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Follow the Energy: Relevance of Cosmic Evolution for Human History

Eric J. Chaisson, Wright Center and Physics Dept., Tufts University
Harvard College Observatory, Harvard University

Abstract: Planetologists now searching for microbial life on Mars know well to "follow the water," and anthropologists studying the behavior of modern men and women on Earth are often said to "follow the money." Likewise, big historians seeking a unified view of life and civilization in the Universe at large would do well to "follow the energy." Energy, the ability to do work, is a powerful concept upon which to build an all-inclusive, interdisciplinary, historical, yet quantitative narrative extending from big bang to humankind.

Introduction

Emerging now from modern science is a unified scenario of the cosmos, including ourselves as sentient beings, based on the time-honored concept of change. Change does seem to be universal and ubiquitous, much as the ancient Greek philosopher Heraclitus declared long ago. Twenty-five centuries later, evidence for change abounds, some of it obvious, other subtle. From galaxies to snowflakes, from stars and planets to life itself, we are weaving an intricate pattern penetrating the fabric of all the natural sciences—a sweepingly inclusive view of the order and structure of every known class of object in our richly endowed Universe. This is the essence of an undergraduate course on "cosmic evolution" that I have taught for each of the past 27 years, mostly at Harvard, a synopsis and syllabus for which can be found via Figure 1.

Cosmic evolution is the study of the sum total of the many varied developmental and generational changes in the assembly and composition of radiation, matter, and life throughout all space and across all time. These are the physical, biological, and cultural changes that have produced, in turn, our Galaxy, our Sun, our Earth, and ourselves. The result is a grand evolutionary synthesis bridging a wide variety of scientific specialties—physics, astronomy, geology, chemistry, biology, and anthropology, among others—a genuine narrative of epic proportions extending from the beginning of time to the present, from big bang to humankind, from formless simplicity to organized complexity. This is truly "big history" writ large (Spier 1996; Christian 2004), yet history that goes beyond mere words, indeed natural history that can be scientifically quantified (Chaisson 2001).

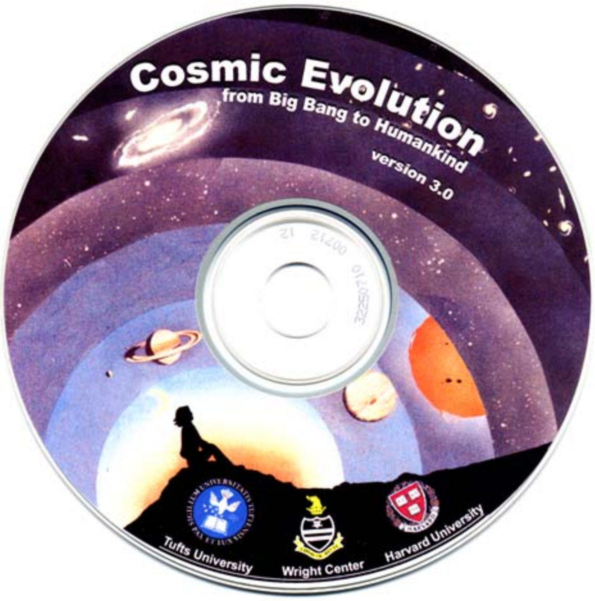

Figure 1. For a multi-media, educational, 460 Megabyte product and course syllabus on cosmic evolution, go to: www.tufts.edu/as/wright_center/cosmic_evolution

Even so, questions remain: How valid are the apparent continuities among Nature's many specialized, historical epochs and how realistic is this quest for unification? Can we reconcile the observed constructiveness of cosmic evolution with the inherent destructiveness of thermodynamics? Is there an underlying principle, a unifying law, or perhaps an ongoing process that creates, orders, and maintains increasingly complex structures in the Universe, enabling us to study everything on uniform, common ground—"on the same page," sort to speak?

Recent research, guided by notions of unity and symmetry and bolstered by vast new databases, suggests affirmative answers to some of these queries: Islands of ordered complexity—namely, open systems such as galaxies, stars, planets, and life forms—are more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All can be shown to quantitatively agree with the principles of thermodynamics, especially non-equilibrium thermodynamics. Furthermore, flows of energy engendered largely by the expanding cosmos do seem to be as universal a process in the origin of structured systems as anything yet found in Nature. The optimization of such energy flows might well act as the motor of evolution broadly conceived, thereby affecting all of physical, biological, and cultural evolution.

Rising Energy Flows

Complexity, like its allied words *time* and *emergence*, is a term easily spoken yet hardly defined. Although used liberally throughout today's scientific community, complexity eludes our ability to characterize it or to measure it, let alone to specify its true meaning. Complexity: "a state of intricacy, complication, variety, or involvement, as in the interconnected parts of a system—a quality of having many interacting, different components." But what does that mean, scientifically? And can we quantify it?

