Advanced Track, Epoch 4

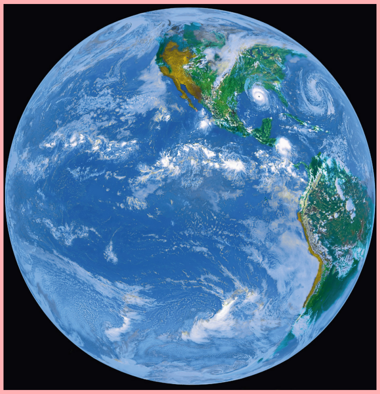
Planetary Evolution

This Advanced Track provides a technical supplement to the introductory web site on cosmic evolution, produced by Eric Chaisson and based on courses taught mainly at Harvard University for the past few decades:
http://www.cfa.harvard.edu/~ejchaisson/cosmic_evolution/docs/splash.html

Currently, this Advanced Track is abbreviated while addressing mainly the concept of energy rate density—a numerical quantity proposed as a useful complexity metric for an underlying, unifying process that guides the origin, evolution, and destiny of all organized systems across the arrow of time, from big bang to humankind. In the summer of 2014, this supplement will grow dramatically, providing much more pertinent technical material at an advanced, quantitative level (suitable for colleague scientists and graduate students) well beyond that presented in the above-linked introductory web site (which is meant for non-scientists and beginning students).

A summary of this Advanced Track is here:
http://www.cfa.harvard.edu/~ejchaisson/advanced_track_sitesum.pdf

Further material related to the subject of cosmic evolution is available at:
http://www.cfa.harvard.edu/~ejchaisson
including a collection of recent research papers easily accessed and downloadable at:
http://www.cfa.harvard.edu/~ejchaisson/current_research.pdf



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Cosmic Evolution

Planetary evolution is a subset of the larger category of physical evolution, which is itself part of the grand scenario of cosmic evolution:

Cosmic evolution = **physical evolution** + biological evolution + cultural evolution.

During this fourth, planetary epoch, energy rate density, $\Phi_m \approx 100$ erg/s/g, at least within those parts of Earth experiencing organized complexity today.

Earth, Generally Considered Internally

Much of Earth's original organization derives from energy gained from accretion of mostly homogeneous, proto-planetary matter in the early solar nebula, whereupon energy flows helped create its subsequent geological complexity, from center to surface. In particular, during Earth's formative stage ~4.6 Gya when it experienced much of its gross ordering into core, mantle, and crust, its value of Φ_m was a great deal more then than now. This is not surprising since almost all of our planet's early heating, melting, differentiating, and outgassing occurred before the oldest known rocks formed ~4 Gya. Its initial energy rate density then characterized the thermal and chemical layering within the early, naked Earth (minus a primordial atmosphere, which escaped, and a biosphere, which did not yet exist); remnants of the internal bulk of our planet is what geologists explore and model today.

Unlike gaseous stars that continue increasing their thermal and chemical gradients via physical evolution well after their origin, indeed often for billions of years thereafter (*cf*, Advanced Track for STELLAR EVOLUTION), rocky planets complexify mostly in their formative stages while accreting much of their material in <1 Gy, after which internal evolutionary events, of a geological nature, comparatively subsided. It is during their earliest years that planets, at least in their bulk interior composition, experience the largest internal flows of energy in their history. Note that we are not yet considering external atmosphere, ocean, and biosphere that subsequently developed on Earth—and for which Φ_m would later rise (see below).

The current value of Φ_m for the entire rocky body of Earth per se is mostly irrelevant in the larger scheme of cosmic evolution since the bulk of our planet's interior is not now further complexifying appreciably. Earth's internal energy flow, mostly in the form of stored heat upwelling from within, derives from 3 sources: gravitational contraction of its formative matter and the sinking of mass concentrations of heavy elements toward the core during differentiation, accretion of additional matter during an early period of meteoritic bombardment up to ~3.8 Gya, and lingering radioactive decay of some of its heaviest, unstable nuclei. All these events combined, today and long past their peak, amount to only a small energy outflow at Earth's surface, measured and globally averaged to be ~63 erg/cm^2/s (Hubbard, *Planetary Interiors*, vanNostrand, 1984). When integrated over the entire surface of our planet's globe, this translates into an effective (geothermal) luminosity of ~3x10^{20} erg/s. (About half of the energy that Earth currently radiates into space derives from decay of radioactive isotopes; heat radiated by Earth *today* totals ~44 TW, of which ^{40}K contributes ~4 TW and ^{232}Th and ^{238}U together contribute ~20 TW, the last of these as measured by antineutrinos emanating from Earth's interior; Kamland Collaboration, *Nature Geoscience,* 2011; doi: 10.1038/ngeo1205).

