

Energy Rate Density. II. Probing Further a New Complexity Metric

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Appraisal of the concept of energy rate density continues, as both a potential quantitative metric for complexity studies and a key feature of a unifying hypothesis for the origin and evolution of material systems throughout Nature writ large. This article extends a recent study reported in this journal, hereby analyzing normalized energy flows for an array of complex systems experiencing physical, biological, and cultural evolution. The results strengthen the comprehensive scenario of cosmic evolution in broad and general ways yet with much deep, empirical evidence. © 2011 Wiley Periodicals, Inc. Complexity 17: 44–63, 2011

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1. BROAD, DEEP, AND PHENOMENOLOGICAL

Regarding the traditional joust of theory and experiment in science, the subject of complexity stresses the former yet largely neglects the latter. Complexity science is less evidence based and less all-encompassing than many practitioners admit. At issue are the challenging search for unity in Nature, the slippery exploration of emergence beyond reductionism, and not least the inherent complexity of the subject itself. Fortunately, a third scientific method exists, most notably used in elementary-particle physics to decipher fundamental forces and structures of matter. Phenomenological modeling aims not only to extract trends and connections among empirical quan-

ties but also to discover basic understanding of underlying processes linking many varied phenomena.

This article reiterates and extends a proposed hypothesis that specific energy flow constitutes a complexity metric and potential evolutionary driver, most recently assessed in what is hereafter called Paper I [1]. There, I probed broadly, deeply, and phenomenologically the scenario of cosmic evolution—a scientific study of sequential change writ large, from big bang to humankind, over the course of ~14 Gy of natural history. I have related this story in recent years in the technical literature [2, 3], in the university classroom [4], and in general books and films [5, 6]. A concise overview of this research was also published earlier in this journal [7].

Academic colleagues often quip that history is “just one damn thing after another,” implying that natural history, which goes all the way back in time, comprises very many and diverse, yet unrelated events. However, interdisciplinarity is gaining favor, “big historians” coming forth, and

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natural scientists increasingly seeking the bigger picture [8]. Indeed, I have always regarded natural history expansively as a long and continuous narrative not only incorporating the origin and evolution of a wide spectrum of systems and structures but also connecting many of them within an overarching intellectual framework. In short, my philosophy of approach firmly roots my research in empiricism, mines data from a wealth of observations across all of space and time, and aims to synthesize history in a seamless story that unifies much of what exists in Nature.

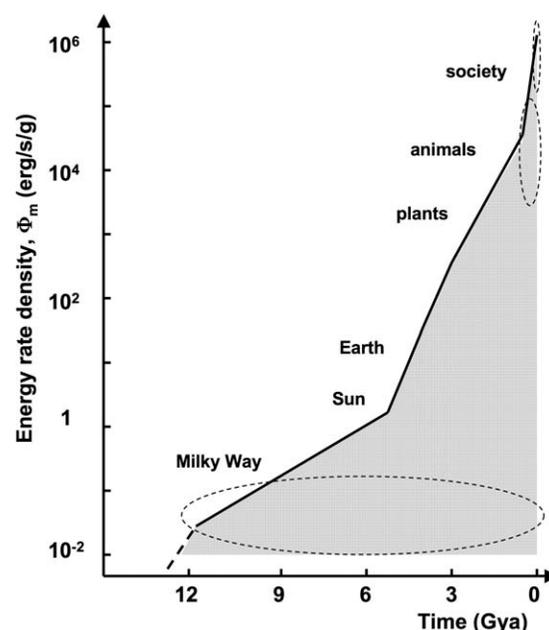
Although guiding changes within and among complex systems, evolution itself need not be a complex process. Nor does it likely pertain only to living systems, which in turn are not the only kind of adaptive systems known. Cosmic evolution, as an interdisciplinary subject that extends the idea of evolution generally to embrace all open, organized, nonequilibrium systems, amounts to nothing less than an inclusive worldview that chronicles changes in galaxies, stars, planets, and life. As done in Paper I for which this article is a sequel, I have here analyzed prominent examples from each of the major phases of cosmic evolution—namely, physical, biological, and cultural evolution. The result is that free energy rate density, Φ_m —the flow of energy per unit time per unit mass (freely available to do work or cause change thermodynamically)—continues to hold generally as a relatively simple quantity describing a common, unifying process that undergirds the growth of complexity characterizing a vast array of systems throughout the Universe.

Figure 1 graphs a grand perspective, albeit one rich in data. Presented there (revised from Paper I) is the rise in Φ_m for a variety of physical, biological, and cultural systems. Those researchers preferring energy rate density expressed in specific power units of W/kg of the mks-metric system should divide erg/s/g of the cgs-metric system used here by 10^4 . The significance of plotting on a single page the same quantity for such a wide range of systems observed in Nature should not be overlooked. I am unaware of any other single quantity that can characterize so extensively a principal system dynamic over >20 orders of magnitude in spatial dimension and nearly as many in time.

2. MILKY WAY GALAXY AND ITS CELESTIAL NEIGHBORS, AMONG MANY PHYSICAL SYSTEMS, HAVE RELATIVELY SMALL VALUES OF Φ_m

Paper I [1] addressed stellar evolution and the ways that stars become increasingly complex with time, both developmentally during their individual “lifetimes” as well as in a truer sense of the term “evolution” over generations of stars. While exploring the historical steps that likely led to our human selves, that earlier article limited analysis

FIGURE 1



Energy rate densities, Φ_m , for a variety of open, organized, nonequilibrium systems, plotted here semilogarithmically at the time of their origin, display a clear increase during the ~ 14 Gy history of the Universe. The shaded area includes a huge ensemble of changing Φ_m values as systems evolved and complexified. The three dashed ovals from bottom to top outline parts of this graph that are explored in greater detail for physical, biological, and cultural systems in Figures 2, 3, and 4, respectively.

mostly to our parent star, the Sun, with brief generalizations to other types of stellar systems. Likewise, here for galaxies, this study concerns mostly our home Milky Way Galaxy and some of its celestial neighbors.

The Galaxy (conventionally written with a capital “G” to distinguish our own such system, the Milky Way, from myriad others) displays a 2-4-arm spiral configuration, probably with a linear bar through its center, visually measuring ~ 30 kiloparsecs (kpc; $1 \text{ pc} \approx 3.26$ light-years) across a differentially rotating, circular disk of thickness ~ 0.5 kpc. The entire system has been observationally estimated to contain $\sim 10^{11}$ stars, of which our Sun is one of the great majority within the disk and ~ 8 kpc from its center. Visual inspection of stars and radio observation of nebulae show that our Galaxy’s rotation remains constant to a radial distance of at least 15 kpc, implying that the mass of the system within this radius is $\sim 2 \times 10^{11} M_\odot$ (where $M_\odot \approx 2 \times 10^{33} \text{ g}$), an extent delineated by its spiral arms comprising stars and loose interstellar gas. The integrated luminosity, L , or net energy flow in the Galaxy, measured at all wavelengths throughout the electromagnetic spectrum and including contributions from interstellar gas

and dust, cosmic rays, and magnetic fields, as well as stars, is $\sim 3 \times 10^{10} L_{\odot}$ (or $\sim 10^{37}$ W, where $L_{\odot} \approx 4 \times 10^{33}$ erg/s) within 15 kpc and very low surface brightness (if any luminosity at all) beyond [9]. Thus, *prima facie*, for the Milky Way, the inverse of the astronomers' standard mass-to-light ratio, $(M/L)^{-1} \approx (7 M_{\odot}/L_{\odot})^{-1} = \Phi_m \approx 0.3$ erg/s/g, which approximates that listed in Table 1 of Paper I. These values of M , L , and Φ_m are typical of many normal galaxies observed throughout the Universe, namely, those whose principal constituents are vast quantities of thermally emitting and baryonically constructed stars distributed in spiral or elliptical structures [10, 11].

The above estimates for M and thus for Φ_m do not include dark matter, an enigmatic ingredient of the cosmos that currently troubles much of modern astrophysics. If Newtonian gravity binds our Galaxy, then such dark matter, which is probably mostly nonbaryonic in nature, is needed to keep it from rotational dispersal; angular velocities of interstellar clouds in the Galaxy's extremities remain high far (~ 40 kpc) from the galactic center; the implication being that this huge physical system is even bigger and more massive, containing at least as much dark matter as luminous matter. Observations to date [12] imply a diffuse spherical halo at least 10 times larger diameter (~ 300 kpc) than the disk, a Galaxy several times as massive as that given above (i.e., $\sim 10^{12} M_{\odot}$), and a consequent Φ_m value equal to at most a third of that derived above, or ~ 0.1 erg/s/g. This article is concerned neither with the composition of the dark matter (the leading contenders for which are faint, compact halo objects and weakly interacting elementary particles) nor with the ongoing puzzle that this peculiar substance has thus far escaped observational detection at any wavelength. Suffice it to say that an invisible halo apparently exceeds the inner domain of stars, gas, and dust once thought to represent the full dimension of the Galaxy, and that the dark matter has much M yet little L that then affect estimates of Φ_m , hence system complexity.

