2 Non-equilibrium Thermodynamics in an Energy-Rich Universe

Eric J. Chaisson

Wright Center & Physics Department, Tufts University, Medford, MA 02155, USA.

Summary. Free energy, the ability to do work, is the most universal currency known in the natural sciences. In an expanding, non-equilibrated Universe, it is free energy that drives order from disorder, from big bang to humankind, in good accord with the second law of thermodynamics and leading to the production of entropy. On all scales, from galaxies and stars to planets and life, the rise of complexity over the course of natural history can be uniformly quantified by analyzing the normalized flow of energy through open, non-equilibrium, thermodynamic systems.

2.1 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 Heraclitus claimed long ago: "Nothing permanent except change . . . all flows." 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.

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 produce, 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.

Yet questions remain: How valid are the apparent continuities among Nature's 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 does create, order, and

A. Kleidon and R.D. Lorenz (Eds.): Non-equil. Thermodyn., UCS 2, pp. 21–31, 2005.

maintain all 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 that produce entropy to maintain order – are more than balanced by great seas of increasing disorder elsewhere in the environments beyond those systems. All can be shown to be in quantitative agreement 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 (Chaisson 2001).

2.2 Time's Arrow

Figure 2.1 shows an archetypal sketch of cosmic evolution – the "arrow of time." Regardless of its shape or orientation, such an arrow represents an intellectual guide to the sequence of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos in the early Universe to order more recently. That sequence, as determined by a large body of post-Renaissance data, accords well with the idea that a thread of change links the evolution of primal energy into elementary particles, the evolution of those particles into atoms, in turn of those atoms into galaxies and stars, and of stars into heavy elements, further in turn the evolution of those elements into the molecular building blocks of life, of those molecules into life itself, and of intelligent life into the cultured and technological society that we now share. Despite the compartmentalization of today's academic sciences, evolution knows no disciplinary boundaries.

As such, the most familiar kind of evolution – biological evolution, or neo-Darwinism – is just one, albeit important, subset of a much broader evolutionary scheme encompassing more than mere life on Earth. In short, what Darwinian change does for plants and animals, cosmic evolution aspires to do for all things. And if Darwinism created a revolution in understanding by helping to free us from the notion that humans basically differ from other life forms on our planet, then cosmic evolution extends that intellectual revolution by treating matter on Earth and in our bodies no differently from that in stars and galaxies beyond.

Time's arrow implies no anthropocentrism. It merely provides an intellectual roadmap that symbolically traces increasingly complex structures, from spiral galaxies to rocky planets to reproductive beings. Nor does the arrow mean to imply that "lower," primitive life forms biologically changed directly into "higher," advanced organisms, any more than galaxies physically change into stars, or stars into planets. Rather, with time – much time – environmental conditions suitable for spawning primitive life eventually changed into those favoring the emergence of more complex species; likewise, in the earlier Universe, environments ripe for galactic formation eventually gave way to conditions more conducive to stellar and planetary formation; now, at least on Earth, cultural evolution dominates. Change in environments usually precedes change in systems, and the resulting system changes have *generally* been toward greater amounts of order and complexity.

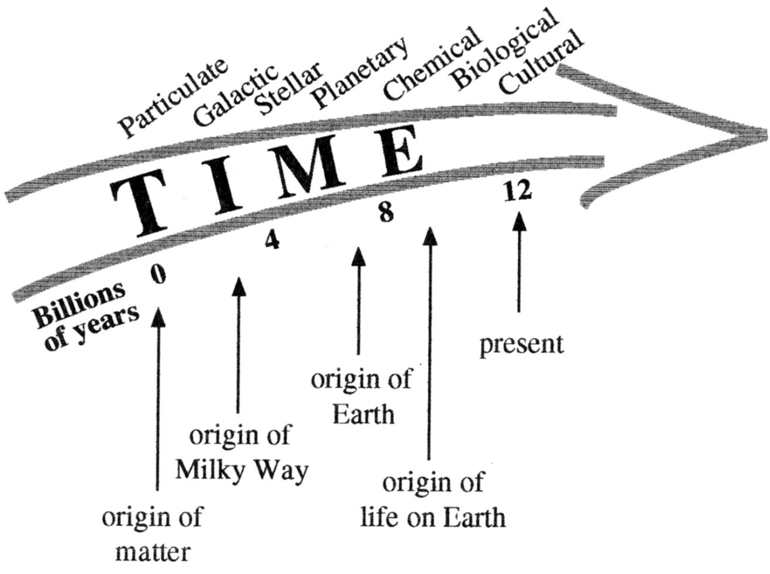

Fig. 2.1. This symbolic "arrow of time" highlights salient features of cosmic history, from its fiery origins some 14 billion years ago (*at left*) to the here and now of the present (*at right*). Labeled diagonally across the *top* are the major evolutionary phases that have produced, in turn, increasing amounts of order and complexity among all material systems: particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. Cosmic evolution encompasses all these phases. Time is assumed to flow linearly and irreversibly, unfolding at a steady pace, much as other central tenets are assumed, such as the fixed character of physical law or the mathematical notion that $2 + 2 = 4$ everywhere

