accidents in confined spaces, the octopi discover that they are breathing oxygen in seawater. They begin organic chemistry to get better insulation for the copper wires. They learn to control heat and to make dry glass enclosures to do chemical reactions. Thermodynamics comes in the next century.

The ease in transporting material leads to a renewed interest in mechanics. The octopi are familiar with levers from antiquity and their own jet propulsion. By now they can make limited vacuums by cooling vent water in a glass container. They time the fall of bodies. Soon they have Newton's laws. They then try to model the currents in the ocean. It takes two centuries but they work out that the Earth is rotating. They get gravity from tides, and that the Moon orbits the Earth and the Earth and Moon orbit the Sun. The surface of the ocean is liquid except near the poles. The annual variation of currents indicates that the Sun supplies heat.

They get the theory of general relativity by trying to get a form of Newton's laws that will work in the moving coordinate system of the ocean. They are already using light to get at the properties of seawater. The experiment that the speed of light is the same in all directions is easy by then. The equivalence of mass and energy looks like an infinite power source. The octopi go looking for it.

They already know that the rare element radium glows. They make instruments to detect radioactivity. They also realize that there is a lot of energy available if they can make hydrogen into helium. They have good enough electronics by now to make atomic accelerators. They get the basic data needed to do astrophysics and how deduce how the Sun gets its energy.

Their penchant for careful surveying leads to plate tectonics. They have good magnetometers developed from earlier compasses. They confirm they are right by detecting the magnetic stripes.

Evolution comes from biochemistry and the study of the microbes that hang out at hydrothermal vents. The octopi already know that they are similar to squid and the idea that they had a common ancestor is widespread from antiquity. There are not a lot of seafloor species to provide other obvious cases. The discovery stirs up no religious trouble. Brown's fate and instant exoneration broke the creditability of the zealots.

Octopus eyes are sensitive enough to detect flashes from high-energy solar neutrinos. Their atomic physics is good enough that they expect this. They detect other sources of neutrinos. They have sent some robotic probes to the sea surface and know that dry land exists from the chemistry of sediments washed into the deep sea. They now set out to view the cosmos with much of science at mankind's current level in hand. Their astrophysicists see their first star, the Sun, 400 years after Brown stirred things up.

The octopi build telescopes that can be put on dry land. Their robotics are good but they need to move about in cooled pressurized compartments. They also need to stay out of the blinding light of the Sun. They confirm that the mass and spectra of the Sun are what they expect if it is 4.5 billion years old. They then give their attention to whether the Sun is as expected one of the stars. This is routine but high tech science. It takes them a few years to get the telescopes good enough to get parallax. It takes them two decades to get a reasonable map of the galaxy and to resolve the expanding universe. Brown was wrong about a cozy finite universe with just the Earth and a void, but no zealots are left to rejoice. Octopus historians note the irony.

Twenty years after reaching the sea surface, they begin to send robotic probes to the Moon and the other planets. Octopi everywhere on the seafloor await the latest news by electronic communication. Their scientists realize that lasers and radio transmissions may come from other habitable planets and set up SETI. They launch planet-finder telescopes. They debate whether intelligent life could ever arise on land.

Essay exercises

Discuss the penchant for measuring in modern science. Using this book (and other sources such as *Rare Earth*) find three discoveries that came about mainly from systematic measuring. Pick one and discuss its implications to the general issue of how common habitable planets are.

The deep-sea octopi in this Epilogue would have faced the issue of whether their planet is old or young. Assume that they did not yet have traveled to the sea surface or possess radioactivity dating. Discuss how they might go about getting at the duration of geological processes. Include evidence that might lead them to think that the Earth is old as well as the Earth is young. There is also info in *Rare Earth*.

That last sentence of this book deals with the octopi discussing whether intelligent life could originate on land. There are no people but the land is otherwise similar to that which we see. Using *Rare Earth* and this book (and other sources if you find them relevant) write an octopus dialogue on this issue.

There is some license in the octopi story. That is, I did not figure out precisely how to get this or that device fabricated and working underwater. One reviewer for a publisher, for example, went ballistic because it would be impossible to make glass containers underwater. Obviously intelligent life with excellent robotics would get by wherever they lived. If you are familiar with some field of engineering, figure out how the octopi would accomplish a task of your choice early in their technological history.