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The cosmic environment for the growth of complexity

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Abstract

The unifying scenario of cosmic evolution is outlined by following the natural changes among radiation, matter and life in standard, big-bang cosmology. Using aspects of non equilibrium thermodynamics, especially energy flow considerations, we argue that it is the contrasting temporal behavior of various energy densities that have given rise to the environments needed for the emergence of galaxies, stars, planets, and life forms. We furthermore argue that a necessary (though perhaps not sufficient) condition—a veritable prime mover—for the emergence of such ordered structures of growing complexity is the expansion of the Universe itself. Neither demonstrably new science nor appeals to non-science are needed to explain the impressive hierarchy of generative change, from atoms to galaxies, from cells to society. © 1998 Elsevier Science Ireland Ltd. All rights reserved.

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1. Introduction

Cosmic evolution is the study of change through time—the totality of the many varied changes that have occurred throughout all time and across all space. More specifically, cosmic evolution comprises the generative and developmental changes in the assembly and composition of radiation, matter, and life throughout the Universe. These are the changes that have produced our Galaxy, our Sun, our Earth, and ourselves (Chaisson, 1979).

Fig. 1 shows the arrow of time, which provides an archetypical illustration of cosmic evolution. Regardless of its shape or orientation, such an arrow represents an intellectual road map of the sequence of events that have changed systems from simplicity to complexity, from inorganic to organic, from chaos to order. That sequence, as determined from a substantial body of post-renaissance observations, is galaxies first, then stars, planets, and eventually life forms. In particular, we can identify seven major construction phases in the history of the Universe: particulate, galactic, stellar, planetary, chemical, biological, and cultural evolution. These are the specialized phases—separated by discontinuities on localized scales—that are responsible for the disciplinary and fragmented fields of reductionistic science.

As such, the modern subject of biological evolution—neo-Darwinism—is just one, albeit important, subset of a much broader evolutionary

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scheme encompassing much more than mere life on Earth. In short, what Darwinism does for plants and animals, cosmic evolution aspires to do for all things. Also, if Darwinism created a revolution in understanding by helping to free us from the anthropocentric belief that humans basically differ from other life forms on our planet, then cosmic evolution is destined to extend that intellectual revolution by releasing us from regarding matter on Earth and in our bodies any differently from that in the stars and galaxies beyond.

Of central importance, we can now trace a thread of understanding—a loose continuity of sorts—linking the evolution of primal energy into elementary particles, the evolution of those particles into atoms, in turn of those atoms into galaxies and stars, the evolution of stars into heavy elements, the evolution of those elements into the molecular building blocks of life, of those molecules into life itself, of advanced life forms into intelligence, and of intelligent life into the cultured and technological civilization that we now share. These are the historical phases—much the same as those noted above, but now reidentified from a broader, integrated perspective—that are responsible for the interdisciplinary world view of the present paper. The claim here is that, despite the compartmentalization of modern science, evolution knows no disciplinary boundaries.

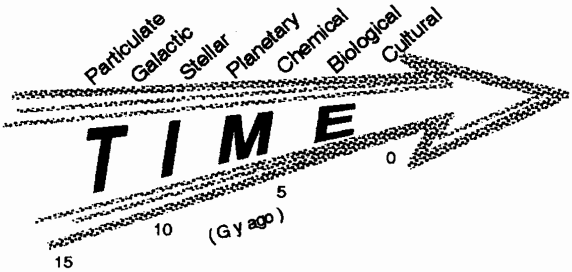

Fig. 1. An arrow of time can be used to highlight salient features of cosmic history, from the beginning of the Universe to the present. Sketched diagonally along the top of this arrow are the major evolutionary phases that have acted, in turn, to yield increasing amounts of order, form, and structure among all material things. Despite its drawn implication of 'time marching on', the arrow implies nothing strictly deterministic; rather, much as for its most celebrated component—neo-Darwinism—the twin elements of chance and necessity, of randomness and determinism, embed all aspects of the cosmic evolutionary scenario.