Figure 2.2 illustrates the widespread impression that material assemblages have become more organized and complex, especially in relatively recent times. This family of curves refers to islands of complexity comprising systems per se – whether giant stars, buzzing bees, or urban centers – not their vastly, increasingly disorganized surroundings. A central task of complexity science aims to explain this temporal rise of organization.

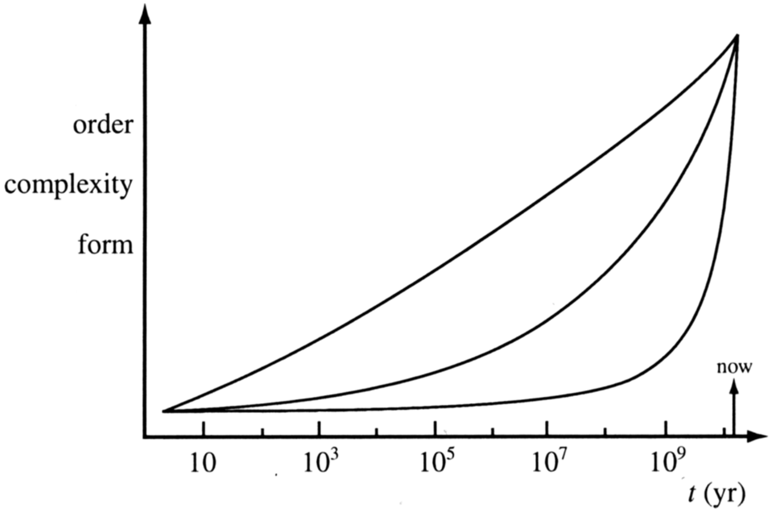

Fig. 2.2. Sketched here qualitatively is the rise of order, form, and structure typifying the evolution of *localized* material systems throughout the history of the Universe. This family of curves connotes the widespread, innate feeling that complexity of ordered structures has *generally* increased over the course of time. Whether this rise of complexity has been linear, exponential, or hyperbolic (as drawn here), current research aims to specify this curve, to characterize it quantitatively. All subsequent graphs in this article have the same temporal scale

2.3 Cosmological Setting

The origin of Nature's many varied structures is closely synonymous with the origin of free energy. Time marches on, equilibrium fails, and free energy flows because of cosmic expansion (Gold 1962; Layzer 1976), all of it summarized by the run of energy densities shown in Fig. 2.3. Here, the essence of change is plotted on the largest scale – the truly big picture, or "standard model," of the whole Universe – so these curves pertain to nothing in particular, just everything in general. They track the main trends, minus devilish details, of modern cosmology: the cooling and thinning of radiation and matter, largely based on observations of distant receding galaxies and of the microwave background radiation – all this change fundamentally driven by the expansion of the Universe.

Radiation completely ruled the early Universe. Life was then non-existent and matter itself only a submicroscopic precipitate suspended in a glowing fireball of intense light, x rays, and gamma rays. Structure of any sort had yet to emerge; the energy density of radiation was too great. If single protons tried to capture single electrons to make hydrogen atoms, radiation was then so fierce as to destroy those atoms immediately. Prevailing conditions during the first few tens of millennia after the origin of time were uniform, symmetrical, equilibrated, and boring. We call it the Radiation Era.

Eventually and inevitably, as also depicted in Fig. 2.3, the primacy of radiation gave way to matter. As the expanding Universe naturally cooled and thinned, charged particles assembled into neutral atoms, among the simplest of all structures; the energy density of matter began to dominate. This represents a change of first magnitude – perhaps the greatest change of all time – for it was as though an earlier, blinding fog had lifted; cosmic uniformity was punctured, its symmetry broken, its equilibrium gone perhaps forever. The Universe thereafter became transparent, as photons no longer scattered aimlessly and destructively. The bright Radiation Era gradually transformed into the darker Matter Era about 10^5 years after the big bang, which is when the free energy began to flow.

