

# Energy Rate Density as a Complexity Metric and Evolutionary Driver

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*The proposition that complexity generally increases with evolution seems indisputable. Both developmental and generational changes often display a rise in the number and diversity of properties describing a wide spectrum of ordered systems, whether physical, biological, or cultural. This article explores a quantitative metric that can help to explain the emergence and evolution of galaxies, stars, planets, and life throughout the history of the Universe. Energy rate density is a single, measurable, and unambiguous quantity uniformly characterizing Nature's many varied complex systems, potentially dictating their natural selection on vast spatial and temporal scales. © 2010 Wiley Periodicals, Inc. Complexity 16: 27–40, 2011*

**Key Words:** energy; complexity; evolution; thermodynamics; universe

## 1. PRÉCIS OF COSMIC EVOLUTION

**F**or nearly three decades, I have endeavored to strengthen our modern understanding of the scientific interdisciplinary of cosmic evolution. This is an inclusive worldview that chronicles the origin and evolution of galaxies, stars, planets, and life, especially as pertains to humanity on Earth and our place in the Universe. The subject is basically a phenomenological discourse on countless, ongoing changes in the history of the cosmos, reified by the rise of complexity within and among evolving systems throughout Nature writ large.

Cosmic evolution as a general study of change is not new; its essence extends back at least 25 centuries to the

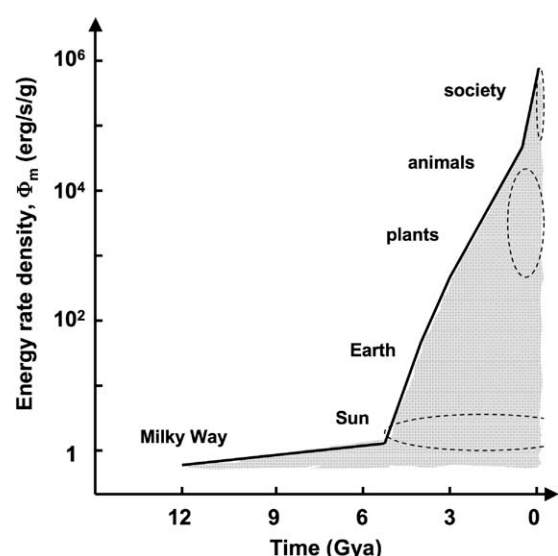
philosopher Heraclitus, who arguably made the best observation ever while noting that “everything flows and nothing stays.” This remarkably simple idea is now essentially confirmed by modern scientific reasoning and much supporting data. As recently summarized [1, 2], I have sought to undergird this broad, integrated subject with quantitative analyses, thereby attempting to advance the topic from subjective colloquy to objective empiricism.

This article reports on new research to model energy flow in complex systems from the big bang to humankind during ~14 Gy of natural history. Whether living or nonliving, complex systems are open, ordered, nonequibrated structures that acquire, store, and express energy. Energy does seem to be a common feature among such organized structures; energy flow may well be the most unifying process in science, which helps to provide a coherent explanation for the origin, existence, and complexification of a whole array of systems—notably, how they emerge,

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**FIGURE 1**



Energy rate densities,  $\Phi_m$ , for those representative systems listed in Table 1, plotted here semilogarithmically at the time of their origin, display a clear increase for a wide spectrum of objects observed in Nature. The shaded area includes a whole array of  $\Phi_m$  values as systems evolve. The three dashed ovals from bottom to top outline parts of this graph that are further explored in greater detail for physical, biological, and cultural evolution in Figures 3, 4, and 5, respectively.

mature, and terminate during individual lifetimes as well as across multiple generations.

Energy is not likely the only useful metric to measure complexity in ordered, evolving systems. This article is not meant to be critical of alternative proposals, such as information content or entropy production; the literature is replete with controversial claims for such measures, many of them asserted with dogmatic confidence. I have earlier offered reasons why I regard these and related alternates as unhelpful for general complexity metrics, as their use is often narrow and qualitative. By contrast, I have embraced the concept of energy largely because I can define it, measure it, and clearly express its units, indeed I have proposed ways to quantify this decidedly thermodynamic concept in a consistent manner [3, 4; see also Refs 5–7].

The chosen metric, however, can neither be energy alone nor even merely energy flow. Life on Earth is likely more complex than any star or galaxy, yet the latter engage vastly more energy than anything now alive on our planet. Accordingly, I have sought to normalize energy flows for all complex systems by their inherent mass; this better enables more uniform analysis, allowing effective comparison between and among virtually every kind of

system encountered in Nature. This, then, has been and continues to be my working hypothesis: Energy rate density, a mass-normalized (free) energy flow denoted by  $\Phi_m$ , is perhaps the most common currency available to do work thermodynamically to build structures, evolve systems, and create complexity.

Here, I aim to probe deeper the concept of energy rate density to explore its usefulness more quantitatively than in earlier work referenced above. To keep this article to a manageable size, I shall limit discussion to one prominent example from each of the three major disciplines of physical, biological, and cultural evolution, namely, stars, plants, and civilization. I shall also restrict my analysis to systems known to have fostered life on Earth, thereby making this article of interest not only to complexity and evolutionary scientists but also to “big history” academics concerned mainly with the long historical path that led specifically to humankind on Earth [8, 9]. Subsequent articles will address other complex systems, both in greater depth yet continuing breadth, including generally and inclusively the quantitative energy budgets of galaxies, planets, microbes, animals, brains, and machines.

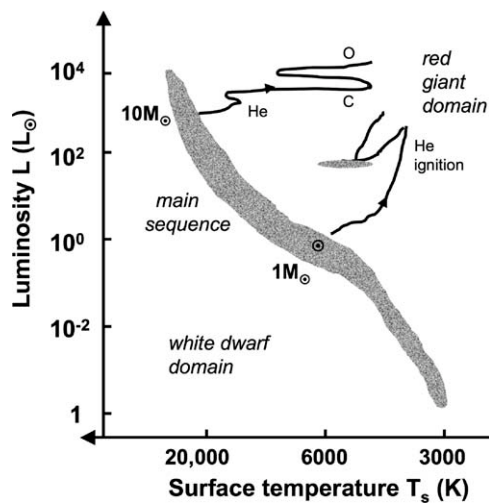
Figure 1 summarizes previous work on this subject, depicting how physical, biological, and cultural evolution over ~14 Gy transformed homogeneous, primordial gas into increasingly intricate systems. The graph shows the rise in values of  $\Phi_m$  computed for a range of structures observed in Nature and of known scientific age. Numerical values are listed in Table 1, details for which can be mostly found elsewhere [3, 10, 11]. The values given are typical for the general categories to which each system belongs, yet as with any simple, unifying theme—especially one like cosmic evolution that aspires to address all of Nature—there are variations. And it is likely that from those variations arose the great diversity among complex, evolving systems everywhere, as suggested later in this article.

**TABLE 1**

Average Energy Rate Densities

System	Age (Gya)	$\Phi_m$ [erg/s/g]
Human society	0	500,000
Animals, generally	0.5	40,000
Plants, generally	3	900
Earth's geosphere	4	75
Sun	5	2
Milky Way	12	0.5

**FIGURE 2**



The subject of stellar evolution is fortunate to have a single graph that encapsulates many of the salient changes experienced by stars. In this Hertzsprung-Russell diagram linking  $L$  and  $T_s$ , the main sequence (shaded area) maps a range of stellar mass for stars fusing  $H \rightarrow He$  from bottom right to upper left. The lower evolutionary track graphed here traces a  $1-M_\odot$  star (such as the Sun) leaving the main sequence and ascending the red-giant branch as its core shrinks and envelop expands. Eventually, with higher core  $T_c$ , nuclear fusion ignites  $He \rightarrow C$  as the aged star becomes a red giant. The upper track represents more massive stars (in this case,  $10 M_\odot$ ) that undergo repeated upgrades in their fusion cycles at accelerated rates, looping back (to the left with renewed nuclear ignition) and forth (with core contraction) while fusing  $He$ ,  $C$ , and  $O$  (Adapted from Ref. 12).