2. Matter

Although modern cosmology—the study of Nature on the grandest scale—stipulates that matter only later emerged from the radiation of the early Universe, it is pedagogically useful to quantify first the role of matter and thereafter the primacy of radiation. In this way, the potentially greatest change in the history of the Universe—the transformation from radiation to matter—can be clearly and mathematically justified.

Imagine an arbitrary shell of mass, m, and radius, r, expanding isotropically with the Universe at a velocity, v, from some central point. The sphere within the shell is not necessarily meant to represent the entire Universe, as much as an exceedingly large, isotropic gas cloud—in fact, larger than the extent of a typical galaxy supercluster ($\cong 50$ Megaparsecs across) which comprises the topmost rung in the known hierarchy of matter assemblages in the Universe. Invoking the principle of energy conservation, we quickly arrive at the Friedmann–Lemaitre equation that describes a family of models for the Universe in bulk,

$$H^2 - \frac{8}{3}\pi G \rho_m = -kR^{-2},$$

where H is Hubble's constant (a measure of galaxy recession in an expanding Universe), G is the universal gravitational constant, ρ_m is the matter density, and k is a time-dependent curvature constant. R is a scale factor which relates the radius, r, at any time, t, in cosmic history to the current radius, r_0, at the present epoch—namely, $r = Rr_0$. Solutions to the above equation specify three general models for the Universe:

- the Universe can be 'open' (i.e. k negative) and thus recede forevermore to infinity (and beyond).
- the Universe can be 'closed' (i.e. k positive) wherein its contents eventually stop, thereafter contracting to a point much like that from which it began.

- the Universe is precisely balanced between the open and closed models; in fact such a model Universe would eternally expand toward infinity and never contract.

Consider the simplest case, when $k=0$ in the above equation, also known as the Einstein–de-Sitter solution. Here, we find the critical density for closure,

$$\rho_{m,c}=3H^2/8\pi G,$$

which, when evaluated for G and for H ($\cong 65$ km/s per Mpc), equals 10^{-29} g/cm^3. This is ~ 6 atoms in each cubic meter of space, or about a million times more rarefied than the matter in the 'empty space' between Earth and the Moon. Whether the actual current density is smaller or larger than this value, making the Universe open or closed, respectively, is not currently known, given the uncertainty concerning 'dark matter' within and around galaxies.

To follow the evolution of matter throughout cosmic history, we appeal to the conservation of material particles in the huge sphere noted above, $\rho_m=\rho_{m,0}R^{-3}$, substitute into the special ($k=0$) case of the Friedmann–Lemaitre equation, and manipulate,

$$\int dt=\left(\frac{8}{3}\pi G\rho_{m,c}\right)^{-0.5}\int R^{0.5}\,dR$$

The result is that $t=2/3H^{-1}$, which accounts for the deceleration of the Universe, and also suggests that the Universe (for the special $k=0$ case) is ~ 12 billion years old. (Neither H nor t is known to better than 30% accuracy.) This equation additionally stipulates how the average matter density thins with time,

$$\rho_m\cong 10^6 t^{-2}$$

where ρ_m is expressed in g/cm^3 and t in s.

Fig. 2 plots this evolution of matter, in bulk, throughout all of universal history.

3. Radiation

The same analysis regarding matter can be applied to radiation in order to map the change of temperature with time. Again, for the simplest $k=0$ case,