Thermodynamics tells us not what will happen, only what *can* happen. This analysis suggests that changing environmental conditions gave rise to the *potential* growth of order and structure. Once symmetry broke and equilibrium failed a few thousand centuries after the start of all things, the temperatures of matter and of radiation diverged with time; thereafter gradients were naturally established owing to cosmic expansion. And this apparently did lead to order among localized systems able to select and utilize, perhaps optimally, the available free energy, resulting in a trend of increasing rates of entropy production (also Lineweaver, this volume).

Figure 2.4 graphs the run of entropy, S, for a thermal gradient typical of a heat engine, here for the whole Universe. This is not a mechanical device running with idealized Newtonian precision, but a cosmological setting potentially able to do work as locally emerging systems interact with their environments – especially those systems able to take advantage of increasing flows of free energy resulting from cosmic expansion and its naturally growing gradients. Although thermal and chemical (but not gravitational) entropy must have been maximized in the early Universe, hence complexity in the form of any structures then non-existent, the start of the Matter Era saw the environmental conditions become more favorable for the potential growth of order, taken here as a "lack of disorder." At issue was timing: As density ρ decreased, the equilibrium reaction rates ($\propto \rho$) fell below the cosmic expansion rate ($\propto \rho^{1/2}$) and non-equilibrium states froze in. Thus we have a seemingly paradoxical yet significant result that, in an expanding Universe, both the disorder (i.e., net entropy) and the order (maximum possible entropy minus actual entropy at any given time) can increase simultaneously – the former globally and the latter locally. All the more interesting when comparing the shape of this curve of potentially increasing order ($S_{max} - S$) in Fig. 2.4 with our earlier intuited sketch of rising complexity in Fig. 2.2.

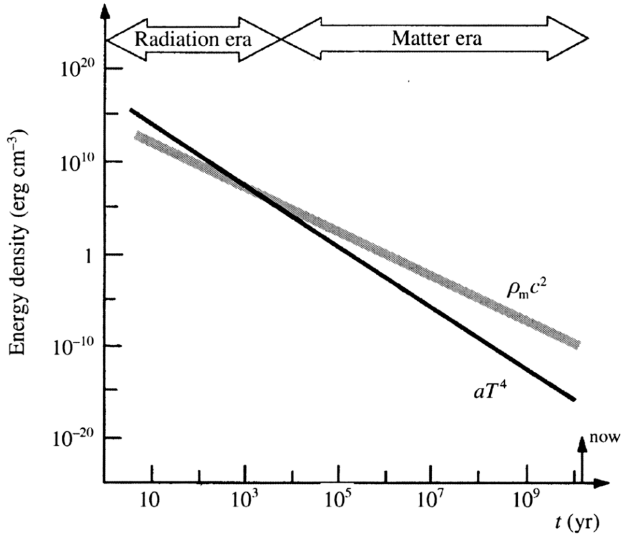

Fig. 2.3. The temporal behavior of both matter energy density (ρc^2) and radiation energy density (aT^4) illustrates perhaps the greatest change in all of history. Here, ρ is the matter density, c the speed of light, a the radiation constant, and T the temperature. Where the two curves intersect, neutral atoms began to form. By some 10^5 years, the Universe had changed greatly as thermal equilibrium and particle symmetry had broken, and the Radiation Era transformed into the Matter Era. A uniform, featureless state characterizing the early Universe thus naturally became one in which order and complexity were thereafter possible. The thicker width of the matter density curve represents the range of uncertainty in total mass density, whose value depends on the (as yet unresolved issue of) "dark matter." By contrast, the cosmic background temperature is well measured today, and its thin curve can be accurately extrapolated back into the early Universe. The startling possibility, recently discovered, that universal expansion might be accelerating should not much affect these curves to date

2.4 Complexity Rising

Complexity, like its allied words *time* and *emergence*, is a term easily spoken yet poorly 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, much as for radiation and matter above?

Researchers from many disciplines now grapple with the term *complexity*, yet their views are often restricted to their own specialties, their focus nonunifying; 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 (Szathmary and Smith 1995); others prefer morphology and flexibility of behavior (Bonner 1988); still others cite numbers of cell types (Kauffman 1993), cellular specialization (McMahon and Bonner 1983), or even physical sizes of organisms per se. Using fluid flow, such as energy, as a basis, Ulanowicz and Zickel (this volume) suggest another method to specify organization and complexity of a system. However, few of these attributes are easily quantified, fewer still serve to measure complexity broadly.

