Available online at www.sciencedirect.com

SCIENCE DIRECT®

Ecological Modelling 178 (2004) 17–28

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

Energy hierarchy and transformity in the universe

Mark T. Brown*, Howard T. Odum✠, S.E. Jorgensen[1]

Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611, USA

Abstract

Many properties of the universe discovered in recent years by progress in astrophysics and cosmology are found consistent with the principles of energy hierarchy developed for other scales of time and space. Energy and mass are converged and concentrated by autocatalytic self organization of aggregates of matter, galaxies, stars, and black holes. As energy passes through energy transformation series, concentrations at centers increase, energy flows decrease, territories of support increase, intervals between feedback pulses to lower levels increase, and intensity of episodes of recycles of mass and energy increase. Emergy (spelled with an 'm") puts structures and processes on a common basis. Transformities (emergy/energy) indicate position of each form of energy of the universe in the universal energy hierarchy. High energy radiation is returned to background radiation by a dispersing cascade of absorption by matter and reradiation. The red shift increase with distance may be attributed to the greater mass and gravity of centers of systems of increasing scale. The second law of thermodynamics accounts for energy tranformations at each scale of size and time, except at the lowest level where self organization of background radiation and background materials can form an equilibrium hierarchy. Using estimates of density of the background energy and matter, a preliminary calculation is made of the sun's share of the universe's resources, deriving transformities of the sun, earth, and life in units of the universe's background emergy.

Keywords: Hierarchy; Tranformations; Emergy

1. Introduction

Many of the properties of Science, including environment and economy, appear to fit the concepts of energy hierarchy proposed as an energy law (Odum, 1996, 2001). This paper considers the ways the energy hierarchy principles may apply to the larger scale of astronomy and the universe. If the expectations of energy hierarchy are found in space, the generality of energy hierarchy concepts can be extended, perhaps also helping to choose among theories in astrophysics. In this paper, the expectations of the energy hierarchy are compared with the observations of cosmic structure and processes. On this large scale, where gravity is the major force, let's see how the principle of self organization for maximum empower develops units, spatial convergence, divergence, and recycle of matter and energy. As in earlier studies of other realms, drawing a hierarchical energy systems diagram is a useful methodology for organizing facts about energy and matter while considering theories.

A preliminary "ecological view" of the universe was presented to a Swedish Academy audience in Stockholm in 1989 (Odum, 1995). Using conventions of the energy systems language, astronomical components

* Corresponding author. Present address: Department of Environmental Engineering Sciences, Box 116350, University of Florida, Gainesville, FL 32611-6350, USA. Tel.: +1-352-392-2309; fax: +1-352-392-3624.

E-mail addresses: mtb@ufl.edu (M.T. Brown), sej@dfuni.dk (S.E. Jorgensen).

URL: http://www.ees.ufl.edu/homepp/brown/.

✠ Deceased.

[1] Tel.: +45-35-3060-01, fax: +45-35-375-744.

0304-3800/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2003.12.002

were diagrammed from left to right in order of increasing scale, concentration and turnover time with recycle of matter and energy. This paper assembles additional evidence and arguments, and illustrates with a numerical example.

1.1. Energy hierarchy concepts as used on earth

In common language, the word "hierarchy" means that many units at one level contribute to a few units at a higher level, with the high level feeding controls back to those at the lower level. A military organization is an example. Because of the second law, any energy transformation uses many calories of available energy of one kind to generates a few calories of available energy of another kind. Hence, energy transformations are an energy hierarchy. When there are several transformations in series, the network has many levels of energy hierarchy.

The energy hierarchy concept was developed by generalizing from ecological food chains (Odum, 1971, 1976, 1988, 1996) and offered as an energy law — one that follows from the second law and Lotka's (1922a,b) principle of self organizing for maximum power, offered as the fourth energy law (1922a, 1922b):

> An energy transformation is a work process that converts one or more kinds of available energy into a different type of available energy.

> Emergy (spelled with an "m") is the available energy (exergy) of one kind required to be used up previously, directly and indirectly, to generate the inputs for an energy transformation. Units of emergy are emjoules, emcalories, or emergs of one form of energy. On earth, solar energy is used as the common denominator (solar emjoules, solar emcalories, or solar emergs). This paper uses ergs (10^{-7} J) for energy and emergs for emergy.

> All energy transformations can be arranged in a series, and the position of an energy flow in the series is marked by the transformity. Transformity is the emergy required in transformations divided by the energy in the transformed product. Numerically, transformities are the same whether expressed in emjoules, emcalories, or emergs. (transformity = emjoule/joule = emcalorie/calorie = emerg/erg). Transformity (quotients) can be calculated from energy flows or from accumulated energy storages. On earth, if available energies are expressed as solar emergy, the transformities are greater than one.