Our Galaxy is part of an extended celestial neighborhood called the Local Group, which spans ~ 2 Mpc in diameter [13]. As surveyed to date, this minor galaxy cluster contains three big, normal galaxies and ~ 50 smaller, or dwarf, galaxies; none of the dominant systems, including the Milky Way and the Andromeda (M31) galaxy ~ 800 kpc away, resides at the dynamical nucleus of this cluster. Andromeda has much the same vital statistics as our Milky Way: its mass within its observed disk out to ~ 20 kpc from its core is $\sim 3.4 \times 10^{11} M_{\odot}$, and with an integrated $L \approx 5 \times 10^{10} L_{\odot}$, M31's value of Φ_m would normally be ~ 0.3 erg/s/g; but rotation-curve analysis of its outlying stars and gas clouds well into its halo implies that its total mass, including dark matter, is $\sim 2 \times 10^{12} M_{\odot}$, decreasing its Φ_m value to ~ 0.05 erg/s/g. And so, it is for nearly all normal galaxies: $\Phi_m \approx 0.5$ erg/s/g without dark matter,

and typically an order of magnitude smaller with dark matter included. The irregular and dwarf galaxies of the Local Group are different, given that their observed stellar velocity dispersions imply that these smaller systems are even more dark-matter dominated. Prominent among our Galaxy's ~ 20 satellites (most with remarkably similar $10^{6-8} M_{\odot}$ within ~ 0.3 kpc [14, 15]) are the Large and Small Magellanic Clouds, satellite irregular galaxies (of masses $\sim 10^{10}$ and $5 \times 10^9 M_{\odot}$, sizes ~ 4 and 2 kpc, and distances ~ 50 and 60 kpc, respectively); it is unclear if these Clouds are beyond the Galaxy or within its extended, nearly spherical halo, which is a remnant of an earlier evolutionary stage where old Population-II stars with low heavy-element ($> \text{He}$) abundances ($\sim 0.1\%$ by mass) predate the younger, higher-elemental-abundance ($\sim 1\%$ as in the Sun), Population-I stars in the galactic disk. Computer simulations of the early Universe that includes cold, non-relativistic dark matter (" Λ CDM standard cosmology" model [16]) predict that $> 10^3$ dwarf galaxies should now inhabit the Local Group, but only ~ 50 have been found thus far [17]. Most of these dwarfs are extremely faint ($10^{4-6} L_{\odot}$; $M/L \approx 10^2 M_{\odot}/L_{\odot}$ [18]), implying that others might not be missing but merely yet undetected substructures of dark matter having even lower L [15]. Given the observed underabundance of heavy elements within the dwarf galaxies having high dark-matter density, these and other mini-galactic systems are widely considered to be ancient vestiges of an earlier era in cosmic history when stellar evolution had not yet produced many elements $> \text{He}$. Estimates of Φ_m vary from 0.02–0.1 erg/s/g for the Milky Way's well-known dwarf galaxies to 10^{-3} – 10^{-2} erg/s/g for the newest such fainter objects found [19, 20]; unseen dwarfs, in turn (see below), must be among the least luminous galaxies in the Universe with $M/L > 10^3 M_{\odot}/L_{\odot}$ and $\Phi_m < 10^{-3}$ erg/s/g.

Galaxy formation is not well understood; theories abound but data are crude [21]. Galaxies are dim and distant, and research into their origin and evolution is tentative. Unlike most stars seen today, the bulk of each galaxy likely emerged long ago in time, thus far away in space now, hence their formative stages are observationally elusive; furthermore, their evolution (also unlike stars) is strongly influenced by environmental mergers and acquisitions as galaxies collide often within their parent clusters. A few decades ago, observations implied that virtually all galaxies are uniformly old; each seemed to have originated by means of fast (< 1 Gy) monolithic events that caused the dissipative collapse of massively primordial ($> 10^{12} M_{\odot}$; $\sim 90\%$ H, 9% He) protogalaxies in the first few Gy of the Universe [22]. Theories, however, could not account for the rapid assembly of such huge systems; even aided by gravity, chance alone cannot collect $\sim 10^{68}$ atoms to form even a single galaxy in the entire age of the Universe, and accelerants in the earlier Universe could not be discerned

to enhance the origin of galaxies. Furthermore, observations of the Milky Way's halo show distinct differences in populations of stars within old (>10 Gy) globular clusters, implying that galaxy construction was not likely a singular, ancient event [23]. Shifting views then proposed, by contrast, that galaxies originated much more slowly as part of a gradual, prolonged buildup over many Gy, indeed that they are now mostly still forming; hierarchical-merger scenarios became popular, whereby normal galaxies assembled when smaller building blocks ($\sim 10^{6-9} M_{\odot}$ typical of dwarf galaxies) collided and merged frequently [24, 25] while also perhaps accreting globular clusters and cold intergalactic gas [26]. Current observations are generally consistent with this hierarchical model, as young galactic fragments at great distances often appear smaller in size and more irregular in shape than nearby, present-day counterparts. However, recent findings [27–30] temper this scenario, reporting that many distant galaxies are already large, robust, and nearly fully formed, prompting a partial retreat to the original ideas that the bulk of each galaxy (>90% of its present being) formed quickly within the first few Gy—not necessarily by top-down collapse of one big gravitating system, rather more likely by rapid bottom-up collection of many smaller ones. Emergence of the latter is now understood to have been aided by tiny seeds of mostly dark matter that began as quantum fluctuations in the very early Universe ($\sim 10^{-32}$ s), now seen imprinted as density inhomogeneities on maps of the 3-K cosmic microwave background radiation emitted ~ 400 ky after the big bang [21, 31, 32].

Chaotic hierarchical clustering of dark-matter clumps provides the conceptual framework for modern studies of galaxy evolution, describing a process of upward assembly that began many Gya and continues, albeit at greatly reduced rate, to the present. Ample evidence exists that galaxies have evolved and are still evolving, in response to external factors—usually gentle accretion of dwarf galaxies, globular clusters, and loose gas, but sometimes violent, major mergers with other huge galaxies long after the first protogalaxies emerged [32]. Direct imaging of irregular galaxy fragments [33] and quasar absorption (Lyman- α) spectroscopy of intergalactic neutral H clouds [34] reveal a multitude of galaxy building blocks ($\sim 10^9 M_{\odot}$ each spread over ~ 3 kpc) in the earlier Universe at (Doppler redshift) $z > 2$, or >10 Gya; bigger (~ 100 kpc) Ly α -emitting “blobs” are observed [35] at even earlier epochs, $z \approx 3$, or ~ 11 Gya, and although all these primeval systems are near current detectability limits, most have $(M/L)^{-1} = \Phi_m < 0.1$ erg/s/g and often much less. Galactic encounters among such minor, oddly shaped blobs predominantly occurred long ago (>10 Gya) when the Universe was smaller and denser, subjecting the progenitors of today's massive galaxies to higher collision cross-section. Computer simulations show that the extensive dark-matter halos surrounding

most, if not all, galaxies predominate galaxy interactions, if only because those halos make galaxies much larger than their optical appearance implies, thereby increasing the probability of close encounters and mass assembly. That such major mergers replenish H fuel supplies while shocking and compacting loose galactic gas to make more stars, and thus probably lowering galaxies' M/L ratio (by probably only a few factors since both L and M increase, and only temporarily during brief ~ 10 -My episodes), is evident in “starburst” galaxies specifically and in enhanced stellar birthrates observed in the Universe generally. Most stellar activity peaked during $1 < z < 3$, thus between 7 and 11 Gya, which is probably the period in cosmic history when galaxy formation matured and galaxies' Φ_m values increased substantially [36]. In contrast to rare extraluminous galaxies (for which $\Phi_m = 1$ –10 erg/s/g), some of the dimmest galaxies, such as the ultrafaint, neighboring dwarfs in Ursa Major and Bootes, apparently have the largest fractions of dark matter yet few heavy elements, raising the intriguing possibility of “dark (or ghost) galaxies” [37]—a new category of very ancient, seemingly starless galactic systems, each ($\sim 10^9 M_{\odot}$) composed of almost entirely ($\sim 99\%$) dark matter emitting hardly any detectable energy ($\sim 10^{4-6} L_{\odot}$, hence $M/L \geq 10^3$, which is less than some individual stars in the Milky Way), and, therefore, having minute values of $\Phi_m \leq 10^{-3}$ erg/s/g. Such faintest of the dwarfs are almost surely pristine remnants of the earliest phase of galaxy formation—all of which implies that Φ_m likely increases slightly as galaxies evolve since, during infall/mergers, gravitational potential energy converts to star formation and other in situ galactic energies. Matter thereby acquired is spread over smaller volumes in six-dimensional (three-space, three-velocity) phase space and therefore less randomly distributed in real space, causing galaxies to become more ordered and organized, thus less entropic and more complex.

Here is a brief account of a widely accepted view of the origin and evolution of the Milky Way, minus lingering, controversial details, yet one that explains much galactic structure observed today as well as the kinematical and chemical properties of its stellar populations [32, 38–41]—a view that supports the idea that our Galaxy is a “cannibal” that consumed at least hundreds of smaller galaxies or galactic fragments during its lifetime. Although we cannot look directly into the past and watch our own Galaxy forming and evolving, we can study other, similar systems, including their representative building blocks. The great majority of the Galaxy likely originated within the first 1–4 Gy by means of dynamic, out-of-equilibrium mergers among several smaller systems, themselves contracting pregalactic clumps of mostly dark matter having masses $\sim 10^{7-8} M_{\odot}$ —comparable to the smallest dwarf galaxies and the biggest globular clusters, all of which have low heavy-element abundances that imply ancient formation from

relatively unprocessed gas. Today's dwarf galaxies in the Local Group are probably surviving remnants of those immature building blocks that have not yet merged with the Milky Way [42], and the ~ 160 known globular clusters in the halo may be archaic fossils (gravitationally stripped cores) of some of those dwarfs that did merge [23]. Initially, an irregular region ~ 30 kpc in diameter whose oldest stars now outline that birth, the Galaxy's baryonic gas and dust eventually settled into a thin spinning disk whose dimensions roughly match those measured today (noted above) and where abundant young stars are found and others are still forming. Timescales for subsequent evolution during the past ~ 10 Gy wherein the Galaxy's size, shape, and composition were altered are still debated, although a recently discovered thick (~ 2 kpc) disk containing middle-aged stars (7–10 Gy old; $\sim 0.5\%$ heavies) may represent an intermediate stage of star formation that occurred while the gas was still falling into the thinner plane. It also remains unclear if the original building blocks of galaxies contained already formed, even older (Population-III, 0% heavy-element) stars or if they resembled (and may still include) the dwarf galaxies seen today, some of which do have stars, others merely atomic gas.