Researchers from many disciplines are now grappling with the term *complexity*. Yet their view is often restricted to their own specialties, their focus non-unifying, indeed few can agree on either a qualitative or quantitative use of the term. Some, for example, aspire to model biological complexity in terms of non-junk genome size; others prefer morphology and flexibility of behavior; still others cite numbers of cell types, or even physical sizes of organisms per se. However, few of these attributes move beyond mere words, fewer still serve to measure complexity broadly.

Energy—especially energy flow—is a more useful metric for quantifying complexity on all scales. From galaxies to stars to planets to life, the rise of complexity over the course of all time can be reasonably quantified by the normalized flow of energy. Physical systems are well modeled by their energy budgets; but so are biological systems, now that science has gone beyond the *élan vital* or peculiar "life force" that once plagued biology; cultural systems, too, can be so modeled, for machines, cities, economies and the like are uniformly described, at least in part, by energy flow.

All complex structures are subject to the rules of thermodynamics. Not the kind of equilibrium thermostatics governing isolated, idealized systems that most of us studied in formal schooling, rather the non-equilibrium thermodynamics of open, complex systems at the frontiers of science today. Resources flow in, wastes flow out, and system entropy actually decreases locally while still obeying thermodynamics' cherished second law that demands environmental entropy increase globally, all the while energy orchestrates changes throughout.

But it's not just energy. It can't be, for the most primitive weed in the backyard is surely more complex than the most intricate nebula in the Milky Way. Yet stars have much more energy than any life form, and the larger galaxies still more. Our complexity metric cannot merely be energy, nor even just energy flow. That energy flow must be normalized to open systems' bulk, thereby putting all such systems "on that same page." And when that's done, we find a real and impressive trend—one of increasing energy per time per mass for all ordered systems across more than 10 billion years of natural history.

Figure 2 shows how such an "energy rate density," symbolized by Φ_m, is a useful way to characterize, indeed to quantify, complexity of a system—any system, physical, biological, or cultural (Chaisson 2001). Energy—the ability to do work—is the most universal currency known in the natural sciences. And in an expanding, non-equilibrated Universe, it is free energy that drives order from disorder, in time eventually aiding the emergence of all structures and organizations seen around us. Neither cosmic strings nor extra dimensions are evident; indeed no new science is needed.

Cosmos, Life, and Civilization

First, consider stars and their progressive changes. Stars surely grow in complexity as their thermal and elemental gradients steepen with time; more data are needed to describe stars as they age. Normalized energy flows increase from protostars at “birth” (Φ_m~0.5 erg/s/g), to main-sequence stars at “maturity” (~2), to red giants near “death” (~100). These values are essentially light-to-mass ratios, converting gravitational energy into luminosity rate and then normalizing by the mass of the system; the present-day Sun, for example, has $4\text{x}10^{33}$ erg/s and $2\text{x}10^{33}$ g, whereas a typical red-giant star (with increased internally ordered thermal and elemental gradients) has an order-of-magnitude higher luminosity for the same mass, hence a larger value of Φ_m (*cf.*, Fig. 2). On and on, the nuclear cycles churn; build up, break down, change—a kind of stellar “evolution” minus any genes, inheritance, or overt function, for these are the value-added qualities of biological evolution that go well beyond the evolution of physical systems.

Second, consider plants among animals. With few exceptions, rising complexity is generally manifest throughout the biosphere, especially when modeled by energy-flow diagnostics. Life forms process more energy per unit mass (Φ_m~$10^{3\text{-}5}$ erg/s/g) than does any star, and increasingly so as biological evolution proceeds. These values are specific metabolic rates, again normalizing incoming energy to system mass: plants, for example, need 17 KJ for each gram of photosynthesizing biomass and they get it from the Sun (only 0.1% of whose radiant energy reaches Earth’s surface), thus for a biosphere of 10^{18} g, $\Phi_m \sim 10^3$ erg/s/g; more ordered 70-kg humans take in typically 2800 kcal/day and thus have a considerably higher value of $\Phi_m \sim 10^4$ erg/s/g; in turn, human brains require ~20 W/day for proper functioning of their ~1300-g cranium, so Φ_m is yet higher, ~10^5 erg/s/g (*cf.*, Chaisson 2001 for many more calculations). Onward across the bush of life—cells, tissues, organs, organisms—we find much the same story. Starting with life’s precursor molecules and proceeding all the way up to plants, animals, and brains, the same *general* trend typifies life forms as for inanimate galaxies, stars or planets: The greater the complexity of a system, the greater the flow of energy density through that system—either to build it or to maintain it, and often both.