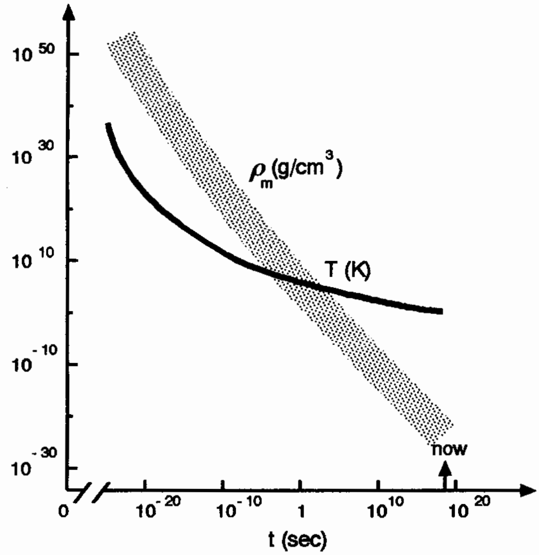

Fig. 2. A log–log plot of ρ_m, the density of matter on average, and of T, the temperature of radiation on average, over the course of all time, to date. These plots refer to nothing in parcticular, just everything in general. The width of the line drawn for ρ_m represents the considerable range of uncertainty in the value of ρ_m observed today, by contrast, T is very accurately measured today.

$$H^2=8\pi G\rho_{r,c}/3R^4,$$

where ρ_r is the equivalent mass density of radiation. Here the R^4 term derives from the fact that radiation scales not only as the volume ($\propto R^3$) but also by one additional factor of R because radiation (unlike matter) is also affected linearly by the Doppler effect. And noting that $\rho_r c^2=aT^4$, where a is the universal radiation constant for any black-body emitter and T is the temperature of radiation, we find the temporal dependence of average temperature throughout all time (in seconds),

$$T\cong 10^{10}t^{-0.5}.$$

The universal radiation, having begun in a fiery explosion (called the 'big bang'), has now cooled to 2.7 K, the average value of the cosmic microwave background measured today by radio telescopes on the ground and satellites in orbit. Fig. 2 also plots this run of T versus t.

For the first hundred centuries of the Universe, radiation had reigned supreme over matter. All space was flooded with photons, especially light, X rays, and γ rays, ensuring a non-structured, undifferentiated, (virtually) informationless, and highly uniform blob of plasma; we say that matter and radiation were intimately coupled to each other—thermalized and equilibrated. As the universal expansion paralleled the march of time, however, the energy housed in radiation decreased faster than the energy equivalently contained in matter.

To see this, compare the energy densities of radiation and matter, and especially how these two quantities have evolved in time. First convert the matter density derived earlier to an equivalent energy density by invoking the Einsteinian mass (m)–energy (E) relation, $E = mc^2$—that is, by multiplying the above equation for ρ_m by c^2. Now, some 12 billion years after the big bang, $\rho_{m,0}c^2 \cong 10^{-9}$ erg/cm^3, whereas $aT_0^4 \cong 4 \times 10^{-13}$ erg/cm^3; thus, in the current epoch, $\rho_{m,0}c^2 > aT_0^4$ by several orders of magnitude, proving that matter is now in firm control (gravitationally) of cosmic changes, despite the Universe still being flooded today with (2.7-K) radiation. However, given that $\rho_m c^2$ scales as R^{-3} and aT^4 scales as R^{-4}, we conclude that there must have been a time in the past when $\rho_m c^2 = aT^4$, and an even earlier time when $\rho_m c^2 < aT^4$. Manipulation of the above equations shows that these two energy densities crossed over at $t \cong 10000$ years, well less than a million years after the big bang. Fig. 3 is a graphical presentation of the contents of this paragraph (Field and Chaisson, 1985).

This crossover represents a preeminent change in all of cosmic history. The event, $\rho_m c^2 = aT^4$, separates the Radiation Era from the Matter Era, and designates that time (~ 10000 years) at which the Universe gradually began to become transparent. Thermal equilibrium was destroyed and symmetry broken, causing the radiative fireball and the matter gas to decouple; it was as though a fog had lifted. Photons, previously scattered innumerable times by subatomic material particles (especially free electrons) of the expanding, hot, opaque plasma in the Radiation Era, were no longer so affected once the electrons became bound into atoms in the Matter Era. This crucial and dramatic change was over by ~ 100000 years, when the last throes of the early plasma state had finally transformed into neutral matter. The microwave (2.7-K) radiation reaching Earth today is a relic of this signal phase transition, having streamed unimpeded (except for being greatly red-shifted) across space and time for most of the age of the Universe, granting us a 'view' of this grandest of all evolutionary events that occurred long, long ago.