Studies of the composition of stars in the galactic disk suggest that the infall of halo gas is still occurring today; the star-forming lifetime of a spiral disk may be prolonged by the arrival of fresh gas from the Galaxy's surroundings. However, it is unlikely that any major mergers impacted our Milky Way, otherwise its fragile thin disk would not have survived. Models of star formation and stellar nucleosynthesis imply that the fraction of heavy elements in disk stars should be significantly greater than observed, unless the gas in the disk is steadily being diluted by relatively unevolved gas arriving from the halo (or beyond) at rates of perhaps $5\text{--}10 M_{\odot}/\text{y}$. Recently discovered in the galactic halo are several streams of stars with similar orbits and compositions, each thought to be remnants of dwarf galaxies torn apart by the Galaxy's tidal field and eventually "digested" by our Galaxy, much as other dwarf companion galaxies were probably "consumed" by it long ago [43]. The small Sagittarius dwarf galaxy ($\sim 10^9 M_{\odot}$), the closest member of the Local Group now approaching the center of the Milky Way's far side, has been experiencing its death throes for the past ~ 3 Gy and will likely be assimilated into the Milky Way within another 1 Gy [44]; simulations imply that the Magellanic Clouds will eventually meet the same fate [45]. Upwards of a thousand mini-galaxies must have been likewise captured, shredded, and dissolved into the formative Milky Way long ago, their stellar inhabitants now intermingling with our Galaxy's indigenous population. Such galactic archaeology is supported by recent observations of the nearby Andromeda galaxy, where relics of past cannibalism between it and its satellite dwarf galaxies (notably filamentary streams of stars in its halo) show

the hierarchical process at work [46]. Nonetheless, the intergalactic debris now seen within major galaxies such as the Milky Way are minor additions to already mature galaxies. Dwarf galaxies are analogous to interplanetary asteroids and meteoroids that continually impact Earth long after the bulk of our planet formed 4.6 Gya; the current terrestrial infall rate of ~ 40 kton/y, or an accumulated $< 10^{20}$ g in 1 Gy, is negligible compared to the mature Earth totaling 6×10^{27} g. Most galaxy development is over, if not yet entirely done, as building-block acquisitions continue to add $\ll 1\%$ of total mass per encounter—much of it providing fuel for continued galaxy evolution as assimilated galaxies, no matter how small, bring in new stars, gas, and dark matter that often trigger waves of star formation.

Generalizing to other galaxies [47], most normal, mature galaxies display $\Phi_m = 0.01\text{--}1$ erg/s/g—values comparable to or a little less than those of normal stars (cf., Paper I). This is not surprising since, when examined in toto, galaxies are hardly more than huge collections of stars plus dark matter. Despite their majestic splendor and blue-rich (youthful) color, spiral galaxies as physical systems are not overly complex compared to many other forms of organized matter, especially biological and cultural systems (cf., Section 5). Nor is it surprising that reddened (aged) elliptical galaxies—huge balls of myriad old stars yet without much interstellar gas or internal structure—typically have the largest values of M/L among normal galaxies, thus the smallest values of $\Phi_m = 0.02\text{--}0.05$ erg/s/g; elliptical galaxies, as open, nonequibrated, thermodynamic systems, illustrate relative simplicity, in fact resemble vast collections of chaotic constituents high in entropy. Ellipticals, often termed "red and dead" galaxies owing to abundant red giant stars (cf., Paper I), may be examples of the ultimate fate of our Milky Way, especially since Andromeda and the Milky Way seem destined in several Gy to experience a close encounter, possibly merge, and trigger another round of starburst activity likely to transform these two grand spirals into an elliptical near astronomical death [48]. In contrast to normal galaxies, some active counterparts, such as anomalously massive ($> 10^{12} M_{\odot}$) radio galaxies or quasars, have $L \approx 10^{38\text{--}40}$ W, hence values of Φ_m as much as ~ 50 erg/s/g, but almost certainly for only relatively short periods of a few tens of My [39]; active galaxies probably resemble active metabolisms among biological systems, such as horses while racing or birds while flying for which Φ_m can increase by an order of magnitude or more above their basal, or normal, energy rates (cf., Section 3). Throughout all of Nature, values of Φ_m display considerable variation within any given type of complex system, depending upon the degree of activity and requiring care when using Φ_m as a complexity diagnostic. That Φ_m does not increase greatly and indefinitely for galaxies is probably dictated by core supermassive black holes ($\sim 10^9 M_{\odot}$) whose jets and winds

assert negative feedback that tends to resist further accumulation of matter and quench additional star formation, thus limiting L and hence Φ_m . (In the case of our Galaxy, its central black hole is massively irrelevant at only $\sim 4 \times 10^6 M_\odot$, currently dormant, and apparently not a major player in the evolution of the Milky Way). At any rate, origin and evolution of active galaxies are subjects for another article; the principal focus of this analysis is our own home Galaxy and some of the evolutionary changes that led to a galactic environment suitable for the emergence of the Sun, Earth, and life.

Figure 2 graphically summarizes the above discussion, plotting estimates of Φ_m against time. This graph depicts the general trend of the Milky Way Galaxy's evolution over ~ 12 Gy but does not show sharp spikes of increased Φ_m that might have occurred during relatively brief (approximately hundred-My) episodes of enhanced star formation caused by significant (although not major) collisions with neighboring dwarf galaxies—events that would have increased both M and especially L , thus potentially yet temporarily raising Φ_m by a few factors during the Galaxy's long mature phase.

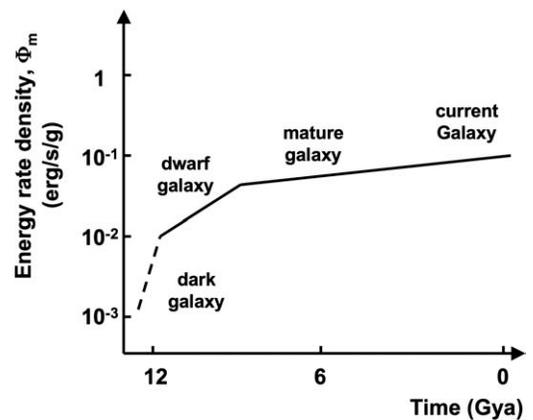
3. BODIES AND BRAINS, AMONG MANY BIOLOGICAL SYSTEMS, HAVE INTERMEDIATE VALUES OF Φ_m

Life depends critically upon energy usage; without a sustained flow of energy all life forms die. Organismal energetics are as fundamental as any process in biology, yet the biosciences lack a general consensus regarding a common quantitative metric specifying the amount of energy needed to optimize life. The issue is exacerbated not only by the vast diversity of Nature's many varied, extant life forms, extending over nearly 20 orders of magnitude in mass from microbes to whales but also by the inconsistent techniques, protocols, and units used in measuring energy-utilizing metabolisms.

This article treats the energy flow in animals in much the same way as for plants in Paper I—as far-from-equilibrium thermodynamic systems. My working hypothesis of energy rate density as a reasonable and consistent complexity metric is hereby extended to more ordered systems, in this section estimating specific (i.e., mass-normalized) metabolic rates for whole bodies and wet brains among a large sample of animals. The results show promise not only revealing a correlation among complexity, evolution, and Φ_m for major taxonomic groups but also numerical values for the last of these falling appropriately between evolutionary systems that are physically simpler and of older origin and those that are culturally younger and more complex.

For plants, the most prominent biological process is photosynthesis, which produces glucose ($C_6H_{12}O_6$) for system structure and adenosine triphosphate (ATP) that acquires, stores, and expresses solar energy throughout the

FIGURE 2



The growing complexity of the Milky Way Galaxy, expressed in terms of Φ_m and plotted within the bottom oval of Figure 1, is shown here in greater detail rising slightly over its ~ 12 Gy existence to date during the physical-evolutionary phase of cosmic evolution. According to the hierarchical theory of galaxy construction, dwarf galaxies and pregalactic clumps of gas merged relatively rapidly in the earlier Universe, such that within several Gy after the big bang our Galaxy had matured to nearly its present size and scale. The value of Φ_m for the Galaxy has continued rising ever since and will likely continue doing so, though only slightly, slowly, and episodically, as more galaxies (mostly dwarfs) collide and merge with our parent Galaxy.

floral world on Earth. By contrast for animals, the principal process is respiration, whereby oxygen (O_2) converts consumed carbohydrates into the organics of tissue structure and synthesizes ATP in mitochondria, which can then release energy when needed for bodily activities. While it is often said that plants are producers and animals consumers, in fact both engage energy as an essential process of life. Most animals aerobically respire to fuel minimal maintenance (basal metabolic rate) as well as to enhance more active lifestyles (field rate) when added O_2 consumption rises to meet increased demand for ATP production during stress, growth, and thermoregulation (and beyond that, though rarely, catabolic anaerobic pathways, such as glycolytic production of lactic acid, can generate additional ATP during brief bursts of maximum activity like that experienced by darting lizards and marathon runners). Paper I examined plants in some detail, suggesting how energy rate density might be judged as both a complexity metric and evolutionary driver; here, animals are likewise analyzed for their Φ_m implications, treating animals in much the same way as for plants, indeed in a consistent manner as for all ordered structures observed in Nature.

A wealth of paleontological and genetic data available today imply that animals (multicellular eukaryotes) generally became increasingly complex with time—both in

structure of individual organisms and in organization of ecological communities—and dramatically so in the Phanerozoic Eon since the Cambrian Period [49–51]. A clear yet rambling succession of life forms, broadly identifiable yet minus transitional details, is evident during the past ~0.54 Gy: invertebrates (>500 Mya), fish (~500 Mya), amphibians (~365 Mya), reptiles (~320 Mya), mammals (~200 Mya), and birds (~125 Mya). Much as suggested in Paper I for plant evolution, energy flow potentially affected animals, linking complexity growth and evolutionary pathways with increasing energy usage, all of it likely in accord with Darwinian descent with modification guided by natural selection—from ectotherms in the hot, damp climates of the Palaeozoic Era, to increasingly diverse animals of intermediate metabolism that thrived in the warm and drier Mesozoic, and then to endotherms in the cooler, fluctuating climates of the Cenozoic. Much of this change occurred by means of random evolutionary opportunities to secure food and escape predation, which initially required transport of O₂ reserves from the open waters and thus elevated states of metabolic energy consumption, followed by the terrestrialization of the vertebrates that required yet more energy largely because reptiles moved on legs and pumped their chests; mammalian adaptation further aided the rising complexification of the animal world, resulting in not least the emergence of energy-hungry primates, including our high-energy human society, the last of these also discussed in Paper I. While none of these energy additives was goal directed, each arguably presented selective advantages for some species throughout a long and meandering evolutionary process during the most recent 10% of Earth's history.