> The flow of usable available energy through a network is power. The flow of emergy is called empower. Empower = emergy flow per time.

The energy hierarchy concepts can be visualized with energy systems diagrams (Odum, 1967, 1971, 1983, 1996) that separate the scales with small fast turnover units on the left and items of larger scale of space and time on the right (Fig. 1). Fig. 1a is a network of energy transformations, which is aggregated into a linear series in Fig. 1b. Emergy flow from the left is constant and conserved through the transformations to the right. Available energy decreases with each transformation step from left to right, but the transformity increases. In Fig. 1c, available energy flow is plotted as a function of the increasing transformity on logarithmic coordinates. This plot is an energy hierarchy spectrum.

The higher the transformity, the more available energy of another kind was required to make it. According to the energy hierarchy concepts, transformations that survive the natural selection processes of self organization reinforce their supporting network with a feedback of its energy output even though its energy flow is less. Commensurate reinforcement with less energy is possible because the systems concentrate outputs spatially (Fig. 1d) and accumulate the products and deliver their feedback actions in pulses (1e).

In terms of Lotka's principle, each transformation that survives self organization is organized to help maximize its power while reinforcing the network. However, the high level transformation processes (lower power flow on the right) are just as important as the low level processes (higher power flows on the left). Maximum power might be misunderstood to mean giving priority to low level processes. In Fig. 1b the empower is the same through the whole series. Therefore, Lotka's principle is clarified by stating it as the principle of self organization for maximum *empower*.

1.1.1. Spatial convergence

From observation and theory, the series of energy transformations in an energy hierarchy converge

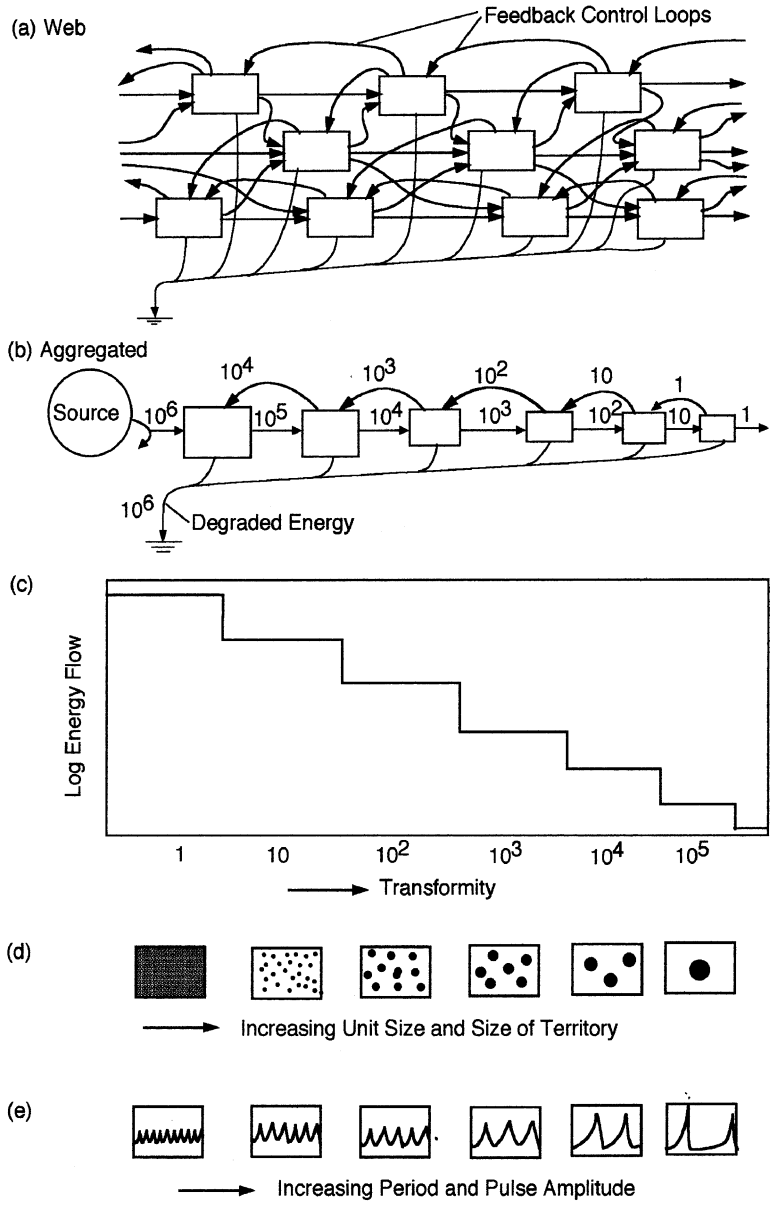


Fig. 1. Summary of concepts of energy hierarchy. (a) Network of energy flows connecting energy transformations in order of declining energy flow; (b) web aggregated as a series with energy flows in steady state; (c) empower and transformity of series with constant empower; (d) increasing size of centers and transformities; (e) decreasing frequency and delivery time of pulses.