Given Earth's total mass of 6x10^{27} g, we compute $\Phi_m \approx 5\text{x}10^{-8}$ erg/s/g for all of our planet interior today—an energy rate density consistent with an ordered yet relatively unchanging physical object (globally considered), much like an already formed, mostly solidified, and largely dormant crystal having $\Phi_m \approx 0$—which, by the way, much of Earth internally is. Even this small heat flow, however, can affect planetary evolution at the surface locally, while driving events with implications for life; tectonic activity represented by recent mountain-building or volcanism such as the Alps or the western United States have current values of Φ_m twice that of geologically old and inactive areas such as pre-Cambrian shields. Not surprisingly, mid-oceanic trenches (see last section below) are sites of greatest radiogenic heat flow at or near the surface of Earth today, reaching values of ~150 erg/cm^2/s, and sometimes double that in especially active vents.

Earlier in Earth's history, when our planet was changing more rapidly during its first ~Gy—developing, settling, heating, differentiating—its value of Φ_m would have been much larger. Taking a surface temperature, $T_s \approx 1800$ K (Hartmann, *Moons and Planets*, Wordsworth, 1993) as an average value of a "magma ocean" during its initial 0.5 Gy, and knowing that energy flux scales as σT^4 (where σ is the Stefan-Boltzmann constant), we can estimate that in Earth's formative years, its energy rate density would have been enhanced by $(1800/255)^4$, making Φ_m *then* several orders of magnitude larger than now. (255 K is used here, not 290 K as for today, since the former is the "balanced T" when the incoming solar energy absorbed equaled the outgoing terrestrial heat emitted for our early, rocky planet, whereas the latter is Nature's [not humankind's] "greenhouse T" boosted in more recent times by the thickening of Earth's atmosphere.)

Primordial Earth

Earth's original value of Φ_m can be approximated by appealing to the conservation of energy (in this case, the 1st law of thermodynamics applied to a gravitating body), setting the gravitational PE of a gas cloud of mass, M, that infalls to form a ball of radius, r, during a time interval, t, equal to the accreted energy gained and partly radiated away while converting that PE into KE, in turn causing a rise in surface temperature, T, to wit:

$$^1/_2\,(GM^2/r) \;=\; 4\pi r^2 t \sigma T^4 \;.$$

Here, σ is Stefan-Boltzmann's constant = 5.7x10^{-5} erg/cm^2/s/K^4 and the term σT^4 is the radiative flux through the surface area; the whole right side of this equation equals the total energy budget of the proto-planetary blob, namely the product of L and t. The fraction $^1/_2$ results from the so-called Virial Theorem, which specifies that half of the newly gained energy of any contracting mass radiates away, lest the formative process halt as heat rises to compete with gravity; thus that part of the energy budget does not participate in formative ordering. The result for early Earth was significant heating, indeed melting, mostly via gravitational accretion, though perhaps aided somewhat later by the decay of radionuclides; however, none of the most abundant radioactive elements, including K, U, and Th noted in the previous section, have half-lives short enough to have participated in much of this early heat pulse, and thus they are neglected in this admittedly simplified treatment.