Ectothermic (or poikilothermic) animals control their body temperature T (~22°C) by means of external heat sources and include both invertebrates (arthropods, worms, mollusks, and their insect relatives) and lower vertebrates (fish, amphibians, and reptiles). As a group, ectotherms have less active metabolisms compared to endotherms, which include mammals and birds, that self-regulate their body T (37–42°C) by digesting food [52]. In fact, low metabolic rates are notably characteristic of all extant reptilian taxa, which were the first fully terrestrial vertebrates and which later gave rise (probably along independent lines of descent during the early Mesozoic) to two major phylogenetic radiations of endothermic mammals and birds. Ectotherms also have lower specific metabolic rates, hence lower values of Φ_m , than their warm-blooded cousins. Here, *in vitro* O₂ consumption rate effectively estimates metabolic rate, but caution is advised regarding wet and dry body mass, for it is wet (living) mass that counts when deriving values of Φ_m in a consistent manner relative to other living creatures; furthermore, it is the basal rate (for fasting, resting, inactive states) that is most telling when making comparisons and not the more active rates experienced

when contending with all the challenges of relying on the environment (ectotherms) or finding enough food (endotherms) to maintain body temperature [53]. Finally, added care is also required regarding incompatible units found throughout the bioscience literature; although the thermodynamic (cgs-metric) units used here may be unfamiliar to some readers, this article, as in Paper I, emphasizes uniformity among physical, biological, and cultural systems; thus, 1-L O₂ consumption equals ~2 × 10¹¹ erg or ~4.8 kcal [54].

Current metabolic data display no clear evolutionary differences in Φ_m values among the ectotherms [55]. Variations are statistically indistinguishable among the lower vertebrates, including fish, amphibians, and reptiles; most of their Φ_m values range between 2 × 10³ and 10⁴ erg/s/g, with a mean of ~4 × 10³ erg/s/g. As expected from paleontology, aerobic capacities were not expanded as life made the transition to land; reptiles and amphibians have no more energy needs than fish of comparable size. Among invertebrates, which are also ectothermic and constitute >95% of all animal species, $\Phi_m \approx 10^4$ erg/s/g, plus or minus ~30%; their slightly higher Φ_m than for the lower vertebrates, if significant, may owe to some invertebrates being active flyers, including minute insects, which likely require more power per unit mass (as do birds, see below). That these mean values are only slightly higher than for some photosynthesizing plants (cf., Paper I) is not surprising. The resting rates for the least evolved respiring ectothermic animals are not likely much more complex than efficiently photosynthesizing land plants; the two processes having matured roughly contemporaneously in the Paleozoic. Occasional outliers and minor overlaps in Φ_m values are evident throughout the evolutionary record for closely complex life forms, as acknowledged here and again below.

In contrast to the ectotherms, endotherms (or homeotherms) have distinctly higher levels of specific metabolism, hence higher values of Φ_m . Many field studies and laboratory measurements of animals having comparable body M and T show basal metabolic rates 5–20 times greater in mammals than in reptiles [55–57]. Three-quarters of all known mammals display a range in Φ_m value, 10⁴–10⁵ erg/s/g, with a mean of ~4 × 10⁴ erg/s/g. Variations in metabolic rates among mammals are apparent throughout these data; besides the most dominant influence of differing body mass, such variations likely reflect environmental conditions, ongoing adaptation, and numerous other factors that influence metabolism such as habits, habitat, climate, diet, and taxonomy [58]. To give a few examples: seals and whales have Φ_m values about twice those of other animals of their size because they need to thermoregulate their bodies in cold water; small desert mammals have lower Φ_m values than others of their size because they have adapted to a scarcity of food and water; and placental mammals have typically thrice the Φ_m value of similarly sized marsupials because they are vi-

viparous and have extra layers of energetically expensive brain mass.

Caution is needed to distinguish between basal (standard) and active (field) metabolic rates [59, 60] because the two can be as different as the fuel consumption of an automobile idling at a traffic light or racing along a highway. For example, a horse expends $\Phi_m \approx 5 \times 10^5$ erg/s/g at maximum exertion, $\sim 3 \times 10^5$ during regular exercise, yet only $\sim 8 \times 10^3$ at rest [61]. Overall, laboratory studies of sustained (field) metabolic rates typical of all free-living animals in the wild display enhancements in Φ_m by factors of 3–10 (and up to 50 for maximum exertion) over their basal rates, but still reveal that mammals outpace reptiles by nearly an order of magnitude [60, 62]. The different rates can nearly overlap for disparate life forms, much as noted two paragraphs above for simple animals (heterotrophic ectotherms) and efficient plants (advanced photoautotrophs). Likewise, endothermic vertebrates at rest and ectothermic insects in flight display comparable metabolic levels, as do maximum Φ_m for darting reptiles when compared with many resting mammals. However, mixing rates creates unfair comparisons and bewildering confusion in the literature does not help. When level assessments are made for the same type of specific metabolic rate, relative Φ_m values are clear and unambiguous: higher vertebrates (mammals and birds) have greater energy rate densities than any of the lower vertebrates or invertebrates.

Birds, also endothermic, evolved from carnivorous, feathered dinosaurs during the late Mesozoic, and among vertebrates have the highest values of $\Phi_m \approx 10^5$ erg/s/g, which can sometimes reach an order of magnitude greater during sustained flight or while earnestly foraging for food for their nestlings. Such high Φ_m might mean that birds' normal metabolisms are more energetic and akin to active (not basal) metabolisms among non-fliers; estimates of basal rates for birds resting at night, which are needed for even comparisons, are scarce and anecdotal. Many passerine (perching, frugivore) birds have $\Phi_m \approx 5 \times 10^5$ erg/s/g, which is $\sim 30\%$ higher ([63] claims this but [60] refutes it) than non-passerine fliers whose energy rate densities are comparable to mammals when active; however, uncertainties linger regarding whether reported avian rates are basal, active, or some sort of operational average. Hummingbirds, for example, when actively hovering can use as much as eight times more energy than their resting rate, yet while sleeping (more than half of each day) when their body T drops to nearly that of the surrounding air their rates decrease to three times less than basal; the former state requires them to ingest nectar daily equal to $\sim 50\%$ of their body mass, whereas the latter subsides on minimal energy stores. Similar basal-active comparisons can be made for mammals, such as for humans who maintain our basal rate by ingesting food daily equal to $\sim 3\%$ of our body mass; yet, our active metabolisms also increase by

more than an order of magnitude above our basal rates when swimming, jumping, or running, for which Φ_m averages 2×10^5 erg/s/g [64]. For all active fliers < 1 kg, Φ_m is less than for comparably massive mammals while running. Furthermore, birds, much like human marathoners and cyclists who consume many times their normal food intake ($\sim 10^5$ erg/s/g), are fueled partly by rapid expression of bodily energy reserves (anaerobic glycolysis), not by sustained, concurrent energy intake; these enhanced metabolic rates are atypical physiologically, hence their overall rates are lower when averaged over time.

In addition to their habitual active states, birds might also have high values of Φ_m partly because they are genuinely more complex than most other animals, including humans. After all, birds normally operate in three-dimensional aerial environments, unlike much of the rest of animalia at the two-dimensional ground level; thus, avian functions, quite apart from structural issues, might be legitimately considered, somewhat and sometimes, more complex than those of the rest of us. Brains aside (though discussed below), the bodies of fliers can arguably be judged more complex than non-fliers, given the former's intricate lung sacs, pectoral muscles, and wing aerofoils that allow a constant, one-way flow of O_2 -rich air that helps birds maintain high metabolic rates to generate enough energy for flight. The act of flying does indeed demand great skill, more energy, and a higher cost of living in general, requiring birds to master (in effect) spatial geometry, materials science, aeronautical engineering, molecular biochemistry, and social stratification. Avian species are impressive by any measure; their speed, maneuverability, and endurance are outstanding among all known life forms.

As implied earlier (Section 2), extraordinary avian physiology might well resemble enhancements in galactic ecology; each category of system—animals and galaxies—having members with exceptionally high metabolisms. In-flight birds, which while temporarily aloft have among the highest animal complexity levels, typify the energetics of briefly erupting active galaxies; each tops the charts of metabolic rates, or L/M ratios, of their respective classes, with values of Φ_m well higher than their basal, or normal rates. For relatively brief durations, such galaxies display values of Φ_m up to ~ 100 times the usual value for normal galaxies. Even high-endurance human athletes or those merely peddling mountains uphill require several tens of times their basal rate during short periods of maximum exertion when power expenditures can reach ~ 3000 W (or $\Phi_m \approx 4 \times 10^5$ erg/s/g), an increase so dramatic as to be comparable to that of airborne birds.

Humans deserve more than a passing note in any zoological discussion, not because we are special but because we are them. Each adult individually normally consumes ~ 2700 kcal/day (~ 130 W) in the form of food to drive our

metabolism. This energy, gained directly from that stored in other (plant and animal) organisms and only indirectly from the Sun, is sufficient to maintain our body structure and temperature as well as fuel our physiological functions and tetrapodal movements. (Note that the thermodynamical definition of a calorie, $1 \text{ cal} = 4.2 \times 10^7 \text{ erg}$ —the amount of heat needed to raise 1 g of H_2O by 1°C —does not equal a dietician's large Calorie with a capital "C," which is 10^3 times more energetic than a physicist's calorie.) Therefore, with a body mass of 70 kg, an average adult human being maintains $\Phi_m \approx 2 \times 10^4 \text{ erg/s/g}$ while in good health. Humans have midrange mammalian metabolic values because our bodies house average complexity among endothermic mammals, all of which harbor comparable intricacy, including hearts, livers, kidneys, lungs, brains, muscles, and guts. Despite our manifest egos, our bodily selves do not have the highest energy rate density among animals, nor are we likely demonstrably more complex than many other mammalian species.