their transformed energies to more concentrated centers, even as the total energy transformed decreases Fig. 1c). One of the reasons for this is that reinforcement feedbacks needed to prevail in self organization can he commensurate with what was required in their formation if they concentrate in area. Centers and the supporting territories of these centers increase with successive transformations along the series from left to right Fig. 1d). An example of spatial hierarchy generated by self organization is the vivid pattern

of night lights of cities and towns as seen from satellite.

1.1.2. Accumulation and pulsing

As suggested by pulses shown in Fig. 1e, units higher in the energy hierarchy (higher transformity) have longer periods of accumulating energy storage but sharper pulses in their feedback actions. Examples are the energy feedbacks of carnivores, storms, governments, and earthquakes to their areas. By storing longer and concentrating their impact from smaller concentrated centers in shorter times, the lesser energy of higher units can have enough impact to reinforce their supporting energy transformation chain (a design that fits the maximum empower principle). The pulsing increases in period and intensity along the series of increasing scale from small scale molecular oscillations to large scale earthquakes Fig. 1e).

1.1.3. Energy quality increase

Although the total energy flow is less, the high transformity energy flows to the right are more concentrated, have more effect per unit, are more flexible in their uses, and in these senses are higher quality. In other words, after self organization, energy flow of higher transformity requires more for its support and has more effect.

1.2. Hierarchy in the universe

With energy hierarchy concepts in mind, let's consider next the characteristics of the universe that appear to fit the energy hierarchy model. That the stars and galaxies of the universe are hierarchically organized has long been recognized. Astronomy and astrophysics texts have many plots of energy and mass distribution that are hierarchical (Jastrow, 1969; Lerner, 1991). For example, many stars are organized around larger gravitational centers, and these in turn on a larger scale are organized around even larger gravitational centers.

1.2.1. Autocatalytic units of space

In the vast realm of space, stars and other units that self organize are gravity produced, as described in astronomy textbooks (Carroll and Ostlie, 1996; Chaisson and McMillan, 1998). Under the pull of gravity, units of matter condense, storing energy and developing structure. The resulting increased gravity captures more material. The potential energy of mass falling inward together is concentrated and transformed into heat and energy of rotation. When the gravity and temperature are high enough, fusion reactions convert the mass of hydrogen into energy, turning such units into light emitting stars. Subsequently, there are sequences of succession not unlike that in ecosystems. All units send out radiant energy which disperses, losing concentration, thus degrading consistent with the second law. Some mass is dispersed outward with heated gas. When diagrammed with energy language symbols (Fig. 2), the autocatalytic units of space are not unlike the consumers of ecosystems which also have growth cycles and pulses.

1.2.2. Pulsing

The self organization of stars is known to operate mechanisms involving sequences of nuclear reaction, centrifugal force, concentration by gravity, and thermal expansion that accumulate the conditions to cause explosive mass expulsion (i.e., supernovae). Periods of energy accumulation followed by pulsing outflows are known or have been proposed for most of the universe's objects ranging from proto-star aggregates and stars to the quasars and black holes of galaxies and clusters of larger scale structure.

1.2.3. Mass

Ninety percent of the mass detected may be ordinary matter, with the rest in the more concentrated, light-emitting, stars, black holes, etc. There are many small stars and fewer large stars. Plots on logarithmic coordinates show nearly straight line relationship of star numbers and star mass. Going from smaller to larger scale, the size and mass of stars increase as their numbers decrease. The turnover times increase, and the territories of influence increase, with increasing distances between centers. The patterns are similar to the energy hierarchy concepts shown in Fig. 1.