In this way, we find an estimated value of $\Phi_m = GM/2rt \approx 10$ erg/s/g for the young Earth, an energy rate density generally larger than that of the less-ordered Sun yet smaller than that of Earth's subsequently more-ordered climasphere (see below), much as might be expected if our cosmic-evolutionary scenario has any validity. With $t \approx 10^{3-4}$ y, we also find $T \approx 3000$ K, a not unreasonable T to which ancient Earth might well have been heated during its accretional stage (Lewis and Prinn, *Planets and their Atmosphere*, Academic Pr, 1984), to be sure much less than the ~60,000 K to which the assembled rock would have been heated had all the acquired energy been stored internally. The time scale for terminal accretion, that is, the total duration needed to sweep clean the primitive Solar System and to form each of the planets, is more like 10^{7-8} y, but the solar nebula cooled and its mineral grains condensed on the order of 10^4 y. During this latter, shorter time the bulk of the planets must have emerged, or else the loose matter in the solar nebula would have been blown away by strong "T Tauri," bipolar solar winds. Furthermore, slow accretion over the course of millions of years would have allowed the newly gained heat to disperse, resulting in negligible influence on its internal T (or a mere few hundred K) and thus an inability to melt rock (as opposed to merely heating it), causing minimal geochemical differentiation, if any.

By contrast, T of a few thousand K, as calculated above for more rapid accretion, was surely high enough to have made rock molten, thus helping (along with the decaying radionuclides) to order our planet's interior as the low-density materials (rich in Mg and Si) percolated toward the surface while the high-density materials (rich in Ni and Fe) sank toward the core—yet not so high T as to make this analysis unrealistic. Those same long-lived radionuclides and the PE realized when huge globs molten metal plunged into the core would have further heated Earth's core enough to establish a robust magnetic field from the dynamo action of mostly spinning iron. The result is a planet that is today well differentiated, with moderate ρ and T gradients, from core to surface: ~12 g/cm^3 to 3 g/cm^3, ~6000 K to 290 K, respectively. We repeat that these heating, flowing, and ordering events occurred long ago on Earth; currently, as averaged over our entire planetary globe, Φ_m internally is very much smaller (~10^{-7} erg/s/g), nor is there much ordering now occurring internally apart from a few "hot spots" that drive today's surface tectonic activity—and, of course, in the climasphere and biosphere, where much externally enhanced order is indeed evident (see next section), not from energy fluxing outward from inside Earth but that fluxing inward from outside, indeed from the Sun.

This, then, would have been a measure of energy flow through Earth proper when it was experiencing its most dramatic ordering phase, virtually completed within a fraction of its first Gy. Much of the early planet's internal structural complexifying would have been driven by ancient Φ_m (of order tenish erg/s/g), then rather quickly developing its patterned ways of layered stratification, core rotation, and mantle convection, after which little further ordering has occurred except externally at and above the surface—where the cosmic-evolutionary story continues.

Earth's External Climasphere

Planets are more complex than either stars or galaxies, and not surprisingly planetary values of Φ_m are also larger—at least for some parts of some planets at some time in their history. (That's why we probably know more about the Sun than the Earth; stars are simpler systems.) Here we examine not our planet's whole globe, from its interior through its surface, since Earth (or any of the planets in our Solar System) are not evolving much now, some 4.6 Gy after their origin. Rather, we are most interested in those parts of our home that are still evolving robustly, still requiring energy to maintain (or regenerate) their structure and organization—and indeed fostering energy-rich and rapidly changing environments that might be conducive to the emergence of even more complex systems, including biological life and cultural society.

Consider, for example, the amount of energy needed to drive Earth's climasphere, the most impressively ordered physical system on our planet today. The climasphere includes those parts of the lower atmosphere and upper ocean that absorb (and then re-emit) solar radiation, and which most affect turbulent meteorological phenomena capable of evaporating copious amounts of water as well as mechanically circulating air, water, wind, and waves. The total solar radiance intercepted by Earth is 1.8×10^{24} erg/s, of which only ~69% penetrates the atmosphere (since Earth's albedo is ~0.31). This external power is several thousand times that now received at the surface from Earth's warm interior, which can thus be neglected (*cf*, previous section). Photosynthesis is an inherently inefficient process (~0.1% overall; *cf*, Advanced Track for BIOLOGICAL EPOCH), so much of the rest of the incoming energy serves to heat things up and thus drive atmospheric winds and ocean currents. Since our planet's air totals ~5×10^{21} g (mainly the troposphere to a height of ~12 km, which contains >90% of the total atmospheric mass) and the mixed ocean layer engaged in weather (to depth of ~30 m) amounts to about double that, Φ_m for planet Earth today is roughly 75 erg/s/g.