The energy budget derived here for humans assumes today's average, sedentary citizen, who consumes ~65% more than the basal metabolic rate of 1680 kcal/day (or $\Phi_m \approx 1.2 \times 10^4 \text{ erg/s/g}$) for an adult fasting while lying motionless. By contrast, our metabolic rates increase substantially when performing occupational tasks or recreational events—again, that's function, not structure. And once again, Φ_m scales with the degree of complexity of the task or activity. For example, fishing leisurely, playing a violin, cutting a tree, and riding a bicycle require about 3×10^4 , 5×10^4 , 8×10^4 , and $2 \times 10^5 \text{ erg/s/g}$, respectively [64]. Clearly, jamming a musical instrument or balancing a moving bicycle are complex functions and, therefore, more energetically demanding activities, than waiting patiently for fish to bite. Thus, in the biological realm, the value-added quality of functionality does indeed count, in fact quantitatively so. Complex tasks actively performed by humans on a daily basis are typified by values of Φ_m that are often larger than those of even the metabolically imposing birds, in part because birds cannot operate instruments or ride bicycles!

This, then, is how humankind, like all of the animal world, contributes to the rise of entropy in the Universe: We consume high-quality energy in the form of ordered foodstuffs, and then radiate away as body heat (largely by circulating blood near the surface of the skin, by exhaling warm, humidified air, and by evaporating sweat) an equivalent amount of energy as low-quality, disorganized infrared photons. Like the stars and galaxies, we too among all other life forms are dissipative structures, thereby making a connection with previous thermodynamic arguments that some researchers might (wrongly) think pertinent only to inanimate systems.

Energy rate density may well qualify as a broad complexity metric for life, but current data preclude strong

Φ_m -related statements about specific evolutionary paths for individual species within major taxonomic groups of the animal kingdom. Suffice it to say that nearly all zoological Φ_m values are tightly confined to within hardly more than an order of magnitude of one another, nestled midway between smaller botanical values for photosynthesizing plants and higher neurological ones for central nervous systems. Further, correlations do link evolution, complexity, and Φ_m for major animal categories, notably those separating reptiles, mammals, and birds. For example, endothermy is surely one of the most striking animal adaptations, requiring extensive restructuring of many parts (including lung, heart, and skeletal muscle) of vertebrate bodies. The greater aerobic heat production in the endotherms is, of course, the basis of their homeothermic condition that grants them independence from environmental thermal fluctuations, and this arguably makes them more complex. Endothermy likely evolved in mammals from reptiles in the early Mesozoic as mitochondrial volume density gradually increased in their respective tissues, causing microscopic metabolisms to accumulate and with them total organismal specific metabolic rates to rise [65]. The original vertebrates (possibly ostracoderms) were active, predatory carnivores with metabolic patterns similar to most modern fish; the transition of vertebrates from aquatic to terrestrial habitats eventually would have enabled greater O_2 use, since O_2 in the aerial environment is more easily accessible owing to its increased diffusivity and concentration. However, most traits related to O_2 consumption do not fossilize and other factors have also been implicated as having granted major adaptive advantages [66]. Thermoregulation itself allows body temperature of mammals and birds to remain both higher and more constant than those of most ectothermic vertebrates, and this alone might enhance prospects for survival; endothermy, with its constant portable microenvironment, surely conferred competitive evolutionary advantages in benign environments and allowed those species so endowed to adaptively radiate into hostile parts of the biosphere. Higher levels of O_2 consumption also likely expanded the range of sustainable exertion and long-distance endurance, granting opportunities for greater complexity to parallel the rise in Φ_m values for mammalian and avian lineages. Regardless of how it emerged, a clear prerequisite underlies endothermy: more energy is required to attain it.

Energy flow was likely only partly responsible for evolutionary advancement of rising complexity. Nonevolutionary effects also surely contributed to the observed range in Φ_m values, for stressful environments thermodynamically drive some organisms to extremes during any given lifetime. For example, aquatic mammals have specific metabolic rates that are necessarily higher (by factors of 2–3) than those of similarly sized land mammals (since, much as for birds, the former operate in a three-dimensional

world, in this case where water conducts heat 20 times faster than air). An opposite extreme is found in desert mammals, whose anomalously low specific metabolic rates reflect food shortages, though they can rehydrate rapidly by drinking the equivalent of a third of their body weight in 15 min. Dietary, water, behavioral, and habitat factors will all likely cause variations in Φ_m values in addition to evolution per se, resulting in rare outliers in such diverse samples of animals. Body mass itself is the biggest cause of variation among metabolic rates among mammals; much the same is true for birds, as body mass alone accounts for >90% of their variation in Φ_m [63]. All things considered, macroscopic life forms display clear and abiding, yet general, trends between evolution-associated complexity and energy rate density.

Quantitative assertions in this section are independent of the ongoing debate about allometric scaling of metabolism among mammals from mice to elephants, nor is it important here whether their mass-dependent metabolic exponent is 2/3 as expected for surface-to-volume principles [67], or 3/4 based on laboratory measures [68] and fractal theory of nutrient supply networks [69]; it may, in fact, be neither [70], as metabolic-rate dependence on body mass likely differs with activity level [71], during lifetime development [72], and among evolutionary lineage [73], and in any case claims of a universal law of bioenergetics for all life forms from bacteria to elephants [74] are mathematically [75] and empirically [55] dubious. Of central import to the present study is the fact that all animals, and not just mammals, but including the whole range of known heterotrophic species, have specific metabolic rates within a relatively narrow range of Φ_m extending over a factor of only ~ 30 ; the far majority of specific metabolic rates for animals vary between 3×10^3 and 10^5 erg/s/g, despite their masses ranging over ~ 11 orders of magnitude from fairy flies to blue whales [55]. Among mammals alone, specific metabolic rates do vary inversely yet weakly with body mass, $\sim M^{-0.2}$. That the smallest animals have somewhat higher Φ_m values probably owes to their frequent eating habits, high pulse rates, robust activity levels, and relatively short life spans; they live fast and die young. By contrast, the largest animals have slightly lower Φ_m owing to their more specialized cells, each of which has only limited tasks to perform and energy needed, thus granting greater efficiency and a longer life.

Regarding brains, which nuclear magnetic resonance (fMRI) imaging shows are always electrically active regardless of the behavioral posture (even while resting) of their parent animal bodies, they too derive nearly all their energy from the aerobic oxidation of glucose in blood; thus, for brains, basal and active rates are comparable. Similar trends in rising complexity noted above for bodies are also evident for brains, though with higher Φ_m brain values for each and every animal type—much as expected

since cerebral structure and function are widely considered among the most complex attributes of life forms [76, 77]. Here, some quantitative details are compiled from many sources, again treating brains as open, nonequilibrium, thermodynamic systems, and once more casting the analysis of energy flow through them in terms of energy rate density. (While I acknowledge several other potentially useful neural metrics—cortical neuron numbers, encephalization quotients, brain/body ratios [78]—I specifically examine brains here for their Φ_m values to be scrupulously consistent with my proposed complexity metric for all complex systems.) However, brain metabolic values culled from the literature often suffer, as noted above for bodies, from a lack of standard laboratory methods and operational units; many reported brain masses need to be corrected for wet (live) values (by multiplying measured in vitro dry masses by a factor of 5 since in vivo life forms, including brains, are $\sim 80\%$ H₂O). Note also that the ratio of brain mass to body mass (used by some neuroscientists as a sign of intelligence) differs from the ratio of brain power to brain mass (which equals Φ_m), nor is “brain power” the same as a colloquial term used in popular conversation, rather here it literally equals the rate of energy flowing through the cranium.

This article makes no attempt to survey comprehensively, rather to synthesize broadly, so representative mean values of brain Φ_m will suffice for a spectrum of extant animals. Comparing mammals and reptiles, $\Phi_m \approx 10^5$ erg/s/g for mice brains (in contrast to $\sim 4 \times 10^4$ for their whole bodies) exceeds $\sim 5 \times 10^4$ erg/s/g for lizard brains ($\sim 3 \times 10^3$ for their bodies) [57]; this is generally the case for all such animal taxa as Φ_m values are somewhat greater for mammal brains than those for reptile brains by factors of 2–4, and those for mammal bodies by roughly an order of magnitude [79]. The great majority of vertebrate fish and amphibians show much the same 5–10 times increase in brain over body Φ_m values [80] with, as often the case in biology, some outliers [81]. Even many invertebrate insects show several factors increase in Φ_m values for their brains ($\sim 5 \times 10^4$) compared to their bodies ($\sim 10^4$), most notably the flying insects [82]. However, for brains in particular, ectotherms generally have only slightly lower values of Φ_m than endotherms, the reason being that on a cellular level brains function in essentially the same way for both warm- and cold-blooded creatures and heat production plays a relatively minor role in brain energy expenditure [83]. Among mammals alone, primates have not only high brain/body mass ratios but also relatively high Φ_m values ($\sim 2 \times 10^5$ erg/s/g) for those brains. Although primates allocate for their brains a larger portion (8–12%) of their total bodily (resting) energy budget than do non-primate vertebrates (2–8%) [79, 84, 85], average primate brains' Φ_m values tend to be comparable to those of brains of non-primates; brain mass-specific, allometric scaling is

even slighter— $M^{-0.15}$ —than noted for bodies above, causing Φ_m brain values to remain approximately constant across 3 orders of magnitude in mammalian brain size [86]. As with bodies above, brains do not necessarily confer much human uniqueness; brains are special, but all animals have them, and our neural qualities seem hardly more than linearly scaled-up versions of those of other primates [87]. Even so, brain function and energy allocation are telling: among living primates, adult humans ($\sim 1.5 \times 10^5$ erg/s/g for brains and $\sim 2 \times 10^4$ for bodies) seem to have the highest brain power per unit mass—that is, not merely ~ 10 times higher Φ_m than for our bodies, but also slightly higher than for the brains of our closest, comparably massive, ape relatives, including chimpanzees. This substantial energy-density demand to support the unceasing electrical activity of myriad neurons within our human brains, which represent only $\sim 2\%$ of our total body mass yet account for 20–25% of the total energy intake [88], testifies to the disproportionate amount of worth Nature has invested in evolved brains—and is striking evidence of the superiority of brain over brawn.