## 2. STARS AS EXAMPLES OF PHYSICAL EVOLUTION

Energy rate density can serve as a useful gauge of stellar complexity, allowing the general evolution of stars to be tracked while passing from “birth,” through “middle-age,” and on to “death.” As stars undergo nuclear fusion that causes them to change size, color, brightness, and composition, their growing complexity can be estimated while increased energy usage drives them toward greater nonequilibrium states, eventually culminating in a return to the simplicity of equilibrium at the end of their productive “lives” as stars. Figure 2 shows perhaps the most useful tool in the lexicon of a stellar evolutionist—the Hertzsprung-Russell diagram graphed for a wide range of visual luminosity,  $L$ , and surface temperature,  $T_s$ .

Note that astronomers usually use the term evolution to mean change, or development, during the lifetime of an individual star. This contrasts with the traditional meaning of the term in biology, in which it refers to generational changes in the traits of a population of life forms. The last section of this article will suggest that populations of stars

also evolve in a broad biological sense, as the overall composition of the interstellar medium and hence of each new generation of stars changes gradually owing to nuclear events within stars, some of which explode as supernovae. Stars, too, can be said to evolve generally, minus any genes, inheritance or competition that comprise the essence of biological evolution affecting systems that are truly alive.

Consider the star known best, the Sun—a typical G2-type star having a current luminosity  $L_\odot \approx 4 \times 10^{33}$  erg/s and a mass  $M_\odot \approx 2 \times 10^{33}$  g, making  $\Phi_m \approx 2$  erg/s/g, as listed in Table 1 (where the dot-circled subscript denotes solar values). This is the average rate of the Sun’s energy release per unit mass of cosmic baryons, which fuse  $\sim 10\%$  of their  $H$  in 1 Hubble time (10 Gy). It is energy flowing effectively *through* the star, as gravitational potential energy during star formation is first changed into thermal energy to heat its core, thence nuclear energy in fusion reactions, and finally electromagnetic energy released from the mature star’s surface. Such a star uses high-grade (undispersed) energy in the form of gravitational and nuclear events to promote greater internal organization, but only at the expense of its surrounding environment; the star emits low-grade light, which, by comparison, is highly disordered energy scattered into wider spatial domains well beyond its internal structure and all in accord with the second law of thermodynamics. However, even this is a relative statement: What is here “low-grade,” dispersed sunlight will, when later reaching Earth, become a “high-grade,” ordering form of energy when compared with even lower grade, infrared energy that is, in turn, re-emitted by Earth. What is waste from one system (the Sun) can be a highly valued energy input for another (the Earth).

Once the young Sun enters the main sequence and ignites  $H \rightarrow He$  fusion, it remains hydrostatically balanced for  $\sim 11$  Gy; its values of  $L$  and  $T_s$  change little. Still, it is instructive to track those small changes, for they show that  $\Phi_m$  does increase throughout the Sun’s long lifetime, even in its relatively stable main-sequence phase. Both theoretical inference and observational evidence reveal that our Sun currently increases its  $L$  at the rate of  $\sim 1\%$  per 100 My. This occurs because, as the Sun fuses  $H \rightarrow He$  within a core zone where  $T_c \geq 10^7$  K, the  $He$  ash accumulates and contracts, albeit slightly; much like a negative-feedback thermostat, the star continually adapts by readjusting its balance between inward-pulling gravity and outward-pushing pressure. As the ashen core so “settles,” it heats yet more, in the process fusing additional  $H$  within an expanding  $10^7$ -K shell overlying the core and thereby increasing the star’s energy production rate, though again only slightly—and very slowly. Accordingly, the Sun must have been dimmer than it is now when it first joined the main sequence as a new star  $\sim 5$  Gya. The young Sun would also then have been somewhat more massive as it regularly loses mass via its solar wind, in fact likely suffered an even faster mass-loss rate in its youthful T-Tauri

phase when its wind resembled more of a gale while clearing the early Solar System of formative debris. Although the Sun's early mass-loss rate is unknown, it was probably a small fraction of the star per se; today the Sun loses  $\sim 2 \times 10^6$  metric tons of particulate matter per second (i.e.,  $3 \times 10^{-14} M_{\odot}/y$ ) and another  $4.3 \times 10^6$  tons/s in equivalent radiation (i.e.,  $\sim 6 \times 10^8$  tons/s of H converted to He at 0.7% efficiency), but that loss hardly affects the Sun as a star, diminishing its total mass by  $\ll 0.1\%$  to date. Computer models [13] imply that  $\sim 5$  Gya, the Sun was about half as luminous yet virtually as massive, making  $\Phi_m$  early on  $\sim 1$  erg/s/g. Thus, over the past 5 Gy,  $\Phi_m$  for the Sun has roughly doubled, and over the course of the next 6 Gy will nearly double again by the time its central H fusion ends. These past and future changes in the state of the Sun can be traced on an H-R diagram like the one in Figure 2, yet even during this quadrupling of its  $L$ , the Sun remains on or close to the main sequence—the locus of  $\sim 90\%$  of the stars in the Universe today.

When the Sun does leave the main sequence in  $\sim 6$  Gy, it will experience a significant increase in  $\Phi_m$ , for by then it will begin to evolve and complexify more dramatically. Post-main-sequence evolutionary changes accelerate in every way: Its  $L$  will increase substantially, its color will change noticeably, its internal gradients will grow greatly, and its value of  $\Phi_m$  will rise much more rapidly than in its first 11 Gy. What follows are some numerical details of this evolutionary scenario, averaged over many models, noting that until nearly the star's demise  $M$  remains practically constant all the while  $L$  and therefore  $\Phi_m$  increase [14, 15].

In  $\sim 6.2$  Gy, the Sun's extremities will expand while exhausting H gas in its core, yet still fusing it within surrounding layers. Its  $L$  will first become nearly twice larger (in addition to its already main-sequence doubled valued of  $L$  today), making then  $L_{\odot} \approx 10^{34}$  erg/s—the result of a bloated object fluxing its energy through a larger surface area as our future Sun enters the so-called subgiant branch of the H-R diagram (Figure 2). By then, its energy output will have increased because its core  $T_c$  will have risen with the continued conversion of ever-more gravitational to thermal energy; He ash accumulating in the core will contract substantially, thus producing more heat, which once again stabilizes the star against collapse. By contrast, its surface  $T_s$  will then have decreased as with any distended object from  $\sim 6000$  to  $\sim 4500$  K, making its previous (as current) external color of yellow more orange. At this point, the star will have become a convoluted object—its envelope expanded past the size of Mercury's orbit while receding into interstellar space and its core contracted to the size of Earth while approaching the quantum state of electron degeneracy. As its He-ashen core then continues compacting under the relentless pull of gravity, its  $T_c$  will approach  $10^8$  K needed to fuse He, all the while its  $T_s$  will have lowered further to  $\sim 4000$  K and

also become redder as the aged star inflates further. Additional complications will be manifest since, although  $H \rightarrow He$  fusion occurs throughout the more voluminous intermediate layers, that process will have switched from the simpler proton-proton cycle to the more elaborate carbon-nitrogen-oxygen (CNO) cycle (wherein those heavy nuclei, especially C, act as nuclear catalysts) mainly because the overlying layers will be then heated to higher  $T$  from the even hotter underlying core. Eventually,  $\sim 0.7$  Gy after leaving the main sequence and following an extremely short period of unstable, explosive He fusion when it first ignites (or “flashes” ferociously for a few hours according to computer models), the star will attain a more stable state on the horizontal branch where it fuses  $He \rightarrow C$  and thence displays  $L \approx 50 L_{\odot}$  (Figure 2), but only for  $\sim 100$  My more—the classic late stage of a red-giant star near “death.” Throughout this period of post-main-sequence evolution, the Sun's internal thermal, density, and elemental gradients will have markedly steepened; its mass will have decreased to  $\sim 0.8 M_{\odot}$  owing to strong winds and serious mass-loss rate caused by its larger size ( $\sim 100 R_{\odot}$ ) and reduced surface gravity; and its core, once laden with mostly H fusing into He, will have become mostly He fusing into C, all of which means a more differentiated internal constitution—a clear sign of an evolved physical system that has become decidedly more complex, as are all red-giant stars.