Incidentally, the IR photons, re-emitted by Earth and equal in total energy to captured sunlight, are both greater in number and lower in energy (~20X difference per photon) than the incoming sunlight of yellow-green (5550 A°) photons, thus contributing to the rise of entropy beyond Earth, even as Earth itself grows more complex and less entropic—again in accord with the 2nd law of thermodynamics.

Just to be clear and honest what is computed here: The whole mass of planet Earth is not used in this mass-normalized, energy-rate calculation for Earth's climasphere for two reasons. First, the heat generated internally by our planet is only a small fraction of the incident solar radiation. Second, that solar energy is deposited mainly into the external surface layers of Earth's atmosphere, upper ocean, and biosphere, from which it then gets re-radiated into the dark night sky. Only the mass of the climasphere per se is relevant in the Φ_m computation, for it is only in this air-ocean interface that the dominant solar radiation at Earth affects and maintains ordering on our planet today.

Energies on Earth

At the surface of Earth today, several other, non-solar energies are continuously operative, all of them (~44 TW) negligible compared to the 120,000 TW arriving at Earth's surface from the Sun. These heat fluxes include:

- ~22 TW from radioactive decay
- ~9 TW from primordial heat
- ~0.3 TW from earthquakes (small, low-level, continuously averaged)
- ~3.5 TW from Moon's gravitational tides
- ~12 TW from hydrologic water flows.

In addition, some episodic events have large fluxes but over short times, for example:

- ~50 TW for typical volcanoes (*eg*, Mt. St. Helens eruption of 1980) lasting hours
- ~2000 TW for large earthquakes (*eg*, Indian Ocean tsunami of 2004) lasting seconds.

By further contrast, the above (mostly geothermal) energy fluxes can be compared to some in the biological domain, to be discussed later in the Advanced Tracks for BIOLOGICAL and CULTURAL epochs, such as:

- ~18 TW for civilization's current rate of energy use
- ~130 TW for plants overall usage of solar energy.

Geothermal energy, and not solar energy, is responsible for driving internal processes that create ocean floor, push plates around, and uplift mountain ranges. The result is a tectonic reshaping of Earth's surface, ongoing for Gy and continuing even today. It does so via three heating sources:

- heat conducted through the lithospheric crust from the underlying warm mantle
- heat produced by radioactive decay of unstable nuclei throughout the planet's interior
- heat convected upwards by circulation of magma in the mantle

Measured heat flows decrease with the age of the ocean floor; the youngest crust near hydrothermal vents (see below) has as much as 250 mW/m^2, whereas hardly 50 mW/m^2 pass through sea floor >100 My old; the average globally is ~85 mW/m^2, and that value translates, again globally, into the ~44 TW of internally generated heat power noted above that continually flows thru Earth's crust today. Of that, ~32 TW flow from the oceans, and of that in turn ~9 TW come specifically from the undersea vents. As noted earlier, this 85 mW/m^2 of geothermal heat pales in comparison (~0.05%) to the 168 W/m^2 of solar radiation absorbed by Earth's surface. Even so, this small internal flux, acting over vast areas and long durations, can tectonically reshape continents and oceans, indeed impart to planet Earth many geological features and changes evident all around us.

Energy Flows on Earth: This research program emphasizes not merely total energy, but energy flows per unit time, for our focus is mostly with the rate of energy change through open, complex systems. The following is a useful compilation of global mean energy flows for some natural and artificial (human-induced) processes and events affecting our world today (Alexander, in Fazzalare&Smith, eds, *Changing Energy Use Futures*, vol 2, Pergamon, 1979):

Earthly Energy Flows

Process or event	Energy flow (cal/m^2/day)
solar energy reaching Earth	7000
solar energy absorbed	4900
weather	100
plant photosynthesis	7.8
hurricanes	4
tides	1.54
animal respiration	0.65
cities	0.45
forest fires	0.3

fossil fuels	0.11
urban fires	0.06
wars	0.05
floods	0.04
earthquakes	0.001
volcanoes	0.0005

Other Planets

Other planets in our Solar System, as well as the debris that never accumulated into the Sun and planets, such as asteroids and meteoroids, can also be diagnosed as for Earth above. Some of these objects do display complexity growth as measured by approximate values of energy rate density.