1.2.4. Energy hierarchy

The energy stored in objects, their temperature and rotation, increase with size and mass. As shown on Hertzsprung–Russell plots of light intensity and temperature, denser stars have higher temperatures and brighter light emission, depending on the stages of development. The cosmic rays reaching the earth made

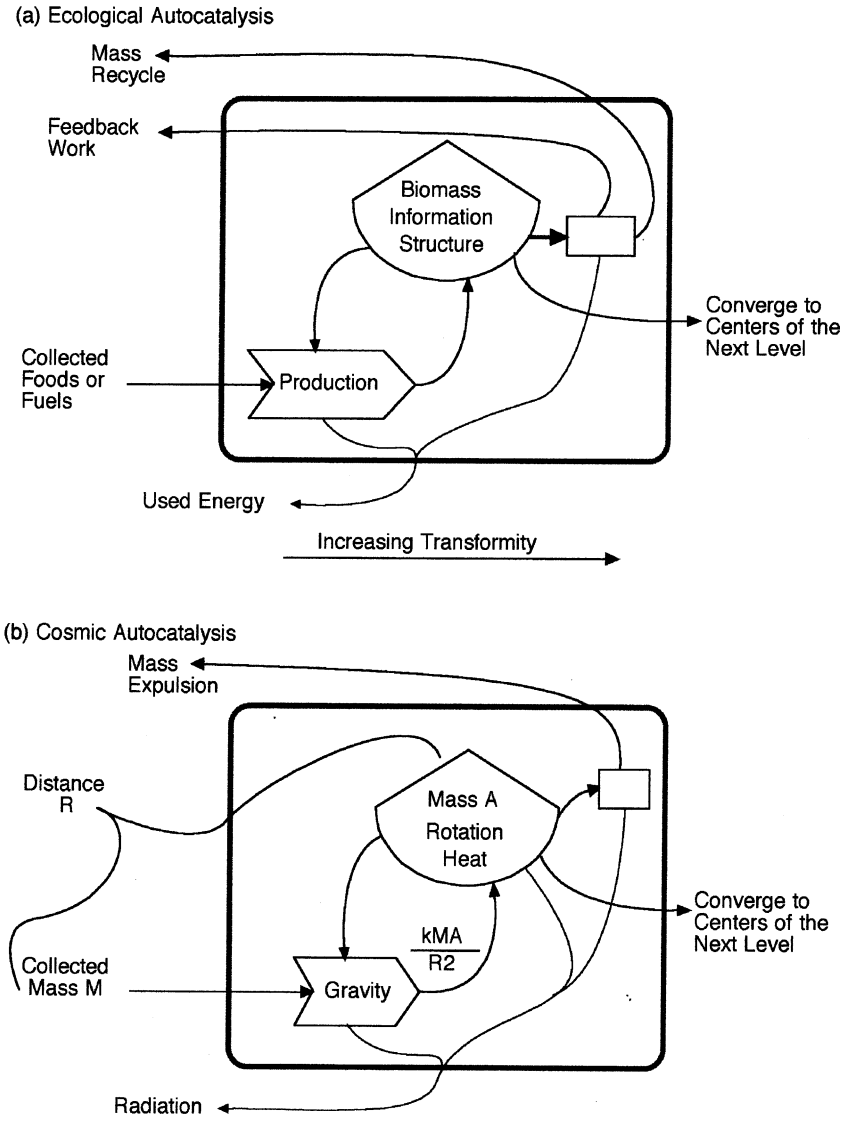


Fig. 2. Design of autocatalytic consumers of space which produce structure and storage using the properties of gravity (modified from Odum, 1983, p. 157).

up of high energy particles and high frequency light suggest the hierarchical energy distributions of their sources. There are many rays with lesser energy and fewer with higher energies.

Fig. 3a shows the distribution of radiant energy in the universe on a log scale as a function of the wavelength and energy of photons. Also see Hoyle et al. (2000, p. 304). Energy quantity decreases but energy concentration (per photon) increases from left to right. With larger scale to the right, the energy required (emergy) increases as does the potential impact of photons in interactions with matter. In a more recent presentation, Henry (1999) plots intensity of diffuse background radiation as a function of frequency, a plot in which the area of the graph is proportional to energy.

The most abundant energy is the background radiation that fits the spectum of emission according to