Ultimately and for a much shorter period of time ( $< 10$  My) as He is consumed and C accumulates in its core, the elderly Sun will likely swell still more and lose more  $M$  while transitioning deeper into the giant domain, where its values of  $L$  and hence  $\Phi_m$  might increase by roughly another order of magnitude. As sketched in Figure 2, the future Sun will likely negotiate these changes by moving back up along the so-called asymptotic giant branch (AGB) typical of the brightest red giants. Multiple shells of H and He will then fuse internally, but its total mass is too small to allow appreciably its core to reach  $6 \times 10^8$  K needed to fuse  $C \rightarrow O$ , thus its central fires will extinguish without synthesizing heavier nuclei. While nearing its end fate, the Sun's constitution will have become more complicated than when it first began fusing as a homogeneous sphere of mostly H gas  $\sim 5$  Gya. The future Sun will be unable to survive the changing conditions; it is destined for deletion from the local population of stars.

The progressively increased complexity described here for a  $1-M_{\odot}$  star is well reflected in its increased  $\Phi_m$  values throughout its stellar evolutionary journey—much as expected for any open, ordered, nonequibrated system both evolving and complexifying. The Sun, in particular, has, and will have, increased its  $\Phi_m$  values throughout its lifetime while repeatedly adapting to its changing circumstances, as listed in Table 2 and plotted in Figure 3.

Rising  $\Phi_m$  well characterizes the Sun as it becomes more structurally complex while physically evolving—but

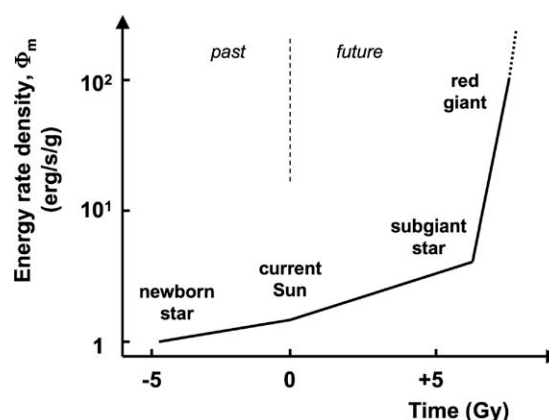


only while fusing as a genuine star. Its ultimate destiny is twofold: a slowly receding outer envelope that gradually disorders by dispersing into the surrounding interstellar medium, and a small, dense, hot core remnant whose C embers glow solely due to stored heat. These latter, so-called white dwarfs are not white-dwarf stars per se, as there is nothing stellar about them; no nuclear fusion occurs within such relatively homogenized spheres of C that are supported only by a sea of electrons obeying the Pauli exclusion principle. Such an end fate for the Sun is not very complex—and not very surprising either, as such a dead star, as with any object—animate or inanimate—has an energy flow below optimum (since typically for white dwarfs with  $\sim 10^{-3} L_{\odot}$  and  $\sim 0.6 M_{\odot}$ ,  $\Phi_m \approx 0.002$  erg/s/g, on their way to becoming black dwarfs in  $\sim 10^{12}$  y when  $\Phi_m = 0$ ).

In contrast to the Sun whose complexity increases only modestly for much of its lifetime, more massive stars demonstrate more strongly a correlation among evolution, complexity, and  $\Phi_m$ . To give one example, owing to its greater gravity, a  $10\text{-}M_{\odot}$  star lives fast and dies young ( $\sim 50$  My) while developing huge thermal, density, and elemental gradients between its core and surface as it fuses progressively heavy nuclei within ordered, concentric shells—a repetitive process that engenders ever-increased energy flows and complexity states. In fact, it is the growing complexity fostered by such stars' rising energy flow that causes them to quickly evolve away from the main sequence toward the supergiant domain, as sketched by the higher, looping track in Figure 2, where for each cycle that yields heavier nuclei, the value of  $\Phi_m$  rises still more [15,16]. Numerically, for the specific case shown in the figure,  $\Phi_m \approx 600, 1800, 2600$ , and  $4000$  erg/s/g, while fusing H, He, C, and O, respectively—enhanced energy flows that will eventually synthesize up to Fe nuclei, exceed optimum values, and explode the star into disordered pieces during a violent supernova. Both Rigel and Betelgeuse, exceptionally luminous members of the constellation Orion, are good examples of such stars now evolving toward this catastrophic fate.

This section has described, at the least, developmental change within stellar evolution, the kind of change termed

FIGURE 3



The complexity of the Sun, expressed in terms of  $\Phi_m$  and plotted within the bottom oval of Figure 1, is shown rising here in greater detail on the left side of the vertical dash (to the present) and on the right side (into the future), thus specifying increasingly ordered structures within the Sun at various stages of the physical evolutionary phase of cosmic evolution. The value of  $\Phi_m$  for the Sun rises gradually while fusing  $H \rightarrow He$  throughout  $>95\%$  of its total  $\sim 12\text{-Gy}$  lifetime. Even while on the main sequence, the Sun approximately quadruples its luminosity and hence its energy rate density while steadily, yet very slowly, growing more complex. Only toward the end of its tenure as a nuclear-burning star does the Sun's core contract enough to trigger  $He \rightarrow C$  fusion, to escalate its internal organization, and to cause a rapid rise in  $\Phi_m$  by about an order of magnitude.

by some biologists [17] *transformational evolution*—mostly gradual (and occasionally episodic) alterations among objects quite apart from any generational selectivity. Mountains sprouting in response to tectonic forces, fertilized eggs developing into mature adults, and normal stars swelling to become red giants are all examples of transformational evolution. Virtually all changes in the inanimate Universe, among many also in the living world, are minimally of this kind. The idea that stars might also experience *variational evolution*, resembling that occurring biologically over generations, is proffered in the last section of this article.

TABLE 2

Energy Rate Densities for the Sun

Stellar type	Time (Gy)	$\Phi_m$ [erg/s/g]
AGB star	+7	$\sim 2000$
Red giant	+6.9	120
Subgiant star	+6.2	4
Current Sun	0	2
Newborn star	-5	1

### 3. PLANTS AS EXAMPLES OF BIOLOGICAL EVOLUTION

All post-Cambrian land plants are multicellular and most obtain their energy via photosynthesis—the most widespread, and probably most important, biological process occurring on Earth today [18]. Photosynthesis provides a useful way to correlate the rise of complexity with biological evolution, especially as fossil records and molecular dating provide robust data on plant origins. Modern plants likely evolved from protists, notably green algae, that have biological metabolisms and physical structures closely

resembling those of today's photosynthesizing organisms; calcified fossils of multicellular green algae, which were freshwater organisms yet were also capable of surviving on land, date back at least to the mid-Ordovician (~470 Mya). Generally, mosses were among the first full-time inhabitants of the land, taking up residency early in the Paleozoic (~450 Mya). Vascular plants, having internal plumbing with leaves, stems, and roots akin to those of modern plants, originated during the late Silurian (~420 Mya, some fossils preserved) and by the mid-Devonian (~380 Mya, many fossil examples) had greatly multiplied and diversified while spreading into copious environments, thereby creating the first forests. Primitive seed plants emerged near the start of the Carboniferous (~350 Mya), though most such species perished during the Permian-Triassic mass extinction (~250 Mya). These earliest seed plants were the gymnosperms, whose "naked" seeds are not enclosed in protective structures and whose modern examples include evergreen trees such as conifers and pinewoods. The angiosperms, by contrast, comprising the flowering plants with enclosed seeds as with most grasses and deciduous trees, were the last major group of plants to appear, evolving rather suddenly from among the gymnosperms during the early Cretaceous (~125 Mya) and then rapidly diversifying ~30 My later. Although the gymnosperms dominated life for at least 250 My, angiosperms later crowded them out; today, almost 9 of 10 land plants are angiosperms, and a nearly continuous record of their fossils is preserved in rocks over the past 50 My.