Brains of birds are also revealing, although the derisive term “birdbrain” is quite unfair to some avian species that demonstrate remarkable cognition [89]. On average, brains of birds are an order of magnitude larger than those of equivalently massive reptiles. Brain/body mass ratios for the cleverest birds, such as crows and ravens that display much intraspecies cooperation and social cunning, are comparable to those of some primates. Brain Φ_m values are also similar, again because less energy of a bird’s total body metabolism is devoted to its brain, probably owing to the formidable energetic requirements of bodily flight. As noted above, the most evolved primates direct to their brains as much as a quarter of their total body metabolisms, whereas birds, like all other animals, allocate much less. This then illustrates a subtle difference between brain/body ratios and relative Φ_m brain comparisons, the latter a potentially better sign of intelligence—if only data were available.

The tendency for complex brains to have high Φ_m values, much as for complex whole animal bodies above, can be tentatively correlated with the evolution of those brains among major taxonomic groups [76]. Further, more evolved brains tend to be larger relative to their parent bodies, which is why brain-to-body-mass ratios also increase with evolution generally—mammals more than reptiles, primates notable among mammals, and humans foremost among the great apes [78, 79]. Part of the reason is that relatively big brains are energetically expensive. Neurons use energy as much as 10 times faster than average body tissue to maintain their (structural) neuroanatomy and to support their (functional) consciousness; the amount of brain devoted to network connections increases disproportionately with brain size and so does the clustering and layering of cells within the higher processing neo-

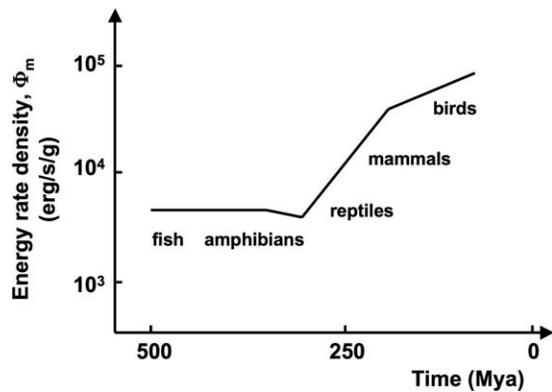
cortex of recently evolved vertebrates [90, 91]. Much of this accords with the “expensive brain” hypothesis [92, 93], which posits that high brain/body ratios are indeed more energetically costly, at least for mammals and many birds, that energy flow through brains is central to the maintenance of relatively large brains, especially for primates, and that relatively large brains evolve only when either brain energy input increases or energy allocation shifts to the brain from some other bodily organ or function. Although the human brain’s metabolic rate is not much greater than for selected organs, such as the stressed heart or active kidneys, regional energy flux densities within the brain greatly exceed (often by an order of magnitude) most other organs at rest. The pressures of social groups and social networking might also drive growth in brain size, cognitive function, and neurophysiological complexity along insect, bird, and primate lineages [94, 95]; evolving societies require even more energy to operate, at least for humankind advancing as suggested numerically in Paper I. Throughout the biosphere, the high-energy cost of brains might reasonably limit brain size and constrain natural selection’s effect on an animal’s survival or reproductive success; indeed, the brain is the first organ to be damaged by any reduction in O_2 . This, then, is the observed, general trend for active brains in vivo: not only are brains voracious energy users and demonstrably complex entities but evolutionary adaptation also seems to have favored for the brain progressively larger allocations of the body’s total energy resources.

Among more recent prehistoric societies of special relevance to humankind, the genus *Homo*’s growing encephalization during the past ~ 2 My may be further evidence of natural selection acting on those individuals capable of exploiting energy- and protein-rich resources as their habitats expanded [96]. By deriving more calories from existing foods and reducing the energetic cost of digestion, cooking was likely central among cultural innovations that allowed humans to support big brains [97]. Energy-based selection would have naturally favored those hominids who could cook, freeing up more time and energy to devote to other things—such as fueling even bigger brains, forming social

TABLE 1

Energy Rate Densities for Some Animal Bodies

Animal type	Time (Mya)	Examples	Body Φ_m (erg/s/g)
Birds	125	Jays, parrots	9×10^4
Mammals	200	Mice, elephants	4×10^4
Reptiles	320	Lizards, snakes	3×10^3
Amphibians	365	Frogs, toads	4×10^3
Fish	500	Carp, goldfish	4×10^3

FIGURE 3

The complexity of animals, expressed in terms of Φ_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 bodies at various stages of the biological-evolutionary phase of cosmic evolution. Note how, within broad categories of animals, endotherms (including mammals and birds) have higher energy rate densities than ectotherms (including invertebrates as well as lower vertebrates such as fish, amphibians and reptiles) among all taxonomic groups found on Earth.

relationships, and creating divisions of labor, all of which arguably advanced culture. As with many estimates of human intelligence, it is not absolute brain size that apparently counts most; rather, brain size normalized by body mass is more significant, just as the proposed Φ_m complexity metric is normalized by mass, here for brains as for all complex systems at each and every stage along the arrow of time, from big bang to humankind.

The net finding for brains, broadly stated though no less true for the vast majority of animals, is that their Φ_m values are systematically higher than for the bodies that house them, nearly all of their brain values falling within a rather narrow range between Φ_m values for lower biological systems (such as plants) and higher cultural ones (such as societies), as sketched in Figure 1. Although absolute brain masses span ~ 6 orders of magnitude, from insects to whales, their Φ_m brain values cluster within a few factors, more or less depending upon their mass and evolutionary provenance, of $\sim 10^5$ erg/s/g.

Table 1 summarizes values of Φ_m for the bodies of a spectrum of mature, adult animals. These are mean values for a wide range of diverse taxonomic groups that are resting (basal) and at normal body T , excerpted and averaged from many of the references noted above. Evolutionary times approximate those at which listed animal types emerged in natural history. Figure 3 plots these values to show the general rise in Φ_m , and hence complexity, with historical time.

4. MACHINES AND COMPUTERS, AMONG MANY CULTURAL SYSTEMS, HAVE RELATIVELY LARGE VALUES OF Φ_m

If cosmic evolution qualifies as a comprehensive scientific worldview, then human society and its many cultural achievements should be included, anthropocentric criticisms notwithstanding. Nature, alone and without sentient, technological beings, could not have built the social systems and technological devices characterizing our civilization today. Humankind itself is surely a part of Nature and not apart from it, indeed an integral module of cosmic evolution writ large; schemes that regard us outside of Nature, or worse atop Nature, are misguided. To examine how well cultural systems resemble physical and biological systems, this section explores, much as done in Paper I for society as a whole, the evolution of cultural complexity as quantified by the same concept of energy rate density.

Foremost among the advances that helped make us cultured, technological beings were the invention and utilization of tools, which require energy to make and use, all the while decreasing physical entropy within those social systems employing them and increasing it elsewhere in wider environments beyond. Thermodynamic terminology may be unfamiliar to cultural anthropologists or world historians, but the primary energy-based processes governing the cultural evolution of technological society are much the same, albeit measurably more complex, as for the evolution of stars, galaxies, and life itself [98]. Thus, caution is urged when claiming teleologically, as done in an otherwise outstanding new publication [99], that the cultural complexity of powered devices differ fundamentally from other forms of complexity because they perform functions for the humans who built them.

Among many current cultural icons, one of the most prominent is the automobile, and not just in developed countries whose citizens can afford this transportation tool. Motor vehicles are ubiquitous on planet Earth, for better or worse archetypal symbols of technological innovation in our modern society. In keeping with the energy-based analysis applied throughout this article, a value of Φ_m can be calculated for today's average-sized automobile, whose typical properties are ~ 1.6 tons of mass and $\sim 10^6$ kcal of gasoline consumption per day; the answer, $\Phi_m \approx 10^6$ erg/s/g (assuming 6 h of daily operation), is likely to range higher or lower by several factors, given variations among vehicle types, fuel grades, and driving times, yet this average value accords well with that expected for a cultural invention of considerable magnitude. Put another way to further illustrate evolutionary trends and using numbers provided by the U.S. Highway Traffic Safety Administration [100] for the past quarter-century, the horsepower-to-weight ratio (in English units of hp/100 lb) of American passenger cars has increased steadily from 3.7 in 1978 to 4.1 in 1988 to 5.1 in 1998 to

5.5 when last compiled in 2004; converted to the units of Φ_m used here, these values equal 6.1, 6.7, 8.4, and 9.1, all times 10^5 erg/s/g, respectively. (By comparison, a literal draft horse's power density equals ~ 745 W/800 kg, or $\sim 10^4$ erg/s/g, a value appropriately within the midst of the mammal body range of Figure 3). Not only in and of themselves but also when compared with less powerful and often heavier autos of >50 ya (whose Φ_m values average well less than half those above), the trend of these numbers confirms once again the general correlation of Φ_m with complexity, for who would deny that modern automobiles, with their electronic fuel injectors, computer-controlled turbochargers, and a multitude of dashboard gadgets are more culturally complex than Ford's model-T predecessor of a century ago?