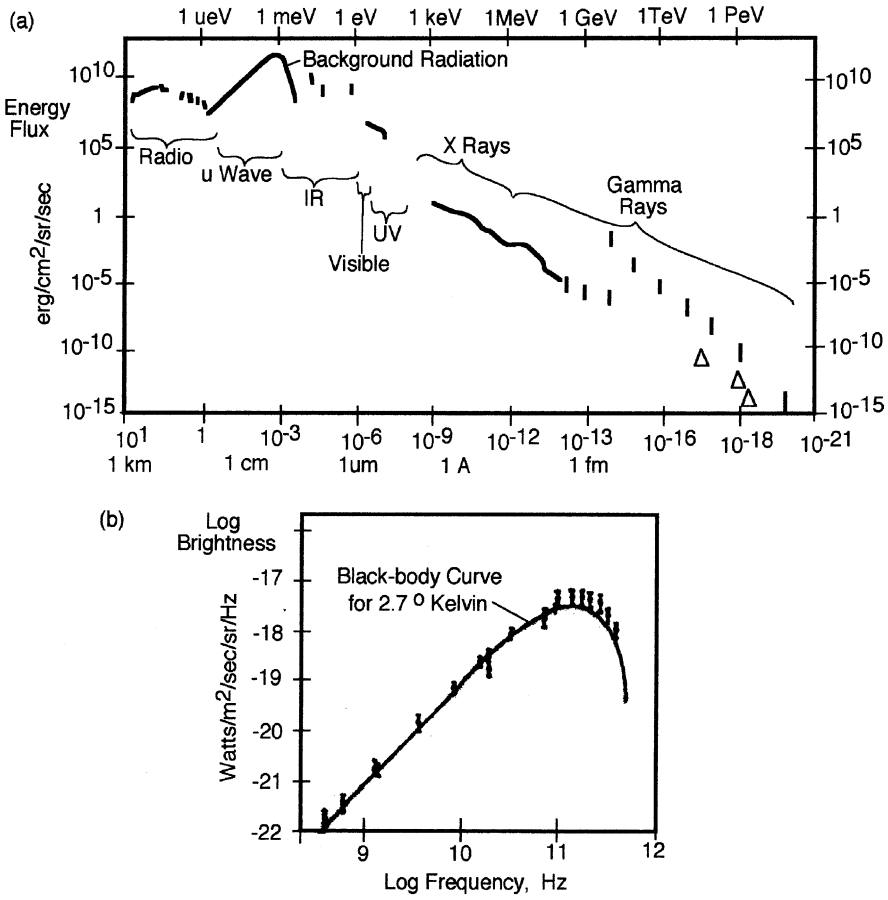


Fig. 3. Spectrum of radiant energy in the universe (from Kolb and Turner, 1986). (a) Radiant energy distribution with wave length; (b) spectrum of background radiation.

Planck's law for blackbodies at 2.7 K Fig. 3b). The universe is uniformly filled with this low quality radiation and with matter that can absorb and reradiate these photons. For the most part, this background matter and energy may be in radiation exchange equilibrium while contributing resources to and receiving recycle from the higher energy systems.

2. An energy systems theory of the universe

Next, lets consider the way the principles of self organization for maximum power and energy hierarchy (Fig. 1) may account for the structure and functions of the universe. How can a fairly uniform distribution of background energy and matter generate and sustain the fantastic forms and variety in the heavens?

2.1. Energy hierarchy within the Maxwell–Boltzmann distribution

A gas in an insulated container at constant temperature has the kinetic energy of its molecules distributed according to the exponential shaped Maxwell–Boltzmann distribution Fig. 4a). The shape of this curve was often explained as the result of the velocities of molecules being distributed at random, according to the bell-shaped Gaussian curve. Kinetic energy is proportional to the square of the molecular velocities. When the velocities are Gaussian, the energy distribution is exponential. This is an

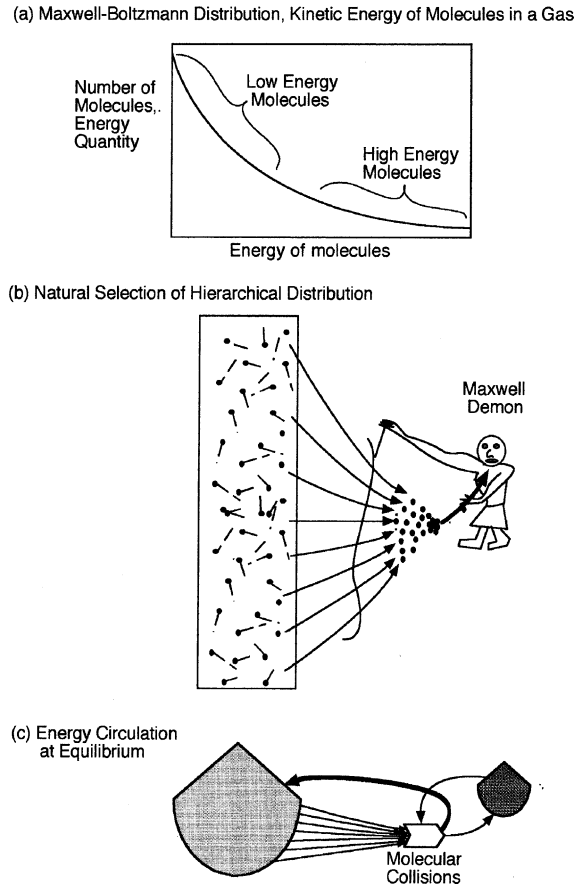


Fig. 4. Hierarchy of energy in the Maxwell–Boltzmann distribution of a gas at equilibrium. (a) Energy distribution; (b) natural selection of a converging design that concentrates energy (Maxwell demon); (c) energy systems view of closed cycle energy flows.

anarchical view of nature, based on the randomness idea.