4. Life

Of all the known clumps of matter in the Universe, life forms, especially those enjoying membership in advanced technological civilizations, arguably comprise the most fascinating complexities of all. What is more, technologically competent life differs fundamentally from lower forms of life and from other types of matter scattered throughout the Universe. This is hardly an anthropocentric statement; after more than 10 billion years of cosmic evolution, the dominant species on planet Earth—we, the human being—has learned to tinker not only with matter and

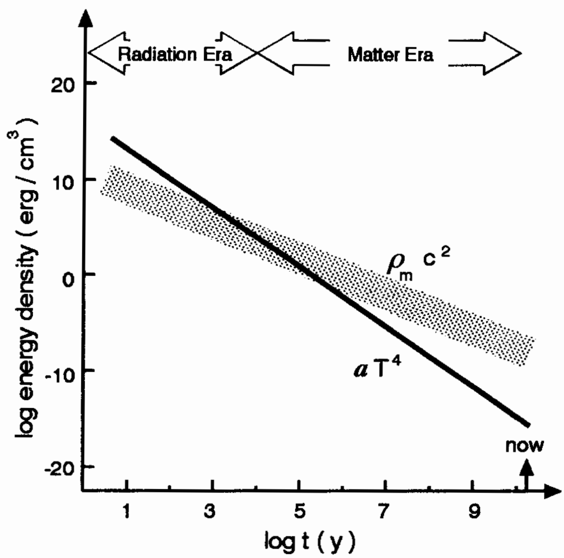

Fig. 3. The temporal behavior of both matter energy density and radiation energy density. The two curves intersect at $t \cong 10000$ years, at which time the Radiation Era changed into the Matter Era.

energy but also with evolution. Whereas previously the gene (strands of DNA) and the environment (whether stellar, planetary, biological, or cultural) governed evolution, twentieth-century Earthlings are rather suddenly gaining control of aspects of both these agents of change. We are now tampering with matter, diminishing the resources of our planet while constructing the trappings of utility and comfort. And we now stand at the verge of manipulating life itself, potentially altering the genetic make-up of human beings. The physicist unleashes the forces of Nature; the biologist experiments with the structure of genes; the psychologist influences behavior with drugs. We are, quite literally, forcing a change in the way things change.

The emergence of technologically intelligent life, on Earth and perhaps elsewhere, heralds a whole new era: a Life Era. Why? Because technology, despite all its pitfalls, enables life to begin to control matter, much as matter evolved to control radiation more than 10 billion years ago. Accordingly, matter is now losing its total dominance, at least at those isolated residences of technological society—such as on planet Earth. Literally, life is now taking matter into its own hands—a clear case of mind over matter, without any Cartesian separation asserted or implied. Such a consummate reductionist viewpoint, materialistic yet not entirely deterministic, also embraces holism as well, for here we postulate a continuous spectrum of complexity all the way up and down the line, from amorphous and uncomplicated protogalaxies to socially stratified cultures of high order (Chaisson, 1989).

A central question before us is this: How did the neural network within human beings grow to the complexity needed to fashion societies, weapons, cathedrals, philosophies, and the like? To appreciate the essence of life's development, especially of life's evolving dominance, we resume our study of the cosmic environment, broadly considered. Also, here we return to some of the thermodynamic issues raised earlier.

5. Growth of complexity

When matter and radiation were still equilibrated in the Radiation Era, only a single temperature is needed to describe the thermal history of the Universe; the absence of any thermal gradients dictated (virtually) zero information content, or zero macroscopic order, in the early Universe. However, once the Matter Era began, matter became atomic, the gas–energy equilibrium was destroyed, and a single temperature was insufficient to specify the bulk evolution of the cosmos. As things turn out, since the random motions of the hydrogen and helium atoms failed to keep pace with the rate of general expansion of the atoms away from one another (Layzer, 1976), the matter cooled faster, $T_m \cong 6 \times 10^{16} t^{-1}$, than the radiation, $T_r \cong 10^{10} t^{-0.5}$.