Living systems generally require larger values of  $\Phi_m$  than inanimate systems not only to maintain their greater structural order (notably the polymer cellulose for tissue and fiber) but also to fuel their complex functions of growth and reproduction. Plants, in particular and on average, need  $1.7 \times 10^{11}$  ergs for each gram of photosynthesizing biomass, and they get it directly from the Sun. Since from *SeaWiFS* satellite sensing, the conversion of  $\text{CO}_2$  to biomass is  $\sim 2 \times 10^{17}$  g annually (i.e., about twice 105 gigatons of C net primary production [19]); Earth's entire biosphere uses energy at the rate of  $\sim 10^{21}$  erg/s [20, 21]. This is  $\sim 0.1\%$  of the total solar power reaching Earth's surface ( $\sim 90$  PW), which means that the electromagnetic energy of only  $\sim 1$  in 1000 photons is converted into chemical energy of plants. Expressed in units of the complexity metric preferred here, given that the total mass of the terrestrial biosphere (i.e., living component only,  $>99\%$  of it in the form of uncultivated land biomass, and  $\sim 90\%$  of that in forests) is  $\sim 1.2 \times 10^{18}$  g (an average from many researchers, not including any potential "deep hot biosphere" [22]), the value of  $\Phi_m$  for the biogeochemical process of photosynthesis is, again on average for the vast majority of Earth's plant life,  $\sim 900$  erg/s/g, as given in Table 1.

It is often said that photosynthesis is a highly efficient process that is not understood, whereas in reality it is a very inefficient process that is rather well understood.

Photosynthesis is limited by a wide range of variables, including light intensity,  $\text{CO}_2$  abundance, environmental T,  $\text{H}_2\text{O}$  availability, and leaf morphology, all of which interact in complicated ways; the process also has optimal ranges for each of these variables, such as a minimum T below which and a maximum T above which photosynthesis will not operate [23]. Photosynthesis is inherently inefficient for the complete metabolic process that converts sunlight into chemical energy stored in glucose molecules, not the higher rate of merely splitting  $\text{H}_2\text{O}$  and releasing electrons. At the molecular level, the maximum quantum efficiency is  $\sim 28\%$ . However, only 45% of solar radiation is within the visible band (400–700 nm) where the light-harvesting pigment chlorophyll-a is active, thereby reducing the actual molecular efficiency to only  $\sim 12\%$ . Furthermore,  $\sim 1/3$  of the absorbed energy is needed to power plant respiration, and  $\sim 1/5$  of sunlight is typically blocked by overlying canopy, leaving only  $\sim 6.5\%$  as the theoretical maximum efficiency of any plant [24].

More organized fields of higher order plants, such as herbs and shrubs, and especially cultivated crops, such as rice and wheat, can photosynthesize more than an order of magnitude more efficiently than the global average, their values of  $\Phi_m$  often being in the range of 3000–18,000 erg/s/g. Abundant deciduous trees, with their larger absorbing leaves, capitalize on the short, hot summers by photosynthesizing fast, yet their leaves die young when compared with evergreen trees that achieve slower, steadier growth year round; averaged annually, net productivity and efficiency of the two types of trees are comparable, 0.5–1% or 5000–10,000 erg/s/g. Among the rarest of plants, the more complex  $\text{C}_4$  type plants (that initially assimilate  $\text{CO}_2$  to make 4-carbon sugars) have photosynthetic efficiencies of 2–3.5%, which is about twice that of the simpler, more widespread  $\text{C}_3$ -type plants (having 3-carbon sugars), although both use the Calvin-cycle to fix  $\text{CO}_2$ . This is probably because the  $\text{C}_4$  pathway, which fossil and genetic records imply was an evolutionary advance  $\sim 30$  Mya—either to cope with draught or declining  $\text{CO}_2$  levels or as an adaptation to open, tree-less environments, and possibly both [25]—uses less  $\text{H}_2\text{O}$  and  $\text{CO}_2$ , employs greater nutrient uptake and displays longer growth cycles. The most highly cultivated  $\text{C}_4$  plants, such as maize and sugarcane that have been made more efficient (up to 3.5%) by advanced agricultural practices of recent times, probably cannot be fairly compared with fields of wild grasses and genetically unaltered trees and shrubs; in any case, they altogether produce  $<1\%$  of the total yield of organic matter globally [26]. Genetic engineering promises to better the efficiency of photosynthesis still more, but this is mostly cultural, not biological evolution.

Independent evidence suggests that energy use was likely a factor in the evolution of more advanced species of plants, especially the stunning diversification and rapid

rise to ecological dominance of the angiosperms in the mid-to-late Cretaceous. Angiosperms have higher growth rates and nutrient needs than gymnosperms; they sequester more nitrogen and phosphorus in their leaves, which then decompose quicker, and thus, by positive feedback, create richer soil conditions for their own growth. Hence, the angiosperms probably used higher energy budgets than gymnosperms, allowing the former to out-compete the latter during one of the greatest evolutionary radiations in the history of life [27]. Furthermore and theoretically, hierarchies in energy density (if not energy rate density) have long been expected for organisms ascending the trophic ladder in ecosystems [28, 29].

In contrast to many of these higher plants, the lower (nonvascular) plants have distinctly smaller values of  $\Phi_m$ . Among the simplest photosynthesizing life forms are the sea-based phytoplankton that resemble early, single-celled microorganisms from which all plants arose, including microscopic eukaryotic algae and the even more primitive, prokaryotic cyanobacteria that made (as some still do today) the stromatolites. Nearly half of photosynthetic productivity worldwide is of marine origin (to ocean depths  $\leq 100$  m), while the remainder is of mainly terrestrial land plants. Photosynthetic efficiencies for naturally occurring microalgae are poorly documented, but satellite-sensor measurements of solar-energy utilization imply overall values averaging 0.3% and at most 0.1% for plants on continental landmasses and in ice-free waters, respectively ([19; see also Ref. 30]; such low efficiencies do approximate those computed above for the photosynthetic process operating today for the bulk of Earth's biomass, and thus likely include not only phytoplankton and a variety of protists but also green algae that have ancestral links to land plants more than any other simple species. These efficiency estimates are neither biofuel production rates that can be higher for algae than for conventional crops owing largely to algae's short-doubling time nor are they laboratory idealized or commercially hyped values. The sea-based measures can be considered representative of energy utilization for some of the earliest protists—at least as far back as  $\sim 0.5$  Gya when the fossil record implies that algae became widely abundant, probably as much as  $\sim 1.7$  Gya when eukaryotic phytoplankton evolved in Proterozoic oceans [31], and possibly  $\sim 3$  Gya when rocks that old trapped traces of chlorophyll that probably facilitated photosynthesis in primitive algae and prokaryotic cyanobacteria [32]. Aquaculture farming (including genetic modification,  $\text{CO}_2$  enhancement, and active fertilization) under controlled conditions can better microalgae efficiencies, but that again is cultural evolution and not indicative of flora in the wild early on.