Third, consider society and its cultural evolution. Once again, we can trace social progress, in terms of normalized energy consumption, for a variety of human-related advances among our hominid ancestors. Quantitatively, that same energy rate density increases from hunter-gatherers of a million years ago (Φ_m~10^4 erg/s/g), to agriculturists of several thousand years ago (~10^5), to industrialists of contemporary times (~10^6). Again, an array of energy-per-unit-mass values can be used to track ancestral evolution, a highly averaged value of which derives from ~6 billion inhabitants using ~18 TW of energy to keep today’s technological civilization fueled and operating, thus Φ_m now nears 10^6 erg/s/g, and sometimes exceeds that value for specialized energy needs (again, see Chaisson 2001 for a whole host of examples, some of which are plotted in Figure 2). And here, along the path to civilization, as well as among the bricks and chips we’ve built, energy is a key driver. Energy rate density continues rising with the increasing complexity of today’s multifaceted, fast-paced, gadget-rich society.

Relevance for Human History

Energy—the core of a modern, historical worldview—should not be overlooked while seeking a broad, quantifiable metric for “big history.” Whether acquired, stored, and/or expressed, energy has the advantage of being defined, intuitive, and measurable. Normalized energy flow also aids in unifying the sciences—namely, to diagnose aspects of physical, biological, and cultural systems in a uniform manner, rather than fragmenting them further, indeed rather than complexifying unnecessarily the very subject of complexity science that we now seek to understand. More than any other single factor, energy flow would seem to be a principal means whereby all of Nature's diverse systems have naturally spawned rising complexity in an expanding Universe.

The imposing hierarchy of our cosmic-evolutionary scenario—from myriad stars to Earthly life—provides an underlying, uniform, quantitative basis upon which to understand the emergence and development of contemporary civilization. By "following the energy" over more than 10 billion years of history, we appreciate how increasingly complex systems came to use energy more efficiently in the past. Effective energy use will also likely determine humankind's fate in the future.

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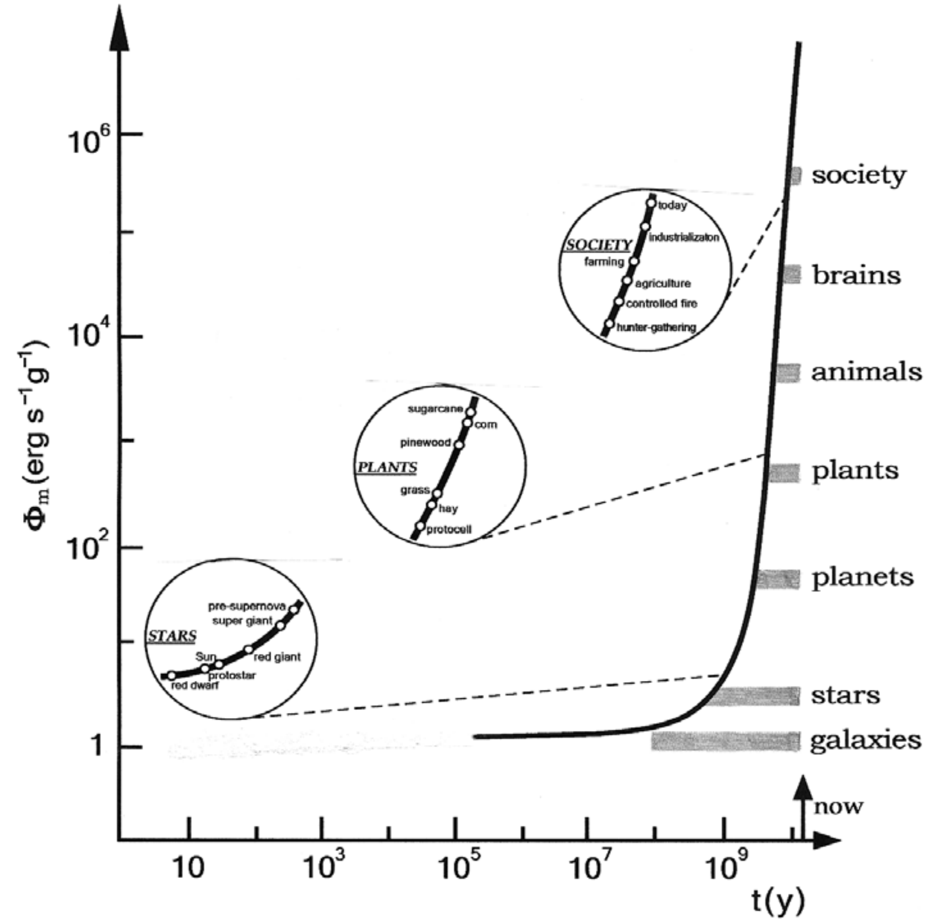

Figure 2. The rise of free energy rate density, Φ_m, plotted as histograms starting at those times when various open structures emerged in Nature. Circled insets show greater detail of further measurements or calculations (Chaisson 2001) of Φ_m for three representative systems—stars, plants, and society—typifying physical, biological, and cultural evolution, respectively.