Such a thermal gradient is the patent signature of a heat engine, and it is this ever-widening gradient that enabled matter, in the main, to 'build things'. At least theoretically, the environmental conditions became naturally established to permit a rise in 'negentropy' of statistical mechanics (Schröedinger, 1944) or in 'information content' of the information sciences (Shannon and Weaver, 1949)—both factors qualititatively synonymous with the term 'complexity' (Lewin, 1992). Such non-equilibrium states are suitable, indeed apparently necessary, for the emergence of order, thus we reason that cosmic expansion itself is the prime mover for the gradual construction of a hierarchy of structures throughout the Universe (Fig. 4).

The key question is this: have the many and varied real structures known to exist in the Universe displayed this sort of progressive increase in order during the course of time? The answer is yes, and more. Yet how shall we quantify that order without resorting to tricky empirical values of negentropy whose measurements are virtually impossible, or slippery interpretations of information content whose meaning and connotation are unclear (Marijuán, 1996; Matsuno, 1996)? In the spirit of not having to invent any new science, we return to the non-equilibrium thermodynamics of open systems (Prigogine, 1980). Here, we are not concerned with the absolute value of a structure's

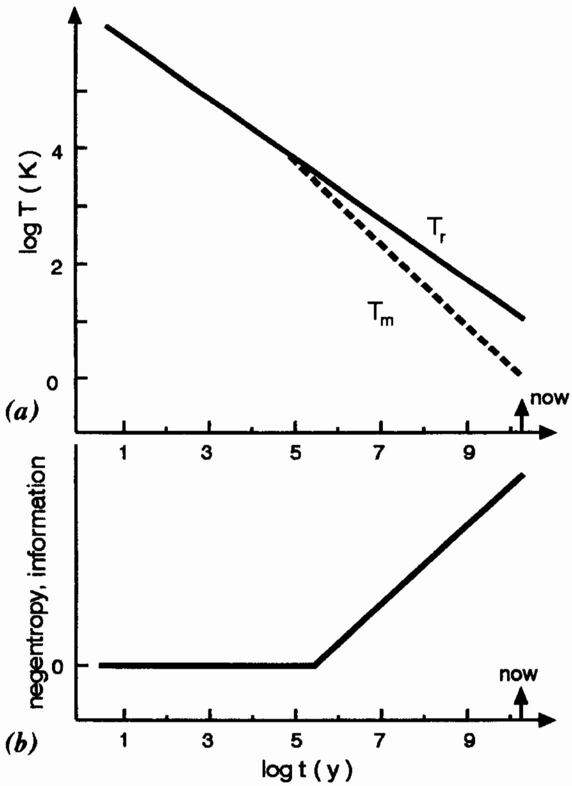

Fig. 4. (a) The temperature of matter and radiation went their separate ways once these quantities became fully decoupled at $t \cong 100000$ years. Since that time, the Universe has been in a non-equilibrium state—a kind of cosmic heat engine; (b) the potential for rising negentropy or information content—unquantified here but conceptual synonyms for 'complexity'—is broadly proportional to the growing thermal gradient in the Universe.

total free energy (available for work) as much as with its free energy density; it is the organized energy density that best characterizes the degree of order or complexity in any system, just as it was radiation energy density and matter energy density that were important earlier in the Universe. In fact, what is most important is the rate at which free energy transits a complex system of given size. In Table 1 below (Chaisson, 1998), we list our calculated values of $\mathcal{F}$, the free energy rate densities for six representative structures (and their specific cases computed in parentheses). We also list the ages (in years) of such structures, dating back to their origins in the observational

Table 1
Some estimated free energy rate densities

Structure	Age (10^9 years)	$\mathcal{F}$ (erg/s per cm^3)
Stars (Sun)	10	4
Planets (Earth's climasphere)	5	80
Plants (biosphere)	3	1000
Animals (hominid body)	0.01	17 000
Brains (human cranial)	0.001	150 000
Society (modern culture)	0	750 000

record. Fig. 5 plots these results. Clearly, $\mathcal{F}$ has increased steadily as more intricately ordered structures have emerged throughout cosmic history, and dramatically so in relatively recent times.