Consider first the terrestrial, inner planets of our Solar System. Computations yield a similar value of Φ_m for Venus as for Earth, much as expected given that its bulk properties (mass, radius, etc.) resemble Earth's closely; Venus is truly Earth's sister planet. Its formation, leading to a somewhat ordered core, mantle, and crust (enough to show evidence of volcanism on radar maps made by orbiting spacecraft), is consistent with an internal value of Φ_m (~9 erg/s/g) virtually equal to that of Earth in its early years, ignoring for the moment both planets' external atmospheres; there, additional complexity subsequently evolved on Venus, which although it is radiated more intensely by the Sun also has a thicker atmosphere than on Earth, making Φ_m today for Venus again comparable to that for Earth today. Mercury and Mars, each having a mass roughly a tenth that of Earth, would have heated and ordered less during their gravitational contraction and accretion. Their modeled interiors imply only slight differentiation, comparatively smaller cores, and not much global magnetism; indeed their values of Φ_m (~2 erg/s/g) are somewhat less than those for early Earth, again as expected for smaller material gradients and energy flows (per unit mass), and ultimately less complex, now mostly dormant, worlds.

Our Moon, too, is not as ordered as Earth and its small value of Φ_m (~0.5 erg/s/g) confirms it. Its accretion T (~800 K) was sufficient to have heated but not melted much rock or caused much internal differentiation, rather it is consistent with a uniform basalt mantle surrounding a minute metallic core, as inferred from intensive robotic and crewed exploration of the Moon in recent decades. So we shouldn't be surprised that our nearest cosmic neighbor is a poorly ordered hunk of nearly homogeneous rock; it never did manage to acquire a robust energy flow, from inside to outside, nor develop any atmosphere at all, thus never did become very complex. Asteroid-sized objects, even as large as Ceres (at ~900 m in diameter, the largest in its class), as well as all smaller objects in the Solar System, experience insignificant internal energies and very low surface T for any reasonable accretion time scale, thus we reasonably conclude that all asteroids and other such Solar System debris are uniformly constructed, largely unordered and devoid of much complexity.

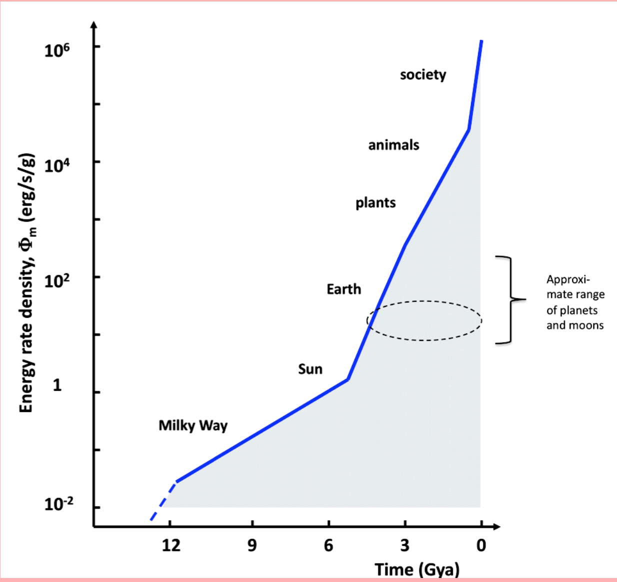
By contrast with the terrestrial planets, the much larger jovian planets of our Solar System, represented most prominently by Jupiter, are moderately complex. Considering the accretional heating that would have generated the bulk of Jupiter's order, and providing for a somewhat longer accretion time, $t \approx 10^4$ y, we find a value of $\Phi_m \approx 30$ erg/s/g. This is consistent with a priori expectations; just looking at Jupiter would suggest enhanced order and complexity, and its high radiogenic heat flow (even today, equal to twice the energy it receives from the Sun) would seem to demand it. Not unreasonably stated based on its rather large value of Φ_m, Jupiter's complexity compares favorably to that of a red-giant star. Theoretical models of Jupiter's interior do somewhat resemble the steep thermal and pressure gradients characteristic of well-evolved stars; Jupiter's core is thought to be as high as 40,000 K, its pressure as much as 50 million bars, both of these properties a great deal different from its "surface" values of 300 K and 10 bars, respectively.