Table 3 summarizes various plant efficiencies,  $\varepsilon$  [33, 34], noting that they and their associated  $\Phi_m$  values are averages for a wide spectrum of members within a given plant type. As with galaxies, stars, and any inanimate systems,  $\Phi_m$  val-

**TABLE 3**

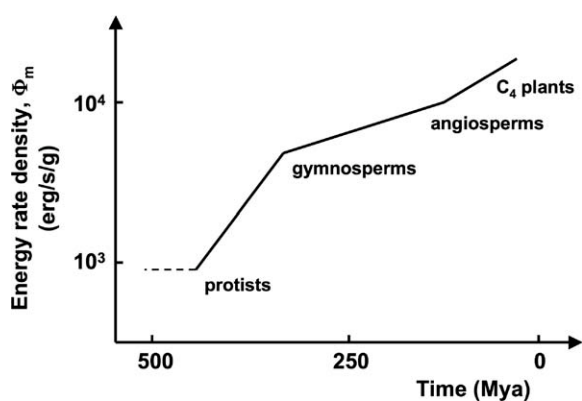
Energy Rate Densities for Some Plants

Plant type	Time (Mya)	Example	$\varepsilon$ (%)	$\Phi_m$ [erg/s/g]
Tropical grasses ( $\text{C}_4$ )	30	Maize, sugarcane	2.5	22,500
Temperate zone herbs	125	Wheat, tomato	1.5	13,500
Deciduous trees	125	Oak, beech	0.8	7,200
Evergreen trees	350	Pine, fir, larch	0.6	5,500
Protists	>470	Phytoplankton, algae	0.1	900

ues for life forms can range considerably, often over an order of magnitude or more—as in the case here for more complex, evolved plants. Variations occur among the plants because they do not equally absorb all incoming sunlight and do not convert all harvested energy into biomass.

Values for  $\Phi_m$  listed in the right column of this table are relative to all plants in general with  $\varepsilon = 0.1\%$  having  $\Phi_m \approx 900$  erg/s/g, as noted above. Those values clearly increase from bottom to top, where flowering angiosperms (topmost entries) are widely considered more botanically complex than the unprotected-seed gymnosperms; the former have more specialized cell chemistry and more intricate reproductive structures. Taken together, the tabulated entries generally agree with this article's hypothesis correlating normalized energy flow, biological evolution, and increased complexity. In Figure 4, some of these  $\Phi_m$  values during post-Cambrian times are plotted.

Further numerical check on the complexity metric discussed here is provided by measuring plants' energy yields when they or their fossil-fuel remnants are burned under controlled, laboratory conditions [35, 36]. Chemical energy stored within glucose bonds of the plants during photosynthesis is then released as heat. For example, an acre ( $4047 \text{ m}^2$ ) of softwood trees like white pine (a gymnosperm) annually produces  $\sim 4 \times 10^6 \text{ g}$  (4.5 tons) of biomass, which if burned yields  $\sim 2 \times 10^{10} \text{ erg/s}$  (6500 Btu/lb, 20% moisture); and since an annual average of  $\sim 120 \text{ W/m}^2$  (solar) realistically reach Earth's surface in temperate latitudes where such trees grow,  $\varepsilon \approx 0.4\%$  and  $\Phi_m \approx 3500$  erg/s/g, both of which approximate quoted values in Table 3 for evergreen trees. By contrast, hardwoods like red oak (an angiosperm) contain  $\sim 50\%$  more heat content, which is why they burn "hotter" and often longer in a fireplace, again in accord with values for deciduous trees in Table 3. Such enhanced values of  $\Phi_m$  are not surprising given that a piece of fine, dense wood typically has a greater degree of

**FIGURE 4**

The complexity of plants, expressed in terms of  $\Phi_m$  and plotted earlier within the middle oval of Figure 1, is shown here rising in more detail to highlight some of the increasingly intricate structures for a variety of photosynthesizing plants at various stages of the biological evolutionary phase of cosmic evolution. Note how flowering angiosperms have higher energy rate densities than gymnosperms or protists, and, in turn, more organized, cultivated  $C_4$  crops such as maize and sugarcane still higher values.

organization than loose, uncultivated biomass. In turn, bituminous coal or refined gasoline ( $\sim 15,000$  Btu/lb), which of course are also mostly fossilized organic plant products, have  $\Phi_m$  values roughly twice that of raw wood; fossil fuels are more concentrated, which is why their energy rate densities are higher. The same acre, if planted with sugarcane, would produce nearly 20 tons of biomass annually, and upon burning would make  $\Phi_m$  several times greater, again in reasonable agreement with the tabulated values above for the more evolved  $C_4$  crops.

#### 4. HUMAN SOCIETY AS AN EXAMPLE OF CULTURAL EVOLUTION

Cultural systems are among the most complex phenomena in the known Universe. Human actions, largely dependent on energy use and now influenced by rapidly changing environments, are what make social studies so difficult. Unlike in much of the physical and biological sciences, controlled experiments in cultural evolution—humankind interacting (social psychology), cities functioning (urban economics), or nations jousting (parlous geopolitics)—are nearly impossible to conduct objectively. Modeling social behavior, let alone experimenting with it, is much harder to accomplish than manipulating molecules in chemistry laboratories or sending spacecraft to distant planets; the number, diversity, and interconnectedness of factors influencing human relations greatly exceed those affecting the fate of stars or the evolution of plants discussed above.

Consider modern civilization en masse, which can be considered the totality of all humanity comprising a (thermodynamically) open, complex society going about its daily business. Today's nearly seven billion inhabitants use  $\sim 18$  TW to keep our global culture fueled and operating, admittedly unevenly distributed in developed and undeveloped regions across the world [37]. The cultural ensemble equaling the whole of humankind then averages  $\Phi_m \approx 5 \times 10^5$  erg/s/g, as noted in Table 1. Here, I have taken human society to mean literally the mass of humanity, not of its built infrastructure, for what matters is the flow of energy through the human social aggregate. Unsurprisingly, a group of brainy organisms working collectively is more complex than all of its individual human components (who each consume an order of magnitude less energy, lest their bodies fry), at least as regards the hypothesized complexity criterion of energy rate density—a good example of the “whole being greater than the sum of its parts,” a common characteristic of emergence fostered here by the flow of energy through organized, and in this case social, systems.

Rising energy expenditure per capita has been a hallmark in the origin, development, and evolution of humankind, an idea dating back decades [38, 39]. Culture itself is often defined as a quest to control greater energy stores [40]. Cultural evolution occurs, at least in part, when far-from-equilibrium societies dynamically stabilize their organizational posture by responding to changes in flows of energy through them. A quantitative treatment of culture, peculiar though it may be from a thermodynamic viewpoint, need to be addressed no differently than for any other part of cosmic evolution. Values of  $\Phi_m$  can be estimated by analyzing society's use of energy by our relatively recent hominin ancestors. The following few paragraphs gauge energy usage among different types of human groups throughout time, illustrating how, in turn, advancing people used increasing amounts of energy beyond the 2–3000 kcal/day that each person actually eats as food [5, 41–44].

Hunter-gatherers as long ago as  $\sim 300$  ky likely augmented by small amounts the basic energy of food needed to survive. Anthropologists have studied these relatively simple material cultures and the energy flowing through their ecosystems not only by unearthing ancient habitats of extinct forebears but also by observing mores of modern hunting groups extant in today's tropical forests. Besides basic food requirements that granted their (40 kg) australopithecine foraging ancestors  $\sim 2000$  kcal daily, thus  $\Phi_m \approx 22,000$  erg/s/g, small amounts of additional energy were likely used both to gather food and to prepare it for consumption. With the use of fire, in particular and possibly as much as 165 kya, not only for cooking but also heat-treating stone to make better tools [45], the exploitation of energy would have roughly doubled to 40,000 erg/s/g for slightly heavier, archaic *Homo sapiens*. Ample evidence exists that even earlier hominins, notably



*H. erectus*, used pits for roasting animals, and perhaps even in the drying of foodstuffs prior to their preservation and storage to guard against lean periods. Fire also allowed the preparation of certain vegetables known to have been then widely consumed, such as yams that require washing, slicing, and leaching with hot water to remove alkaloid poisons. To what extent hunter-gatherers merely used fire when and where available, in contrast to actually possessing it or controlling it, is unknown—but it does represent, at least in some small way, an addition of primitive culture to the basic metabolic energy used by early humans.