For each structure, the entropy increase of the surrounding environment can be mathematically shown to exceed the entropy decrease of the system per se, guaranteeing good agreement with the second law of thermodynamics. We thus arrive at a clean reconciliation of the evident destructive-

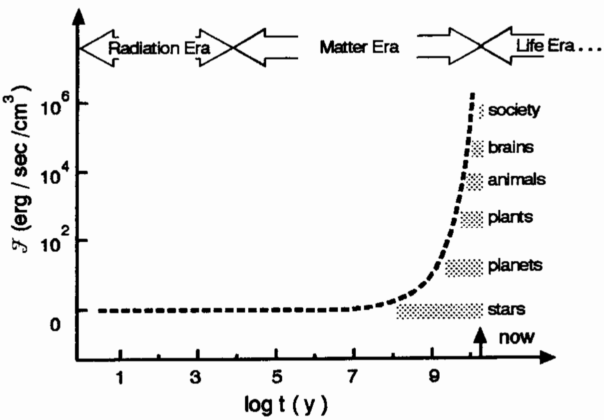

Fig. 5. The rise in free energy rate density, $\mathcal{F}$, plotted as horizontal histograms for those times at which various open structures have existed in Nature, has been dramatic in the last few billion years. The dashed line approximates the rise in negentropy, information, or complexity sketched in the previous figure, but it is energy flow, as graphed here, that best characterizes the order, form, and structure in the Universe. The three principal eras, discussed in this paper, are braketed across the top.

ness of thermodynamics with the observed constructiveness of cosmic evolution. The sources and sinks of such energy flows, indeed through complex, yet disparate, entities such as stars, planets and life forms, all relate back to the time of thermal decoupling in the early Universe, when the conditions naturally emerged for the onset of order and organization.

6. Conclusion

Cosmic evolution accords well with observations that demonstrate an entire hierarchy of structures to have emerged, in turn, during the history of the Universe: energy, particles, atoms, galaxies, stars, planets, life, intelligence, and culture. As a general trend, we recognize an overall increase in complexity with the inexorable march of time—a distinctly temporalized Cosmic Change of Being, without any notion of progress, purpose or design implied. With cosmic evolution as an intellectual basis, we can begin to understand the environmental conditions needed for material assemblages to have become progressively more ordered, organized, and complex, especially in the relatively recent past. This rise in order, form, and structure violates no laws of physics, and certainly not those of modern thermodynamics. Nor is the idea of ubiquitous change novel to our contemporary world views. What is new and exciting is the way that frontier, nonequilibrium science now helps us to unify a holistic cosmology wherein life plays an integral role.

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References

Chaisson, E.J., 1979. Cosmic evolution: a synthesis of matter and Life. Zygon 14, 23–39.

Chaisson, E.J., 1989. The Life Era. W.W. Norton, New York.

Chaisson, E.J., 1998. Order, Form and Complexity, (to be published) Harvard University Press, Cambridge.

Field, G.B., Chaisson, E.J., 1985. The Invisible Universe. Birkhauser, Boston.

Layzer, D., 1976. The arrow of time. Astrophys. J. 206, 559–569.

Lewin, R., 1992. Complexity. Macmillan, New York.

Marijuán, P.C., 1996. From computers and quantum physics to cells, nervous systems and societies. BioSystems 38, 87–96.

Matsuno, K., 1996. Internalist stance and the physics of information. BioSystems 38, 111–118.

Prigogine, I., 1980. From Being to Becoming. W.H. Freeman, San Francisco.

Schröedinger, E., 1944. What is Life? Cambridge University Press, Cambridge.

Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Champaign, Urbana.