An alternate view recognizes that the energy distribution is hierarchical because of self organization principles. From the much larger scale of view, a human sees constant patterns and calls it an equilibrium. Many molecules at low kinetic energy, by their interactions, generate a fewer number at higher energy and velocity. A large number of these generate a fewer number at an even higher energy level, etc. If there is a constant percent at each level to generate those at the next, the distribution is mathematically exponential. Nothing random is needed or implied. If only a sector of the process is viewed on the tiny scale of the molecules, many small energies build a few higher velocity molecules while their average momentum is decreased. In other words, when viewed on a smaller scale, the second law appears.

The distribution is consistent with operation of the maximum empower principle within an equilibrium gas. There is a *natural selection of the design that generates energy hierarchy*. Using the Maxwell Demon metaphor, Brillouin (1962) suggested that there was not enough energy in molecules to support a process of concentrating energy against the gradient. However, the self organizational process converges the energy of many molecules to support a few of higher energy (Fig. 4b) and consequently provides more energy for the selection process. In other words, the natural selection of self organization for maximum power is a kind of Maxwell demon. Fig. 4c is an energy systems summary of the energy hierarchy of a gas in equilibrium (as viewed from a larger scale).

2.2. The self organization of available energy from equilibrium

The Maxwell–Boltzmann distribution shows how a smooth uniform distribution of matter and energy generates a hierarchical “lumpy” distribution of matter and energy. Once there is some mass concentration, its fields of gravity can evolve into autocatalytic units Fig. 2b) and grow (the classical explanation of star formation). Once there is a mass center, background radiation can help raise its temperature because of the spherical geometry of incoming radiation. Self organization may reinforce and select spiral organization and rotation as typically maximizing power transformations and feedback efficiency. Once there are units of higher mass and energy, these can be self organized to converge on higher level centers that have higher concentration and territory of influence, as in any energy consumption chain Fig. 1).

2.3. Energy system diagram of the universe

Using energy systems language, Fig. 5 models the universe showing principal structures, energy, and mass flows. The diagram separates populations of different scale and position in the energy transformation hierarchy from left to right. The background radiation and dilute matter are the lowest concentrations on the far left. These contribute energy and gravity