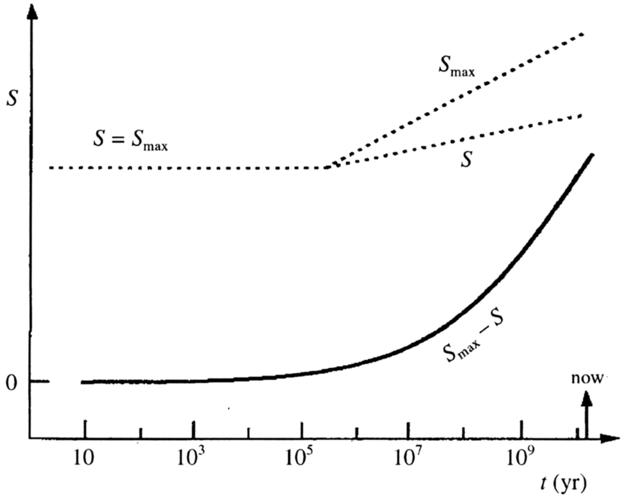

Fig. 2.4. In the expanding Universe, the actual entropy, S, increases less rapidly than the maximum possible entropy, S_{max}, once the symmetry of equilibrium broke when matter and radiation decoupled at $\sim 10^5$ years. By contrast, in the early, equilibrated Universe, $S = S_{max}$ for the prevailing conditions. The potential for the growth of order – ($S_{max} - S$), shown as the thick black curve – has increased ever since the start of the Matter Era. Accordingly, the expansion of the Universe can be judged as the ultimate source of free energy, promoting the evolution of order in the cosmos. This potential rise of order compares well with the family of curves of Fig. 2.2 and provides a theoretical basis for the growth of systems complexity

Putting aside as unhelpful the idea of information content (of the Shannon-Weaver type, which is controversial even if sometimes useful) and of negative entropy (or "negentropy," which Schroedinger (1944) first adopted but then quickly abandoned), I prefer to embrace the quantity with greatest appeal to physical intuition–energy. To be sure, energy–especially energy flow with its degradation to lower temperatures, thus resulting in entropy production – is a more useful metric for quantifying complexity writ large. Not that energy has been overlooked in previous studies of Nature's many varied structures. Numerous researchers have championed energy's organizational abilities, including, for example, physicists (Morrison 1964 and Dyson 1979), biologists (Lotka 1922 and Morowitz 1968), and ecologists (Odum 1988 and Smil 1999).

Physical systems have always been well modeled by their energy budgets. But so are biological systems, now that science has abandoned 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 all described, at least in part, by energy flow. And it is non-equilibrium thermodynamics of open, complex systems that best characterizes resources flowing in and wastes flowing out, all the while system entropy actually decreases locally while obeying thermodynamics' cherished second law that demands environmental entropy increase globally.

Yet the quantity of choice cannot be simply energy, since 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 makeup, enabling all such systems to be analyzed "on that same page." When this is done, as shown in Fig. 2.5, a clear and impressive trend is apparent – one of increasing energy per unit time per unit mass for a wide range of ordered systems throughout more than ten billion years of cosmic history.

Such an "energy rate density," Φ_m, is a useful way to characterize, indeed to quantify, complexity of a system–any system, physical, biological, or cultural (Chaisson 1998, 2001). This should not surprise us, since it was competing energy rate densities of radiation and matter that dictated events in the early Universe, as noted in the previous section.

Consider stars and their progressive changes. Stars do 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" ($\Phi_m \sim 0.5$ 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 potential energy into luminosity rates and then normalizing by the mass of the system; the present-day Sun, for example, has 4×10^{33} erg/s and 2×10^{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. On and on, 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.

Consider plants and animals. With few exceptions, rising complexity is evident throughout biological evolution, especially if modeled by energy-flow diagnostics. Life forms process more energy per unit mass ($\Phi_m \sim 10^{3-5}$

erg/s/g) than does any star, and increasingly so with biological evolution. 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 the planet'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, for human brains with ~20 W/day for proper functioning and a ~1300 g cranium, Φ_m is yet higher, $\sim 10^5$ erg/s/g (see Chaisson 2001 for many more such 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 perceived 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.

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 ($\Phi_m \sim 10^4$ erg/s/g), to agriculturists of several thousand years ago ($\sim 10^5$), to industrialists of contemporary times ($\sim 10^6$). Again, a whole host of energy per unit mass values can be used to track ancestral evolution, a highly averaged value of which today derives from 6 billion inhabitants needing ~18 TW of energy to keep our technological culture fueled and operating, thus Φ_m nearing 10^6 erg/s/g, and sometimes exceeding that for specialized energy needs (again, see Chaisson 2001, for a whole host of examples, many of which are plotted in Fig. 2.5). And here, along the path to civilization, as well as among the bricks, machines, and chips we've built, energy is a principal driver. Energy rate density continues rising with the increasing complexity of today's gadget-rich society.