The postulated evolution-complexity correlation can be more closely probed by tracing the changes in internal combustion engines that power automobiles among many other machines such as gas turbines that propel aircraft [101]. To be sure, the brief history of machines can be cast in evolutionary terms, replete with branching, phylogeny, and extinctions that are strikingly similar to billions of years of biological evolution—though here, cultural change is less Darwinian than Lamarckian, hence quicker too. Energy remains the driver for these cultural evolutionary trends, reordering much like physical and biological systems from the simple to the complex, as engineering improvement and customer selection over generations of products made machines more elaborate and efficient. For example, the pioneering 4-stroke, coal-fired Otto engine of 1878 had a Φ_m value ($\sim 4 \times 10^4$ erg/s/g) that surpassed earlier steam engines, but it too was quickly bettered by the single-cylinder, gasoline-fired Daimler engine of 1899 ($\sim 2.2 \times 10^5$ erg/s/g), more than a billion of which have been installed to date in cars, trucks, aircraft, boats, lawnmowers, etc., thereby acting as a signature force in the world's economy for more than a century. Today's mass-produced automobiles, as noted in the previous paragraph, average several times the Φ_m value of the early Daimler engine, and some racing cars (akin to temporarily active galaxies or metabolically charged race horses) can reach an order of magnitude higher still. Among aircraft, the Wright brothers' 1903 homemade engine ($\sim 10^6$ erg/s/g) was superseded by the Liberty engines of World War I ($\sim 7.5 \times 10^6$ erg/s/g) and then by the Whittle-von Ohain gas turbines of World War II ($\sim 10^7$ erg/s/g). Boeing's 707 airliner inaugurated intercontinental jet travel in 1959 when Φ_m reached $\sim 2.3 \times 10^7$ erg/s/g, and civilian aviation evolved into perhaps the premier means of global mass transport with today's 747-400 wide-body, long-range jet whose engines create up to 110 MW to power this 180-ton craft to just below supersonic velocity (Mach 0.9) with $\Phi_m \approx 2.7 \times 10^7$ erg/s/g.

The rise in Φ_m can be traced particularly well over several generations of jet-powered fighter aircraft of the U.S.

Air Force (though here engine thrust must be converted to power, and for unloaded military jets operating nominally without afterburners typically $1 \text{ N} \approx 500 \text{ W}$, for which Φ_m values then relate to thrust-to-weight ratios). First-generation subsonic aircraft of the late 1940s, such as the F-86 Sabre, gave way to 2nd-generation jets including the F-105 Thunderchief and then to the 3rd-generation F-4 Phantom of the 1960s and 70s, reaching the current state-of-the-art supersonic F-15 Eagle now widely deployed by many western nations; 5th-generation F-35 Lightning aircraft will soon become operational. (Fighter F-number designations do not follow sequentially since many aircraft that are designed never get built and many of those built get heavily redesigned.) These aircraft not only have higher values of Φ_m than earlier-era machines but those energy rate densities also progressively rose for each of the 5 generations of aircraft R&D during the past half century—2.6, 4.7, 5.7, 6.1, and 8.2, all times 10^7 erg/s/g, respectively, and all approximations for their static engine ratings [102].

Another striking example of contemporary cultural evolution—this one a communication tool—is of course the computer, including stunning achievements in memory capacity and data processing speed. At the heart of every computer (as well as smart phones, digital cameras, ATMs, and many other consumer electronics) is the silicon chip whose complexity has grown geometrically in the past few decades. The number of transistors—miniature semiconductors acting as electrical amplifiers and logic gates—that fit within a single microprocessor has doubled every ~ 1.5 y, popularly known as “Moore's law” marking each computer generation; Pentium-II chips of the 1990s that still power many of our home computers hold $>10^3$ times as many transistors (7.5 million) as the Intel-8080 chip (6000 transistors) that pioneered personal computers a (human) generation ago, and today's state-of-the-art chip, the Itanium-2, holds nearly 100 times still more. Chip development has been so rapid and its multiplication so pervasive that our post-industrial society is often claimed to have already built more transistors than any other product in human history, including clay bricks.

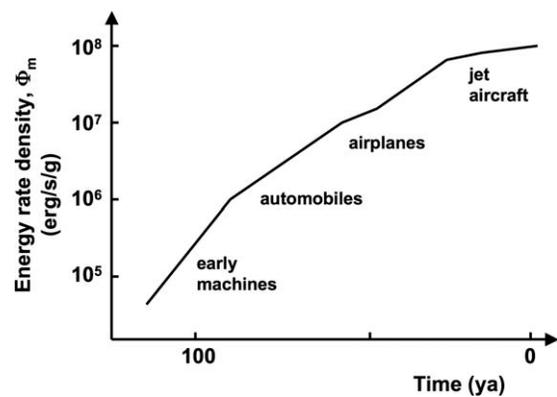
Such stunning advances in computer technology can be expressed in the same quantitative language expressed elsewhere in this article—namely here, the rate of energy flowing through computers made of such densely compacted chips. In all cases, Φ_m values reveal, as for engines above, not only cultural complexity but also evolutionary trends. (To make the analysis manageable, I examined only computers that I personally used in my career, except for the earliest such device.) The ENIAC of the 1940s, a room-sized, 8.5-ton, 50-kW behemoth, transformed a decade later into the even larger and more powerful (125 kW) UNIVAC with ~ 5200 vacuum tubes within its 14.5-ton mainframe. By the 1970s, the fully transistorized Cray-1 supercomputer managed within each of its several (<1 -ton, ~ 22 kW) cabinets

less energy flow yet higher energy rate density as computers began shrinking. By 1990 desktop computers specified much less power and mass (~250 W and ~13 kg), yet Φ_m remained high. And now, MacBook laptops need only ~60 W to power a 2.2-kg chassis to virtually equal the computational capability and speed of early supercomputers. During this half-century span, Φ_m values of these cultural systems changed, respectively: 6.4, 9.5, 32, 20, and 28, all times 10^4 ergs/s/g. Although the power consumed per transistor decreased with the evolution of each new computer generation, the energy rate density increased because of progressive miniaturization—not only for the transistors themselves but also for the microchips on which they reside and the computers that house them all. (Note that I now regard it probably futile to derive, as done earlier [2], values of Φ_m for individual computer chips; chips do nothing by themselves, much as such values are immaterial for individual neurons in brains, molecules in plants or animals, and atoms in stars or galaxies. From a systems viewpoint, Φ_m values are best indicative of the complexity of whole systems, not necessarily their component parts; it is likewise useless to isolate for analysis individual parts of technical apparatus, such as logic gates in computers or spark plugs in engines since such machine pieces cannot function in and of themselves.)

Although these and other cultural Φ_m values often exceed biological ones, machines are not claimed here to be “smarter.” Values of Φ_m for today’s computers approximate those for human brains largely because they number-crunch much faster than do our neurological systems; even laptops now have central-processing units with immense computational features and not surprisingly, in cultural terms, high Φ_m values. That does not make micro-electronic devices more sentient than humans, but it does arguably make them more complex, given the extraordinary rate at which they can functionally acquire and process data—and not least digest energy per unit mass. Accordingly, our most advanced aircraft have even higher Φ_m values than our most sophisticated computers. Modern aircraft rely on computers but also possess many additional, technologically advanced features that together require even more energy density and make them yet more complex. That computers per se are amazingly complex machines, but not amazing enough for them to fly, does suggest that perhaps there is something significant—and perhaps inherently more complex—about both living species and technical devices that operate in three-dimensional environments on Earth; whether insects, birds, or cutting-edge aircraft, these airborne systems exhibit higher values of Φ_m within their respective categories, more so to execute their extraordinary functions than to support their geometrical structures.

Much of this cultural advancement has been refined over many human generations, transmitted to succeeding offspring not by genetic inheritance but by use and disuse of acquired knowledge and skills. A mostly Lamarckian

FIGURE 4



The complexity of technological devices, expressed in terms of Φ_m , rises to illustrate increased utilization of power density by invented machinery during the cultural-evolutionary phase of cosmic evolution. That rise has been dramatic within the past few generations as contemporary civilization has become so heavily dependent upon energy. Note that the timescale over which these curves are plotted is much shorter than for any other graph in this article or in Paper I—roughly the past century of natural history—so it represents only a minute part of the curve in the top oval at upper right in Figure 1.

process whereby evolution of a transformational nature proceeds via the passage of adopted traits, cultural evolution, like physical evolution, involves neither DNA chemistry nor genetic selection that characterize biological evolution. Culture enables animals to transmit modes of living and survival to their descendants by non-genetic, meme-like routes; communication passes behaviorally, from brain to brain and generation to generation, the result being that cultural evolution acts much faster than biological evolution. Even so, a kind of selection acts culturally as noted in Paper I; the ability to start a fire, for example, would have been a major selective advantage for those hominids who possessed it, as would sharpening a tool or controlling energy. It is this multitude of cultural advancements in recent times that accelerate and complexify change—advancements which, in turn with the scientific method, enable us to explore, test, and better understand the scenario of cosmic evolution.

Figure 4 summarizes several of the above-derived, culturally oriented values of Φ_m as pertains to machines. Engines are only one of a multitude of technical devices invented, improved, and now used by humankind on Earth; many other cultural advances could be so chosen and analyzed, and most would display comparably high values of Φ_m . This graph illustrates for today’s technologically sophisticated society, much as for other complex systems considered in this article and in Paper I, how energy rate density parallels the rise of complexity in time.

5. DISCUSSION

Traditionally, complexity science addresses a disparate collection of distinct topics, such as cells, ants, economies, and networks, while often appealing to information theory to decipher general principles of mostly biological and social systems that display emergent and adaptive qualities [103]. Such efforts have met with limited success and an unusual amount of controversy for such a promising new field. Although yielding insight into systems unlikely to be understood by reductionism alone, the real promise of complexity science remains as elusive as when it first arose a generation ago.

This article proffers a different strategy. As in its prequel, Paper I [1], I have explored here a wider array of systems, sought commonalities among all of them, and examined further a single, uniform metric that arguably quantifies changes toward increased complexity. Specifically, this work embraces the concept of energy flow in physical, biological, and cultural systems that are open, organized, and nonequibrated—many of which reveal aspects of emergence, selection, and adaptation. The result is an expansive evolutionary scenario extending over the whole history of time yet one revealing strong similarities among systems as disparate as galaxies, stars, life, and humanity.

