The Rise of Information in an Evolutionary Universe

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This paper outlines the grand scenario of cosmic evolution by examining the ongoing changes among radiation, matter and life in standard, big-bang cosmology. Using aspects of non-equilibrium thermodynamics and information science, 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 developmental change, from quark to quasar, from microbe to mind.

KEYWORDS: free energy, flux density, matter, radiation, life

INTRODUCTION

It is perhaps a sobering thought that we seem to play no special role in the Universe. It is even more humbling at first—but then wonderfully enlightening—to recognize that evolutionary changes, operating over almost incomprehensible space and nearly inconceivable time, have given birth to all that we see around us. Scientists are now beginning to decipher how all known objects—from atoms to galaxies, from cells to people—are interrelated. We are beginning to sketch the scenario of cosmic evolution.

Simply defined, cosmic evolution is the study of change through time. More specifically, cosmic evolution comprises the many

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varied 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.

The arrow of time provides the 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 the small scale—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 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. And if Darwinism created a veritable 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 worldview of the present paper. The claim here is that, despite the compartmentalization of modern science, evolution knows no disciplinary boundaries.

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 extremely 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,

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

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_c, at the present time—namely, $r = Rr_c$. 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.
- 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-deSitter solution. Here, we find the critical density for closure,

$$\rho_{\mathrm{m}} = \frac{3}{8}\frac{H^2}{\pi \mathrm{G}},$$

which, when evaluated for G and for H ($\cong$ 70 km/sec/Mpc), equals 10^{-29} gm/cm^3. This is approximately 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, $\rho_{\mathrm{m}} = \rho_{\mathrm{m,c}} R^{-3}$, substitute into the special ($k = 0$) case of the Friedmann–Lemaitre equation, and manipulate,

$$\int \mathrm{d}t = \left(\frac{8}{3}\pi \mathrm{G} \rho_{\mathrm{m,c}}\right)^{-0.5} \int R^{0.5}\, \mathrm{d}R .$$

The result is that $t = \frac{2}{3} H^{-1}$, which accounts for the deceleration of the Universe, and also suggests that the Universe (for the special $k = 0$ case) is about 12 billion years old. This equation additionally stipulates how the average matter density thins with time,

$$\rho_{\mathrm{m}} \cong 10^6 t^{-2},$$

where ρ_{m} is expressed in gm/cm^3 and t in seconds.

We have therefore derived a way to quantify the evolution of the matter density throughout universal history. Hindsight suggests that it will be more useful to reexpress this quantity in terms of the equivalent *energy* density of that matter. We can do so 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; we shall return to this quantity momentarily in order to compare the evolution of matter's energy density with that of radiation's energy density.

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,

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

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 shift. 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, has now cooled to 2.7 K, the average value in fact measured for the cosmic microwave background.

For the first hundred centuries of the Universe, radiation had reigned supreme over matter. All space was absolutely flooded with photons, especially light, X rays, and γ rays, ensuring a nonstructured, undifferentiated, 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. Today, some 12 billion years after the big bang, $\rho_m c^2 \cong 10^{-9}$ erg/cm^3, whereas $aT^4 \cong 4 \times 10^{-13}$ erg/cm^3; thus, in the current epoch,

$\rho_m c^2 > aT^4$ 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. But, 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 about $t = 10{,}000$ years, well less than a million years after creation.

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 ($\sim 10{,}000$ years) at which the Universe gradually began to become transparent. Thermal equilibrium was destroyed and symmetry broken, causing the radiative fireball and the matter 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 about 100,000 years, when the last throes of the early plasma state had finally transformed into neutral matter. The microwave (2.7-K) radiation now captured by radio telescopes and orbiting satellites is a relic of this dramatic 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.

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 ten billion years of cosmic evolution, the dominant species on planet Earth—we, the human being—has learned to tinker not only with matter and energy but also with evolution. Whereas previously the gene (strands of DNA) and the environment (whether stellar, planetary, geological, 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 makeup 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 ten 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.

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 return to some of the thermodynamic issues raised earlier.

When matter and radiation were still equilibrated in the Radiation Era, only a single temperature was needed to describe the early thermal history of the Universe; the absence of a thermal gradient dictated zero information content, or zero macroscopic order. But once the Matter Era began, matter became atomic, the gas-energy equilibrium was destroyed, and a single temperature was no longer enough to specify the bulk evolution of the cosmos. As things turn out, since the motions of the hydrogen and helium atoms failed to keep pace with the rate of general expansion of the atoms away from one another, 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 has enabled matter, in the main, to build things ever-more complex. At least theoretically, the environmental conditions became naturally established to allow the rise in negentropy of statistical thermodynamics and in information content of information science. 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.*

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. In the non-equilibrium thermodynamics of open systems, we are not concerned with the absolute value of a structure's 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 information content, 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 the table below, we list our calculated values of $\Im$, the free energy flux densities for six representative structures (and their generic classes in parentheses). We also list the ages of such structures, dating back to their origins in the observational record. Clearly, $\Im$ increases dramatically as more intricately ordered structures have emerged throughout cosmic history.

Structure	*Age* (10^9 y)	$\Im$(erg/sec/cm^3)
Sun (stars)	5	4
Earth's climasphere (planets)	4	80
biosphere (plants)	3	1,000
human body (animals)	0.01	17,000
human brain (minds)	0.001	150,000
modern society (culture)	0	750,000

In each case, the entropy increase of the surrounding environment can be shown to exceed the entropy decrease of the system per se, thus allowing a reconciliation of the evident destructiveness of the second law of thermodynamics with the observed constructiveness of cosmic evolution. The sources and sinks of such energy flows, indeed through complex entities such as stars, planets and life themselves, 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.

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, 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, non-equilibrium science now helps us to unify a holistic cosmology wherein life plays an integral role.

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