Agriculturists ~10 kya not only used fire but clearly controlled it, constructed irrigation ditches and terraced fields, probably utilized rudimentary windmills and water-mills, and used draft animals to plow fields more deeply and extensively (such animals typically delivering ~600 W of power, compared to human exertion averaging 75 W)—all with the intent of increasing crop productivity. Such advances have been documented throughout more recent, if still prehistoric, times, especially where remains of fully domesticated varieties of plants and animals are evident in archaeological contexts. Such occurred in many locales globally, including, for example, southwest Asia (~9 kya), the Middle East and Mediterranean (~8 kya), and Meso-America (~7 kya), although agriculture may well have begun in western Asia where collections of wild grains are found ~11 kya among nomadic tribes who were still at the time hunter-gatherers. Later, domestication allowed human societies to actively alter the genetic composition of organisms by breeding (i.e., replacing biological natural selection with human-directed cultural selection, mostly by trial and error and without any knowledge of genes), thereby cultivating plants such as maize (now seven times the size of its original, undomesticated cobs) and sugarcane (now much more efficient than its natural strain as noted in Table 3). The poverty of energy apparently limited cultural development, yet with the onset of agriculture and the use of trained animals, ~10 kya, the equivalent energy available to individual *H. sapiens* (assumed here to be a 50-kg body) increased to ~12,000 kcal/day or  $\Phi_m \approx 10^5$  erg/s/g; in turn, these would have easily doubled with the invention of advanced farming techniques and the invention of metal and pottery manufacturing a few millennia ago. (Today, the most intensive agricultural methods yield as much as 40,000 kcal per day per person.) Ecosystems had clearly shifted from food collection gathered in the wild to food production by deliberately managed plans, and the results included the growth of cities, the dawn of industry, and soon thereafter the advent of professional warriors, regional alliances, and ultimately nation states. Underlying all this cultural advancement was greater energy usage per unit mass at each and every step.

Industrialists of a couple centuries ago learned to use energy to drive machines to power their homes and shops, thereby causing a huge demand for fossil fuels and hydro-power, which in turn revolutionized the production of goods, agriculture, transportation, and communications. Although human population rose greatly by  $\sim 5 \times 10^9$  people since 1800 CE, reaching  $\sim 6 \times 10^9$  by the year 2000, per capita energy usage also increased. Thus, total energy utilized during this period climbed dramatically and globally, much more so than when our earlier ancestors mastered the use of fire or invented solar-driven agriculture. Typically, throughout the world today, each citizen averages  $5 \times 10^5$  erg/s/g, which is roughly an order of magnitude more than our hunter-gatherer forebears. Again, as with estimates of  $\Phi_m$  for stars and plants above, this is an average value within a range of variations, since residents of advanced, OECD countries, such as those in Europe and North America, use several times more, whereas developing countries, such as China, India, and all of Africa, use several times less. For example, per capita expenditure of energy now averages 2.7 kW globally, yet varies regionally from ~0.5 kW for Africa to ~4.5 kW for Europe and to ~12 kW for North America. The result, ecologically, is that the stored photosynthetic energy of fossil hydrocarbons has been added to the daily energy of the Sun (and more recently that of terrestrial nuclear energy as well), all of which are used by human societies in various ways to access more resources and yield yet more productivity as well as to change the fabric and constitution of our earthly environment. Such unprecedented use of energy to produce goods, services, and knowledge (which, in turn, furthers the acquisition of still more energy) has also taken a toll on that environment. Regardless of all else, the second law of thermodynamics demands that as any system complexifies—even a human social system—its surroundings necessarily degrade.

Technologists represent the most developed and energy-intensive, yet wasteful, part of society today, displaying during the past half-century large electricity and transportation allocations in their energy budgets. Distinguished from industrialists, technologists use an energy rate density ( $>10^6$  erg/s/g) that is several times greater than that of traditional commercial society (perhaps, epitomized by astronaut-elites who individually enjoy energy shares of  $\sim 10^7$  erg/s/g while orbiting aboard the International Space Station, or an equivalent per capita energy use of ~1.5 million kcal/day, which is ~500 times more than each of us actually consumes as food daily). Symbolized by the most heavily energy-using countries such as the United States, Canada, Bahrain, and Qatar, technological societies have distinctly higher  $\Phi_m$  values than the average global citizen on Earth today or even than those living in the developed countries of Europe. To give but a single example of such energetic excess: With coordinated

TABLE 4

Energy Rate Densities for Human Society

Human type	Time (kya)	$\Phi_m$ [erg/s/g]	kW per person
Technologists	0	$2 \times 10^6$	12.5
Industrialists	0.2	$5 \times 10^5$	2.7
Agriculturists	10	$10^5$	0.6
Hunter-gatherers	300	$4 \times 10^4$	0.2
Australopithecines	3,000	$2 \times 10^4$	0.1

power generation and widespread distribution systems boosting the effective daily usage of energy, the per-citizen expenditure in all countries averaged 80,000 kcal by 1970, or  $\sim 5 \times 10^5$  erg/s/g; now, early in the 21st century, with  $\sim 25\%$  of the world's total power consumed by only 5% of the world's population mostly living in the United States, this one country averages  $\Phi_m \approx 2 \times 10^6$  erg/s/g. Thus, modern high-tech conveniences, from automobiles, aircraft, and centralized heating/cooling to a wide variety of energy supplements enhancing our information-based society (including wired homes, networked businesses, and consumer electronics of all sorts), have empowered today's individuals well beyond their daily food intake [46, 47]. And it is all still rising—in both absolute energy terms as well as per capita energy accounts.

Table 4 summarizes these cultural advances in energy usage among our relatively recent ancestors. Values of  $\Phi_m$  are given in the same cgs metric units computed earlier in this article, as well as in per capita power expenditure to emphasize the rising energy demands of each member of society. Figure 5 plots these values much as for the above energy-flow analyses of stars and plants—as could be done for all complex systems in Nature, and of which today's increasingly sophisticated, energy-hungry society is just one more example.

## 5. NATURAL SELECTION GENERALIZED

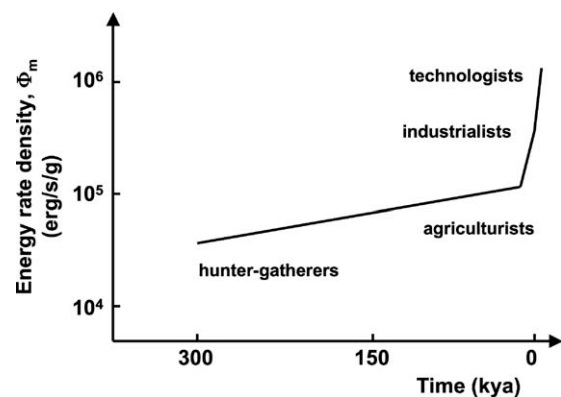
Selection arguably works alongside the flow of resources into and out of all open systems, not just life forms. Moreover, systems of any degree of complexity seem selected partly for their ability to command energy. Energy flow and natural selection likely operate in tandem as systems evolve—the former used by those systems advantageously suited to their randomly changing environments, and the latter nonrandomly eliminating those unable to do so. Conceivably, energy drives systems beyond equilibrium while selection aids the emergence of greater complexity for those systems able to manage the increased energy flow per unit mass. In other words, normalized energy

flow rate may itself be the trait most often selected by successful systems of the same kind.