Discussion in this article is intentionally short; presentation of the above findings is lengthy enough, and the literature cited necessarily long and varied as this phenomenological survey derives from many disciplines. Much of the discussion in Paper I (esp. Section 5) regarding general evolution pertains to systems evaluated in this article as well. When reviewing the big picture, galaxies among physical systems are generally not much different from stars; among biological systems, animals only slightly more complex and evolved than plants; and among cultural systems, advances in technology comparable to those of society itself. Suffice it to list as a bulleted summary the essential results of this research:

- Evolution is a universal phenomenon; including changes in physical, biological, and cultural systems, evolution is a unifying principle throughout natural science.
- Energy is a common currency; specific energy flow (Φ_m) generally correlates with system complexity and may drive, at least in part, the process of evolution itself.
- Selection and adaptation are ubiquitous; the emergence, maintenance, and fate of complex systems are often determined, again partly, by their ability to utilize energy.

Galaxies of all types, including those of dwarf, normal, and active status, have derived Φ_m values that are among the lowest of known organized systems—typically in the range 0.01–50 erg/s/g, with most normal galaxies such as

our Milky Way having <1 erg/s/g. By the quantitative measure promoted here, galaxies are then judged to be relatively simple—unequivocally simpler than intricately structured and purposely functioning life forms. (I formerly thought the opposite and once stated in print that galaxies are complex objects [104], but I now realize that by claiming that our Galaxy resembles a “galactic ecosystem...as complex as that of life in a tide pool or a tropical forest,” I was parsing mere words to describe a subjective impression.) That galaxies are simpler than expected at first glance is not surprising from a systems perspective, for once we retreat and examine their whole systems globally within their extended environments, galaxies are seen to contain hardly more than 10^{9-12} relatively unordered stars. Ellipticals are the epitome of chaotically swarming stars; even spirals are ragged and misshapen when examined at high resolution—the disordered traces of a violent past. The many ongoing collisions experienced by galaxies may keep them from growing too complex; when they collide the result is a mess, not some new order, much as when cars crash creating a wreck rather than a better car. Furthermore, the hierarchical model of galaxy formation, which holds that galaxies are assembled by chaotic merging of smaller pieces, implies that the properties of individual galaxies should be controlled by six independent parameters, including mass, size, spin, age, gas content, and the surrounding environment. But observational surveys of a wide variety of many normal galaxies suggest that all these parameters are correlated with each other, and that galaxy morphology in reality may well be dominantly regulated by a single such parameter—namely, present-day mass [105, 106]. Nor should we be surprised that there is occasional overlap in Φ_m values for stars and galaxies, much as do those for some plants and animals or for society and its tools; overlaps, though rare, are real for comparably complex systems. Sweeping spiral arms adorning some galaxies, as well as their cores, bulges, disks, and halos, are not likely more complex than the many different components of stars—core, convection zone, photosphere, corona, as well as irregular spots and flares on stellar surfaces—indeed stars too are judged relatively simple based on Φ_m measures ($1-10^3$ erg/s/g; cf., Paper I). This is not to claim that galaxy evolution is driven solely by gravity and the energy flows that result from conversion of gravitational potential energy, which can be readily modeled in coarse-grain N-body simulations; a suite of convoluted “gastrophysical” processes at regional levels within galaxies, including cooling and accretion of interstellar gas, transformation of that gas into stars, as well as feedback of energy and momentum from stars back into the gas, all comprise fine-grain, local-level, nature-nurture bookkeeping too disordered to currently simulate [107]. The formation and evolution of galaxies (or development of same—cf., ref 108), as minimally under-

stood today from observations of different objects of different ages in different places, does display, *en masse*, simplicity transforming into complexity—the utter simplicity of the early primordial Universe giving way naturally to one in which matter clumped, structured, and ordered. But complexity is a relative word; some organized matter that came after the onset of galaxies is even more complex, and progressively so—and that is what the term Φ_m seeks to quantify as a uniform and general complexity metric among all ordered systems.

Animals regularly evince intermediate values of Φ_m —typically, 10^{3-5} erg/s/g—and human bodies rightfully are not the most complex among them. So much for human uniqueness; all animals are outstanding in their own ways, and although we do have special traits, so do bees, giraffes, and other large vertebrates. Life seems to have an optimal range of operation and with it an optimal range of normalized energy flow; the vast majority of Φ_m values for both plants and animals generally fit neatly (again with some exceptions and overlaps) between inanimate physical systems having lower Φ_m and more advanced cultural systems having higher Φ_m . That the trend of living systems increasing their Φ_m values with evolution over generations is imperfect should not deter us, for the great diversity of animals will always disclose wide physiological adaptations to extreme environments, and in any case no useful investigation can proceed if it must scotch every ambiguity or justify every exception. The challenge for zoology is to explain the vast diversity of animal species on Earth and if it can do so, even approximately, by means of a single metric, then all the more insightful. In general, the rise of Φ_m parallels the emergence of many of the major evolutionary stages of life: eukaryotic cells are more complex than prokaryotic ones, plants more complex than protists, animals more complex than plants, mammals more complex than reptiles, and so on. Claims regarding the role of Φ_m in evolutionary advances are broad and general, not specific and detailed along individual lineages; the objective here is to identify how well life forms fit quantitatively within the larger scenario of cosmic evolution. Indeed, similarities between galaxies and animals (as briefly noted earlier) are amply evident, including variation within category types, adaptation to changing conditions, and possibly even natural selection among early, interacting galaxies [109], much as argued in Paper I for stars and plants. All these systems are open to their environments, with matter and energy flowing in while wastes flow out, indeed all resemble metabolisms at work on many scales. Although of less complexity, our Milky Way Galaxy is as much a metabolic system as any life form—transacting energy while forming new stars, cannibalizing dwarf galaxies, and dissolving older components. Whether stars, galaxies, or life itself, the salient point seems much the same: The basic differences, both within and among all these many

varied systems, are of degree, not of kind. We have discerned a common basis upon which to compare all material structures, from the early Universe to the present Earth—again, from big bang to humankind inclusively.

Society and its invented machines, in turn, are among the most energy-rich systems with $\Phi_m > 10^5$ egs/s/g, hence plausibly the most complex known. All of the culturally increasing Φ_m values computed here and in Paper I—whether slow and ancestral such as mastering fire and tilling land, or fast and contemporary as with machines and computers that help accelerate today's economy—were and are related to evolutionary events in which energy flow played a significant role. Much of this advancement is the result of culturally acquired knowledge accumulated from one generation to the next, aided and abetted by client selection, rejection, and adaptation, a decidedly Lamarckian process. As different as they are, Darwinian biological and Lamarckian cultural evolution are not unrelated; as might be expected for two adjacent phases of cosmic evolution, the two enjoy a subtle reciprocal interplay. Cultural inventiveness enabled our immediate ancestors to evade some environmental limitations: Hunting and cooking allowed them to adopt a diet quite different from that of the australopithecines, clothing and housing permitted them to colonize both drier and colder regions of planet Earth, and tools allowed them to manipulate their localities, however primitively. Much as for biological organisms before them, specialization permits social organizations to process more energy per unit mass, and this is reflected in increased Φ_m values over the course of time. Likewise, though even more dramatically, present cultural innovations enable 21st-century *H. sapiens* not merely to circumvent the environment but also to challenge it directly. Technology now allows us to fly high in the atmosphere, to explore the deep oceans, and even to journey far from our home planet. Culture and its most common currency—energy; acquired, stored, and expressed—arguably act as catalysts, speeding the course of change on Earth toward an uncertain future.

6. SUMMARY

Cosmic evolution is much more than a history of one unrelated event after another. This subject aims to synthesize, intensively and chronologically, seemingly disparate knowledge derived from the widest variety of observations of Nature. It especially addresses the coupled topics of system change and complexity—the temporal advance of the former having apparently led to spatial growth of the latter, yet the latter feeding back to make the former increasingly productive. Described here is an enduring proposition that an inclusive scientific worldview can rationally explain the origin, evolution, and complexity of all structured systems in the known Universe. As physical, biological, and cultural

evolution merge to create the greater whole of cosmic evolution, galaxies, stars, planets, life, society, and technology all contribute innately to a coherent story of ourselves, our world, and our Universe.

Cosmic evolution, however, is also more than a subjective, qualitative narration of who we are and whence we came. This interdisciplinary scenario, which resembles natural philosophy of old, now comprises an objective, quantitative, scientific approach toward understanding much of what constitutes material Nature. At all times in the Universe and at all places, the laws of thermodynamics seem the ultimate arbiter of Nature's many varied transactions, directing flows of energy through ubiquitous systems of myriad size and scale. Better metrics than energy rate density, Φ_m , may well describe each of the individual systems examined in these two articles, but no other single metric seems capable of uniformly describing them all. That said, there are exceptions, outliers, "black swans," or whatever one wants to call data points that inevitably deviate from the norm. Physicists tend to notice large trends and general patterns in Nature, often seeking grand unifications or at least global explanations based on few and simple principles. Biologists, by contrast, concentrate on minute details and intricate mechanisms, often noting quite rightly abnormalities in the sweeping generalities. Such dual attitudes perhaps signal the true value of this coarse-grained, phenomenological approach, for only when the devilish details are reconciled with the bigger picture will we be able to call it a "complexity science" that synthesizes both for coherent understanding.

Nature is not perfect; it may be perfectly imperfect. Evolution is an erratic, meandering activity—unceasing, uncaring, unpredictable—mixing chance and necessity, randomness and determinism within a messy, complicated Universe. Yet, despite the enormous spans of space, time, and systems considered here, a hallmark of this study is that a single ubiquitous process governing change—a universal quantity, with identical units for all complex systems—can be effectively identified as mass-normalized energy flow. All these systems, among many other manifestations of order and organization on Earth and beyond, seem governed by common drives and attributes, as though a Platonic ideal may well be at work—namely, that the changing, shifting world of natural phenomena and realistic objects masks a deeper, underlying reality of unchanging forms and processes. This does not make cosmic evolution a theory of everything, nor even necessarily a universal theory of evolution; it is, rather, a collection of evolutionary phases—from rudimentary alteration of physical systems, to neo-Darwinian modification of life forms, to Lamarckian reshaping of cultured society—all apparently, consistently, and fundamentally characterized, at least in part, by energy rate density. These findings strengthen the time-honored idea that elegantly simple processes underlie the tangled complexity of our richly endowed Universe.

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