It will be exciting to extend this kind of analysis to the many extrasolar planets now being discovered, but only when we have better estimates than presently of their stellar radiance and of the relevant portions of their masses that are evolving and complexifying.

Φ_m Rising

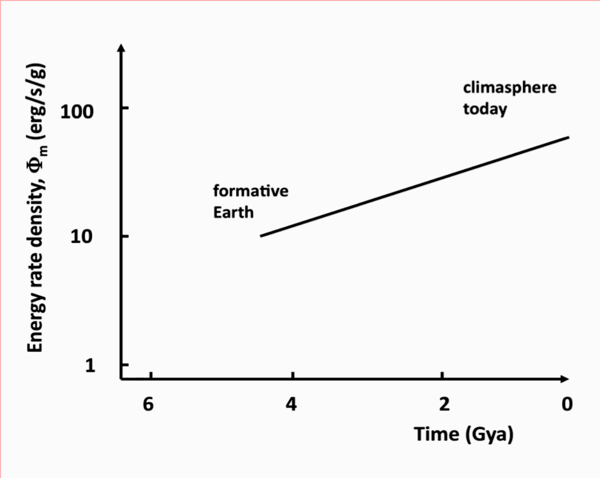
Planetary systems generally, and Earth in particular, can be analyzed in much the same way as for stellar systems (*cf*, Advanced Track for STELLAR EPOCH), especially regarding the issue of rising complexity in Nature, again broadly considered, as well as its potential complexity metric, Φ_m. Energy flow, physical evolution, natural selection, and ordered states provide a package of understanding, both for how it is that planets are typically comparable to or slightly more complex than normal stars—as well as how it was that on (or near) at least one such planet—the third body out from the Sun—conditions ripened for the emergence of the even more highly ordered biological system of life itself.

The figure below plots some of the Φ_m values estimated in this Advanced Track for the PLANETARY EPOCH, thereby extending our analysis further up the master curve of rising complexity in the Universe. In particular, Earth's value of Φ_m began moderately, then grew larger, with care taken to distinguish its internal and external values. Soon after its formation ~4.5 Gya, our planet had an internal value (surface thru core) estimated at ~10 erg/s/g, and an external value that was irrelevant (since neither atmosphere nor ocean then existed). Later, the relative values of Φ_m reversed; internal energy flows weakened, while external energy flows grew through Earth's climasphere (because both the Sun's luminosity increased over time and our planet's ocean and atmosphere formed). Today, Earth's internal value of Φ_m is negligible compared to its external value of ~75 erg/s/g. Overall, combining internal and external contributions, Earth's total value of Φ_m rose somewhat during its physical evolution, not surprisingly given that the atmosphere and ocean did form externally while the bulk of Earth differentiated internally.



This graph repeats the essence of an earlier one (cf, end of Advanced Track for PARTICLE EPOCH), suggesting Φ_m as a measure of rising complexity over all historical time. The dashed oval outlines the range over which Φ_m changed during the course of geological history during the past ~4.5 Gy, and whose values of Φ_m are plotted in more detail in the next figure. The bracket at right outlines ordered structures for a variety of inanimate systems—in this case, for planets and moons at various stages of the physical-evolutionary phase of cosmic evolution.

The next figure plots estimates of Φ_m as Earth evolved over the course of the past ~4.5 Gy, initially ordering and complexifying its system dynamics within its mantle-core-crust interior and later (including now) within its ocean-atmosphere interface. This is just the range noted within the dashed oval of the previous figure.



Values of Φ_m for the evolution of Earth increased by roughly an order of magnitude over the course of the ~4.5 Gy history of our planet. What is shown here is only the change in Φ_m within the dashed oval of the previous figure.

Undersea Vents—Environments for Life's Origin

When ancient Earth was forming and undergoing physical evolution of its entire global bulk several Gya, its value of Φ_m was then some tenish erg/s/g (see above). By contrast, the value of Φ_m today is merely a fraction of that, currently less than a millionth, of its formative value, implying, as expected, that Earth as a whole geological globe is now *relatively* dormant, at least compared to its more active past. Earth's main period of formative ordering is over; its structural complexity developed long ago when vast quantities of accretional energy flowed through our primitive planet. Not that Earth is now geologically dead, far from it; close to the surface, plate tectonics continues to remold the land and sea scapes, and the result is occasional yet rich energy flows at some specific places on Earth.