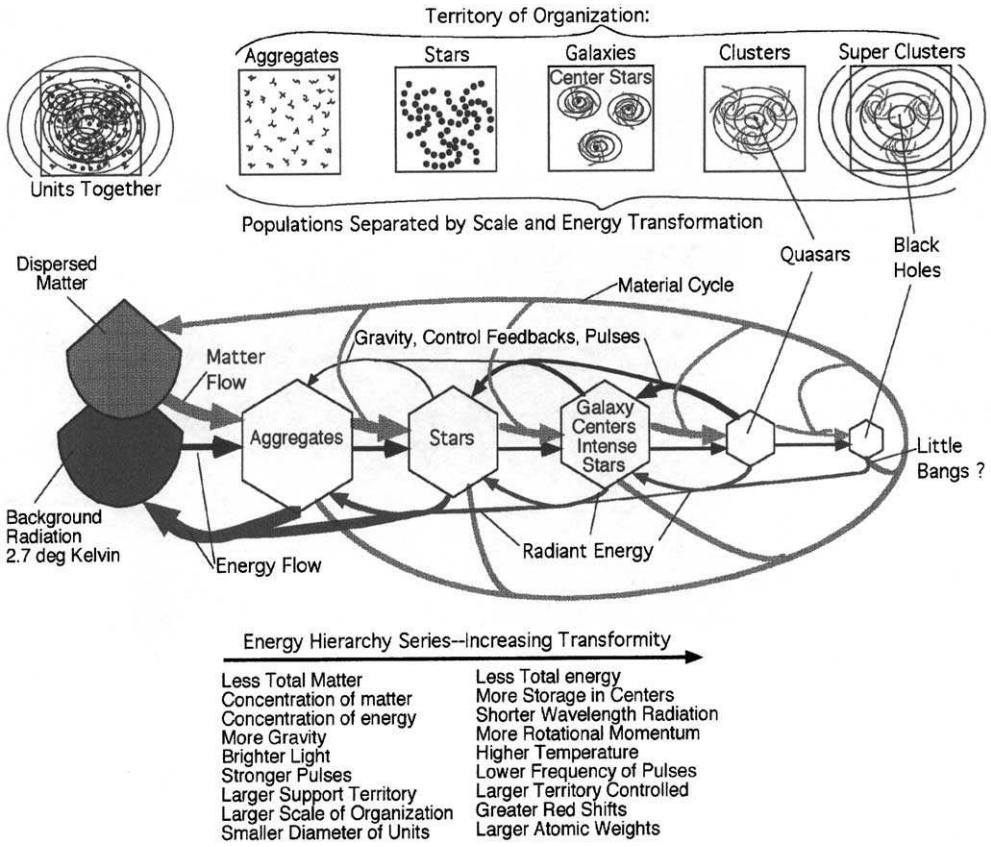


Fig. 5. Energy systems model of energy hierarchy in the universe separating populations of structures and processes according to their scale and energy transformations increasing from left to right.

concentrated mass into matter aggregates. The aggregates condense into higher energy, visible units to the right. For each level of increased scale (galaxies, galaxy clusters, etc.), there is a more intensive center (smaller and denser because of the increased gravity). From left to right, nuclear reactions generate elements of higher atomic weight but in lesser quantities. The larger the territory of organization the higher in energy hierarchy is its center unit. To the far right are black holes with enough gravitational mass to draw in light energy and inhibit outbound radiation. Mechanisms are known or proposed to generate high energy radiation pulses and emissions even by black holes. Hoyle et al. (2000) suggest quasars at the center of clusters are important in pulsing recycle of energy and matter.

The diagram is not a program of development stages. However, development that starts without much initial structure will form the units on the left before those on the right because of the shorter storages and turnover times. Like ecological "succession," the whole system starts with low energy, first growing little organized "weed", next adding hierarchy and diversity, culminating in the largest scale organization with most intense centers on the right. The evolution of some stars to become higher energy centers of galaxies is analogous to local cities that emerge as dense emergy centers of states and nations because of their locations. Like ecosystems and cities, large scale stellar consumption uses up available energy and fuels (nuclear fuel), recycles matter, and completes a sequence of growth and decline. In ecosystems, large scale catastrophic mechanisms often destroy the structures, restarting the growth sequence. By analogy we might expect some black holes to explode as "little bangs." Observations in space are detecting more and more explosive energy dispersals (Schilling, 1999).

For repeating sequences to be sustainable, matter and energy have to he recycled. Some mechanism is required to regenerate the hydrogen and other matter used up in nuclear reactions. Perhaps energy is used to regenerate hydrogen in black holes, as has been suggested. With a universal view, one would expect different areas to be in different stages of the development sequence. Having many populations of units in each category constitutes a steady state on the average.

2.4. AIternate theories of the cosmos

The literature of cosmology is rich with alternative theories that scientific observation and measurement may not yet be adequate to chose. Kragh (1999) reviews in detail many ideas and mechanisms involved in big bang and steady state theories. Both views include efforts to explain the observed hierarchical properties. If the energy hierarchy principles apply to the universe (Fig. 5), its predictions may help understand observations.

2.5. Radiation dispersal and red shifts

Consistent with the energy hierarchy concept of organization (Fig. 1), light dispersing out from a center is a recycle of energy that loses concentration by diverging. Light is also being absorbed by space matter and dark bodies and reradiated at different and lower frequencies cascading down to background (to the left in Fig. 5).

Because of the nature of energy in atoms and molecules, light emitted from space objects is in characteristic wavelengths. Light from moving objects arrives with a changed frequency, the Doppler effect. Doppler effects are observed in rotating galaxies, with blue shifts of light from stars moving toward the earth and red shifts for those moving away. However, most of the starlight viewed from earth has its wavelengths shifted toward lower frequency (longer wavelength), a shift to the red. The most popular interpretation attributes most of the red shifts to an expanding universe accelerating away.

The “tired light theory” (Zwicky, 1929) explains some red shifts as a loss of energy to gravitational pull of intergalactic matter or other mechanisms. Since light maintains constant speed in space, loss of energy requires a shift to a lower energy frequency, a red shift. Recall the wave characteristics of light that are demonstrated by passing light through a slit and observing its spread. Perhaps diverging light on the large scales of space red shifts in proportion to its loss of concentration?