Figure 6 helps to visualize such an energy-selection process at work, where part (a) depicts the general case of a system experiencing repeated opportunities to survive or terminate. Wherever and whenever optimum energy is available, systems capable of drawing power competitively, thereby building structures or functions needed to engage those energies, are favored; selection from among many energy-based choices rewards and nurtures dynamic steady states that create pathways capable of utilizing power per unit mass. Those systems using energy either too much, too rapidly, too little, or too slowly or are rejected and destroyed—the former two cases because systems would burn, the latter two because they lack threshold energy.

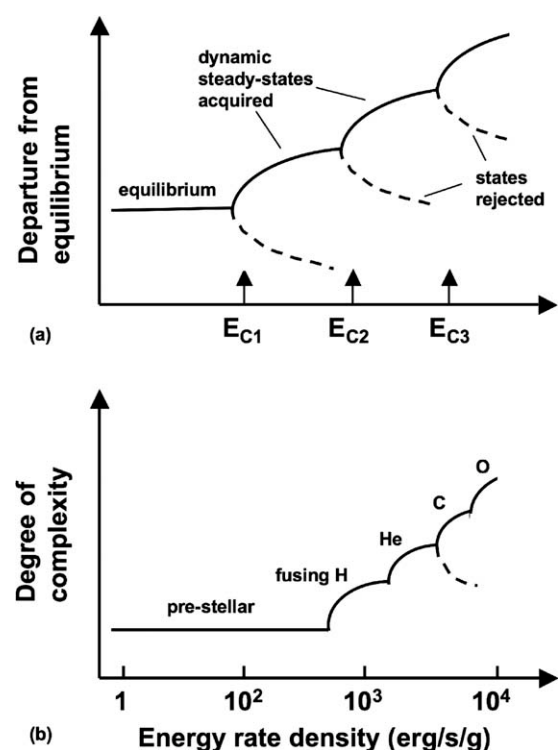
First, consider plants as familiar examples of biological selection among a wide assortment of wondrous life forms adorning Nature. Here selection—that is genuine neo-Darwinism—is clearly at work, making use of energy rate densities well in excess of those for galaxies, stars, and planets. As sketched in Figure 6(a), energy-flow diagnostics display increased complexity for a variety of steady states among plants that, following the solid curve, evade locally and temporarily the usual entropy process. As noted earlier in Figure 4, photosynthesis operates more effectively in flowering angiosperms than in gymnosperms and, in turn, even more effectively in more organized, cultivated ( $C_4$ ) crops such as maize and sugarcane. Similar trends are also evident for animals, yet with typically even higher

FIGURE 5



The complexity of human society, expressed in terms of  $\Phi_m$  and plotted earlier within the top oval of Figure 1, is shown here rising in more detail to illustrate the advance of energy usage by some of our ancestral groups in the cultural evolutionary phase of cosmic evolution. This rise has been truly dramatic in very recent times as our civilization became so heavily wedded to energy for its health, wealth, and security.

FIGURE 6



(a) Natural selection diagrams schematically illustrate how, at certain critical energies, labeled here variously  $E_C$ , systems can spontaneously change, or bifurcate (vertical arrows), into new, nonequilibrium, dynamic steady states. Chance affects the opportunities that arise, but necessity determines which fork systems select, namely which structures and functions are acquired (solid, rising curve) and which become extinct (dashed curves), thus the result is inherently unpredictable as with all of evolution. Such energy-selection diagrams can be drawn for any physical, biological, or cultural system successfully able to adapt and take advantage of increased energy while further complexifying. (b) For the case of the  $10\text{-}M_{\odot}$  star noted earlier, its degree of complexity rises substantially while  $\Phi_m$  increases and the star evolves through several fusion cycles (solid curves). By contrast, the Sun will never succeed in fusing C, hence will never acquire enough  $\Phi_m$  to become overly complex; it is destined to terminate and thus be naturally selected out of the population of stars (dashed curve).

energy rate densities along a broad evolutionary sequence spanning prokaryotes, ectotherms, and endotherms. All this accords with recent arguments in ecology (e.g., [48]) that highly metabolizing opportunists enjoy advantages during periods of change.

It is worth stressing two probable, general guidelines governing energy use, not only here for plants but also apparently for all open, complex structures: Energy flow regulation is likely a necessary, but not necessarily sufficient, condition for the growth, maintenance, and evolu-

tion of ordered systems—much as, for example, in the case of plant growth,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  are also needed. Furthermore, optimum ranges of energy use apparently exist for all ordered systems—as here for plants for which not too much, yet not too little, energy is required for photosynthesis, just as plants enjoy optimal ranges in heating and watering, lest they either desiccate or drown. This differs from the pioneering work of Lotka [49], who, albeit with great insight nearly a century ago, speculated that biological evolution proceeds to maximize the total energy flux through systems; by contrast, the data imply no clear law of maximum (or minimum) production of power (or entropy), indeed no extremum principles of any kind.

We need not dwell on the concept of selection operating throughout the bush of life, for the process is well accepted among biologists today. Yet, natural selection likely pertains to physical and cultural events as well—for whether stars or humans as discussed above, we encounter the same *general* trend found for plants: The greater the perceived complexity of the system, the greater the flow of energy density through that system—either to build it, or to maintain it, or both.

Next, consider stars as a case study of physical evolution, including selection. Growing complexity can serve as an indicator of stellar aging—a developmental process—allowing stars to be tracked as in Figure 2, while their interiors undergo cycles of nuclear fusion, thereby causing them to change in size, color, brightness, and composition while passing from “birth” to “death.” At least as regards ubiquitous energy flow, external environmental interaction, and internal structural modification while experiencing change, stars have much in common with life. None of which claims that stars are alive, nor do stars evolve biologically. Yet close parallels are apparent, including stellar populations, variations, adaptation, selection, and perhaps even a kind of crude replication among the stars—a generational activity—reminiscent of the following scenario that draws upon Darwin’s Malthusian-inspired principle of natural selection—but here a more simplified physical selection minus the sophistication of biological selection is given:

Galactic clouds spawn clusters of stars, only a few of which (the most massive ones unlike the Sun) enable other, subsequent groups of stars to emerge in turn, with each generation’s offspring showing slight variations, especially among the heavy elements contained within. Waves of sequential star formation are known to propagate through many such interstellar clouds like slow-motion chain reactions over eons of time—shocks from the death of old stars triggering the birth of new ones—neither one kind of star displaying a dramatic increase in number nor the process of regeneration ever being perfect. Those massive stars selected by Nature to endure the heat needed to produce heavy elements are in fact the very same stars that often produce supernova blasts that then create new

populations of stars, thereby episodically, gradually, and repeatedly enriching the interstellar medium with greater elemental complexity on timescales measured in millions of millennia. As always, the necessary though perhaps not sufficient conditions for the growth of complexity depend on the environmental circumstances and on the availability of energy flows in such (here, stellar) environments.

To be sure, stars do not merely increase their  $\Phi_m$  values while developing during a single generation of change, much as noted in Figure 3 for the Sun. They also, in a truer sense of the word evolution, display increased  $\Phi_m$  as second, third, and  $N$ th-generation stars emerge in turn from the debris of earlier generations of stars. Much akin to changes within populations of plants and animals over many generations of life forms, populations of stars do also basically alter as the composition and heterogeneity of interstellar space (and hence of each new stellar generation) change over exceedingly long durations of time—minus, of course, any system functionality, genetic inheritance, or species competition, for these are the value-added qualities of genuine biological evolution that go well beyond the evolution of physical systems.