Physical evolution is still well underway within localized, non-equilibrium sites on Earth, and significantly larger values of Φ_m prove it. Despite the cooled, differentiated, and long-ago ordered Earth, a variety of specialized places exhibit enhanced energy flow and consequently increased complexity even today: steam geysers, active volcanoes, and ocean trenches are all examples of Nature's geological heat engines, most of them interacting with the atmosphere and ocean—that is, the climasphere noted above. Even earthquakes, as sites of sudden and violent forces that tend to upset our lives and destroy our cultural edifices, can be considered sources of renewed geological ordering—although often such quakes release energy too far beyond an optimal range for constructive processes, tending to destroy complexity rather than increase it. All these internal forces are basically driven by remnant energy left over from Earth's formation, now present in its hot core and in mantle convective cycles (much like Benard cells) that power continental drift.

Of all the geothermal sources of energy today, the tectonically active underwater ridges and spreading zones are perhaps most intriguing, for it is within the upwelling water of the hydrothermal vents that geosystem organization is most discernable—intriguing because such vents might provide a smooth segue between physical and biological systems along the arrow of time, in particular potentially suitable environments for the chemical evolution of life's origin (*cf,* Advanced Track for CHEMICAL EPOCH), which is that part of the cosmic-evolutionary scenario that transitions from inanimate to animate objects in Nature.

Values of Φ_m on Earth are larger in precisely those locales—climasphere, vents, etc—where living systems are present. Life forms per se certainly do have higher values of Φ_m (*cf,* Advanced Track for BIOLOGICAL EPOCH), and thus it is instructive to explore if their environments might be influencing the rise of Φ_m where the cosmic-evolutionary narrative changes from physical to biological evolution. Below we examine further the rich and complicated ecosystems of numerous and diverse life forms that are powered by suboceanic heat engines, the vents themselves displaying much localized enhancement of order, flow, and complexity on Earth.

Also known as "black smokers" (owing to their ^{32}S-laden emission), submarine vents are narrow seafloor crevices (often called "chimneys") through which pressurized hot water percolates from subterranean regions at typical rates of 1-2 m/s; substantial T gradients and thus much heat throughput are characteristic features. Cold seawater having T ~ 275 K interacts with much hotter water rich in metal sulfides (especially H_2S) leached from molten basalt below, in fact superheated to ~600 K at the vent orifice, the whole mixture upwelling at P ~ 250 bars through vertical chimneys in the suboceanic crust. Such hot, rising fluid is the source of the energy flow that drives and sustains much biological activity in the underwater vents, but not conventional life forms familiar to us at the surface, like most plants and animals whose cells have biological nuclei that divide by mitosis. For example, autotrophic methanogens (simple prokaryotic bacteria) thrive in the scalding heat of the mixture near the central conduit of the chimney, requiring >350 K (*ie*, ~80°C) for optimum growth but not much higher than 385 K. Often called "extremophiles" or "hyperthermophiles" given their high-T status, methanogens differ from common life forms elsewhere on Earth that make a decent living at or near the surface, where environmental conditions seem to be homeostatically controlled at roughly "room temperature," ~290 K (Lovelock, *Gaia*, Oxford U Pr, 1979).

Extremophiles differ in another way as well: Despite their autotrophic traits, they are not dependent on O_2-producing photosynthesis and a visible-light energy supply. No sunlight reaches these submerged vents. Instead, subterranean methanogens operate a parallel process known as chemosynthesis, drawing their (chemical) energy from the oxidation of H_2S within a dark and deep biosphere wholly different from the familiar one near Earth's surface. These are among the so-called archaebacteria, a category of invertebrate life that displays much diversity and durability at the base of a food chain and that symbiotically lives within a remarkable community of 2-m-long tube worms, 10-kg giant clams, and idiosyncratic microbes thriving under what we at the surface would call extraordinarily harsh (indeed toxic, owing to H_2S) conditions—yet they are still C-based life forms operating in a H_2O-based medium. The total biomass of these dark-adapted vent communities is often 1000X denser than the average on the deep ocean floor. They may be direct descendents of the original organisms on Earth (*cf*, Advanced Track for CHEMICAL EPOCH).