Energy – the core of modern, non-equilibrium thermodynamics – ought not to be overlooked while seeking a broad, quantifiable metric for complexity. Whether acquired, stored, and expressed, energy has the advantage of being defined, intuitive, and measurable. Neither new science nor appeals to non-science are needed to justify the imposing hierarchy of our cosmic-evolutionary scenario, from stars to life to society.

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 in science, energy flow would seem to be a principal means whereby all of Nature's ordered, diverse systems have naturally spawned rising complexity in an expanding Universe.

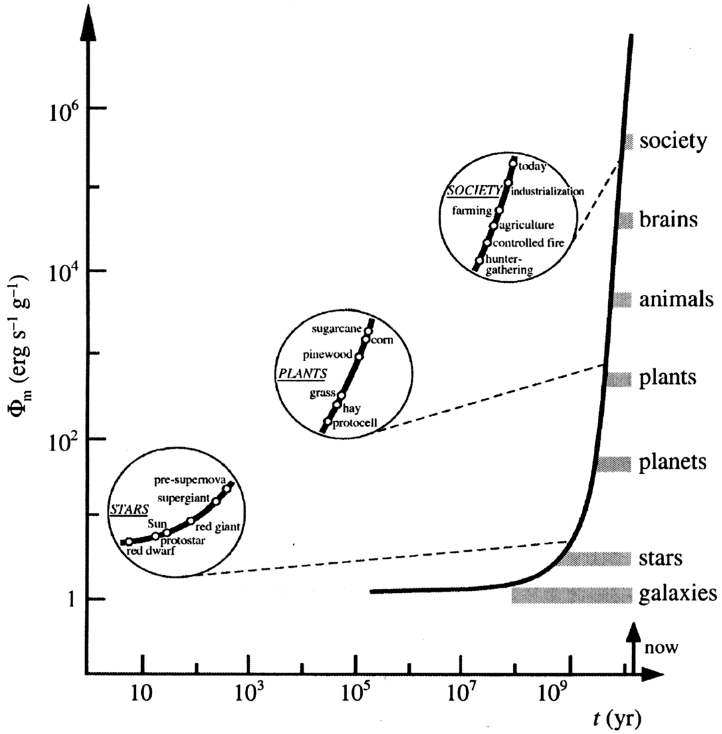

Fig. 2.5. The rise of free energy rate density, Φ_m, plotted as histograms starting at those times when various open structures emerged in Nature. Circled insets show greater detail of further measurements or calculations of Φ_m for three representative systems – stars, plants, and society – typifying physical, biological, and cultural evolution, respectively. Compare with the curve of rising complexity sensed from human intuition (Fig. 2.2) and that from our thermodynamic analysis of potentially increased order in a non-equilibrated cosmos (Fig. 2.4). To repeat, this is not to claim that galaxies per se evolved into stars, or stars into planets, or planets into life. Rather, this study suggests that galaxies produced environments suited for the birth of stars, that some stars spawned environments conducive to the formation of planets, and that at least one planet fostered an environment ripe for the origin of life – each system in turn able to handle increased amounts of energy flow per unit mass in an expanding Universe (Chaisson 2001)

References

Bonner JT (1988) Evolution of Complexity. Princeton University Press, Princeton, NJ.

Chaisson EJ (1998) Cosmic environment for the growth of complexity. BioSystems 46: 13.

Chaisson EJ (2001) Cosmic Evolution: Rise of Complexity in Nature. Harvard University Press, Cambridge, MA.

Dyson F (1979) Time without end: physics and biology in an open universe. Rev Mod Phys 51: 447.

Gold T (1962) The arrow of time. Am J Phys 30: 403.

Kauffman S (1993) Origins of Order. Oxford University Press, Oxford, UK.

Layzer D (1976) The arrow of time. Astrophys J 206: 559.

Lotka A (1922) Contribution to the energetics of evolution. Proc Nat Acad Sci 8: 147.

McMahon T and Bonner JT (1983) On Size and Life. WH Freeman, New York, NY.

Morowitz HJ (1968) Energy Flow in Biology. Academic Press, San Diego, CA.

Morrison P (1964) A thermodynamic characterization of self-reproduction. Rev Mod Phys 36: 517.

Odum H (1988) Self-organization, transformity, and information. Science 242: 1132.

Schroedinger E (1944) What is Life? Cambridge University Press, Cambridge, UK.

Smil V (1999) Energies: A Guide to the Biosphere and Civilization. MIT Press, Cambridge. MA.

Szathmary E and Smith JM (1995) Major evolutionary transitions. Nature 374: 227.