Stars endure for periods that depend largely on their mass. None of the least massive stars ( $<0.5 M_\odot$ ) could have existed for more than a single generation, as these slow-fusing stars would not have had time to move through their evolutionary paces even once; the old, red dwarfs in the globular clusters of our Milky Way are surely ancient, Population-II types having low ( $\sim 1\%$ ) heavy-element abundances. By contrast, sunlike stars endure roughly for the age of the Galaxy ( $\sim 12$  Gy), and some could well have formed early in its history, run out their entire  $\sim 10$ -Gy lifetime, and now be expired. Stars with  $>3 M_\odot$  would have experienced well more than one generation as they last for  $\leq 1$  Gy; several generations of these bigger stars must have come and gone in the history of our Galaxy—as typified by the young, blue, Population-I stars having higher ( $\sim 2\%$ ) heavy-element abundances. And stars with  $\geq 10 M_\odot$  that fuse for merely  $\leq 50$  My must have participated in many generations of heavy-element production. Statistically, within only the first 1 Gy of the Milky Way's existence, all stars  $>5 M_\odot$  had already scattered into interstellar space new elements produced by  $\sim 5 \times 10^8$  supernovae.

All first-generation, Population-III stars fused via the proton–proton cycle; regardless of their mass, they had no heavy nuclei, hence had to use H exclusively. Once that initial generation of massive stars had run its course, their expelled heavies enriched galactic space where supernova concussions mixed the heavies with much loose H. Some of those newly formed stars with high enough  $T_c$  then began fusing via the more involved CNO cycle noted above; a second-generation star, for example, having  $\sim 10 M_\odot$  would have a distinctly higher  $\Phi_m$  value than any such first-generation star. And as heavy-element abundances increased

over the course of generation upon generation of stars,  $\Phi_m$  for enriched stars of given mass would have also necessarily increased. The result is that  $N$ th-generation stars grow ever more complex with time. Our Sun, with its rich complement of heavies that could not have been produced within it, is a product of many such prior generations.

But is there any selection occurring among the stars—any nonrandom elimination? In short, is there any *differential evolution* for physical systems, akin to traditional neo-Darwinism whereby biological systems able to survive change are the ones best adapted to varying conditions? Perhaps there is, for only stars with sufficiently high values of  $\Phi_m$  achieve states of substantial complexity; only those massive main-sequence stars having roughly  $\Phi_m \geq 100$  erg/s/g manage to create considerable order in concentric nuclear layering, their internal step-wise functions of core contraction, enhanced heating, and renewed fusion resembling the general bifurcations of Figure 6(a), where the specific values in Figure 6(b) for a high-mass star are derived from the upper track in Figure 2. By contrast, our Sun, with  $\Phi_m \approx 2$  erg/s/g currently, will in  $\sim 7$  Gy never evolve beyond a rudimentary red giant and never become selected for much greater complexity. Its energy rate density will not likely ever reach those critical values needed for the natural emergence of greater stellar complexity. The Sun will eventually be nonrandomly eliminated from its population of stars.

Much as for biological evolution among living species, the process of selection, generally considered, also seems operative in the physical evolution of nonliving systems (although selective pressures for the latter are likely partly internal and autocatalytic). At least as regards energy flow and structural complexity while undergoing stellar evolution, stars have much in common with life—provided that stars are examined broadly, dynamically, and over extremely long periods of time.

Lastly, consider civilization once more as humankind advanced culturally. Here, the cosmic-evolutionary narrative continues, yet with greater normalized energy flows characterizing our undeniably complex society. As illustrated by Figure 5, social progress, unapologetically expressed in terms of energy consumption and quantified by  $\Phi_m$ , can be traced for a variety of human-related strides among our recent hominin ancestors. And once again selection—in this case, cultural selection—was at work, much as could be sketched as in Figure 6, indeed in much the same way, albeit over shorter durations, as for stars, plants, and any other ordered system.

The technological advancement of humankind is a premier feature of cultural evolution occurring on Earth today. Technology is a cultural practice that decreases entropy locally by artificially manufacturing complex products, yet only with the expenditure of energy that inevitably increases entropy in the larger environment of raw



materials used to make those goods. And the result has been newer technologies systematically casting older ones into extinction, while usually benefiting humanity over the ages. Throughout the past few centuries, people chose shorter travel times, lower transportation costs, and heavier shipping loads; steam-powered iron ships replaced wind-powered clipper ships, while jumbo jets have superseded them all. Likewise, “horsepower” provided literally by horse and mule was first marginalized and then intentionally eliminated by steam and eventually gas engines as work animals on most farms the world over; people elected to concentrate energy for greater efficiency. Typewriters, ice boxes, and slide rules, among many other innovative inventions in their own time, were selected out of existence by the pressure of customer demand and commercial profit, often replaced initially by luxuries that eventually became necessities, such as word processors, refrigerators, and computers.

Machines of the fast-paced 20th century can surely be cast in evolutionary terms—though here, as with all cultural articles, the process is less Darwinian than Lamarckian. Either way, energy remains the driver, and with accelerated pace—a clear display of evolutionary trends as engineering improvement and customer selection over generations of products made machines more intricate and efficient, yet more complex. Modern gadget-filled automobiles, for instance, are better equipped and mechanically safer than their simpler, decades-old precursors, not because of any self-tendency to improve but because manufacturers constantly experimented with new features, keeping those that worked while discarding the rest, thereby acquiring and accumulating successful traits from one generation of cars to the next. Today’s cultural selection works by means of company competition and citizen preference in the social marketplace; Lamarckian use and disuse aids change and improves technology in automotive style, operation, and safety, all of which feed back to increase the pace of our lives and the thrust toward even greater complexity—for the bottom line is that more energy is expended per unit mass to drive those newer vehicles.

All these culturally increasing  $\Phi_m$  values—whether slow and ancestral such as for mastering fire and tilling land, or fast and contemporary as with the vaunted silicon chip that helps accelerate our 21st-century economy—were and are related to evolutionary events in which energy flow and cultural selection played significant roles. However, all of this progress, which has decidedly bettered the quality of human life as measured by health, education, and welfare, inevitably came—and continues to come—at the expense

of greatly increased demand for more and enriched energy—to what end humanity on Earth cannot be certain.

## 6. SUMMARY

Nature writ large is a mess. Yet, underlying unities stretch across the long and storied, albeit meandering, path from the early Universe to civilization on Earth. Evolution is one of those unifiers, incorporating physical, biological, and cultural changes within an inclusive cosmic-evolutionary scenario. Complexity is another such unifier, delineating enhanced structure, function, and diversity within and among galaxies, stars, planets, and life throughout all of natural history. And, potentially more fundamental, supporting both unceasing evolution and rising complexity is energy, whose flows through systems arguably grant opportunities for evolution, including natural selection, to create yet more complexity.

This article has gone beyond mere words, indeed beyond specialized disciplines, in an attempt to explore phenomenologically and more deeply a process that might characterize complexity quantitatively and broadly across many scientific disciplines. Here, energy itself is the mechanism of change. And energy rate density is a measure of the flow of energy through open, nonequilibrated systems, allowing us to gauge all such systems in like manner, as well as to examine how over the course of time some systems were able to command energy and survive, while others apparently could not and did not.

Nature everywhere and whenever displays variants on simple, unifying themes, and cosmic evolution is no different. The  $\Phi_m$  values and historical dates given in this article are estimates, each with ranges and uncertainties, yet it is not their absolute magnitudes that matter most as much as their perceived trends with the march of time. What seems inherently attractive is energy flow as a universal process—specifically, energy rate density as a single, unambiguous, quantitative measure of complexity—that helped to control entropy within increasingly ordered, localized systems evolving amidst increasingly disordered, wider environments, indeed that arguably governed the emergence and maturity of our galaxy, our Sun, our Earth, and ourselves.

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