Undersea hydrothermal vents are far removed from thermodynamic equilibrium; their steep T gradients guarantee it. Although the measured heat flux for the whole Earth averages 63 erg/cm^2/s (see above), flux values often reach nearly an order of magnitude higher at the mouth of the vents. And since the typical vents of cross-section ~1 m^2 and depth ~100 m is so small (compared to all of Earth), the enhanced heat renders vastly larger Φ_m values than the mere 10^{-7} erg/s/g flowing, on average, through our planet today. Values of Φ_m for such vents can reach of order unity, occasionally somewhat higher. Not surprisingly, with these kinds of striking non-equilibrium energy flows, undersea vents are among the premier examples of localized growth of order and complexity within geologically open systems on Earth today. But truly surprisingly (at least when first explored *in situ* by the submersible vessel *Alvin* two decades ago; Corliss *et al.*, *Oceanologica Acta*, v4, p59, 1981), the vents appear to be more than mere sources of geological complexity. They could well be the engine that drove the early emergence of biological complexity as well—an issue not without controversy for those who prefer that life began on or near Earth's surface, or perhaps even fell from the sky already assembled and embedded within rocks or comets traveling through interplanetary space ("panspermia").

Given that the archaebacteria—representing most of the entries, along with the eubacteria and eukarya, in the newly revised, 3-domain bush of life (Woese, *Microbiological Reviews*, v58, p1, 1994; *cf*, Advanced Track for BIOLOGICAL EPOCH)—are probably the most ancient life forms, or at least close to life's last common ancestor (extending back to the Archaean Eon in early pre-Cambrian times, 3.9-2.5 Gya), the hydrothermal vents have become a leading candidate for suitable sites where life on Earth originated several Gya. The contention of some researchers (*eg*, Shock, *Orig. Life & Evol. Biosphere*, v20, p331, 1990) that our planet's surface might have been inhospitable for life's origin—possibly lacking a reducing environment conducive to life, probably lacking protection from harsh solar UV radiation and incoming asteroids once life formed, and almost certainly lacking sufficient NH_3 to help form life—bolsters the idea that deep-sea vents could have provided environmental conditions better suited for the origin of life. RNA sequencing further implies that the earliest organisms were thermophilic, allowing survival in oceans that were heated by volcanoes, hot springs, and asteroid impacts. Accordingly, the vents of the underlying crust of prebiotic Earth—reducing, protective, and rich in NH_3—could have acted as hydrothermal reactors that chemically fashioned biology out of a geological setting.

With the sole energy source being geothermal (and the Sun playing no role), Φ_m can be approximated by appealing to an enhanced flux of 10^3 erg/cm^2/s through the 1-m^3 volume of a typical flow reactor within an otherwise larger vent chimney, where prebiotic species concentrate and interact in water of $\rho \sim 0.2$ g/cm^3 and T ~ 600 K. The answer is $\Phi_m \approx 50$ erg/s/g, a value quite uncertain given the many unknowns among vent properties, yet reasonably approximating the expected complexity range between primordial Earth (~10 erg/s/g) and cellular photosynthesis (~900 erg/s/g).

In Sum

Qualitatively, our cosmic-evolutionary analysis seems to be holding up; quantitatively, despite some simplifications and estimations, our energy-flow calculations compare and contrast reasonably well for all known physical systems along the arrow of time. Since Earth's (climaspheric) value of Φ_m (~75 erg/s/g) exceeds that for the Sun (~2) and is well above that for the Milky Way (~0.1), Earth likely is a more complex system than either its parent star or parent galaxy, albeit not dramatically so.

Accordingly, we suggest that the science of comparative planetology can be used to gauge order, flow, and complexity by undertaking the same kind of thermodynamic analyses performed in the Advanced Tracks for the GALACTIC and STELLAR epochs, as well as for a wide spectrum of ordered systems encountered earlier in the Advanced Track for the PARTICLE EPOCH. And, as we explore further along the arrow of time, we shall find, yet again, that the same kinds of diagnostic tools are applicable to the study of life, intelligence, and society, as documented in the Advanced Tracks for the CHEMICAL, BIOLGICAL, and CULTURAL epochs—with speculations for future growth in complexity noted in the Advanced Track for the FUTURE EPOCH.