Light is known to act as a mass, exerts pressure, and its rays are bent by gravity. The larger the mass and gravity of the light source, the larger is the red shift (large shifts from quasar light for example). This relationship might be expected if gravity of the emitting center removes energy from light traveling away (a mechanism of energy efficiency?). More distant objects have larger red shifts. This follows from the energy hierarchy concepts. The larger the scale of an organized pattern, the further away is its center from an earth observer and the more concentrated is its mass-causing red shift. As evidence of hierarchy, there are many small red shifts and few large red shifts (Hoyle et al., 2000). Perhaps all these mechanisms (Doppler effect, energy divergence, and source gravity) contribute to the red shifts we observe from earth.

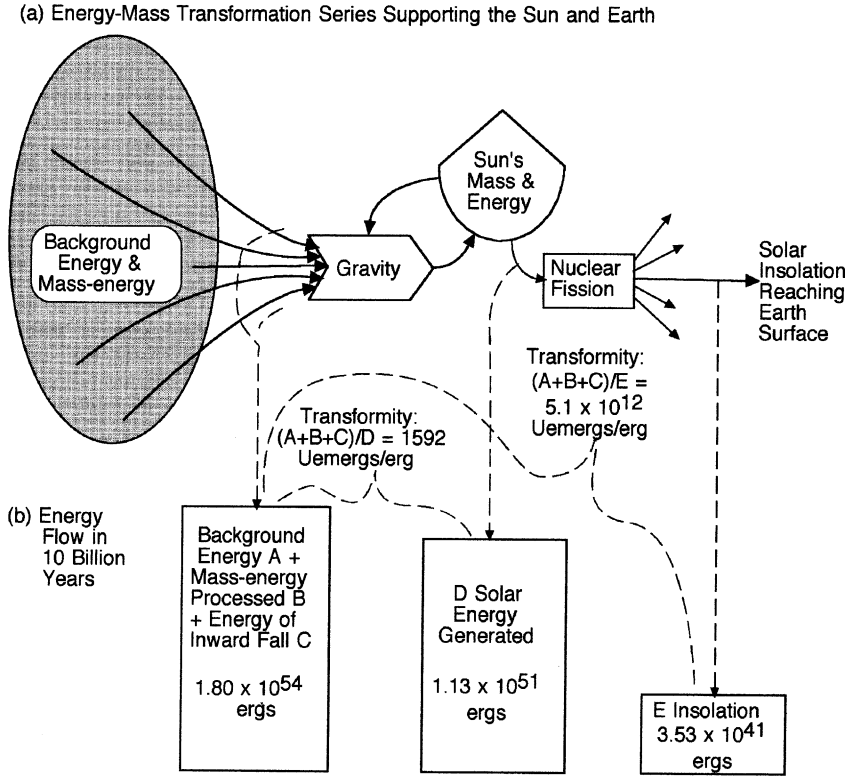
2.5.1. Universe and the second law

If you include the energy converted from mass to heat in nuclear reactions as a major part of the fuel, the autocatalytic consumer units of space (Fig. 5) follow the second law (Fig. 2). They transform abundant energy and mass of lesser kinds into smaller quantities of higher intensity energy and mass, with an overall degrading of energy and mass, and an increase in entropy. However, the available energy for most structures and processes is generated by the self organization of energy hierarchy at the bottom near equilibrium, as already explained (Fig. 4). When phenomena are viewed on each scale of time and space except the lowest background, the second law applies. On each scale, there is steady state only if summed over a long enough time to average out the pulsing.

When viewed as a whole with a long scale of time, the universe could be like the bottom scale, a constant average pattern of structure, mass and energy flows in which the second law merges with the equilibrium concept (Fig. 4). The energy hierarchy concept seems to make the big bang theory unnecessary, although much of what is discussed in this paper could also apply to a post-big bang regime.

2.5.2. Equations of scale

The concepts of energy hierarchy and maximum empower predict equations and designs for each scale, even though the mechanisms for production, autocatalysis, and reinforcement may differ. Even on earth, similar models and quantitative relationships apply when changing from one scale to another, providing you change space, time, and transformity. For examples, the same computer simulation models can be used for microbes and cities, after the units of time, space, and energy are all changed by the same factor (Odum, 1983). Einstein's relativity equations are a means to represent phenomena that involve changing scale of time and space in the realm of gravity and light. Transformities, empower density and other emergy indices may be a simpler way to understand the similarities and differences with scale.



A = Background energy in the volume occupied by the background mass used
= $(2.0 \times 10^{33}$ g of sun)$(4 \times 10^{-13}$ ergs/cm$^3)(5 \times 10^{30}$ cm^3/g) $= 4.0 \times 10^{51}$ ergs

B = Mass-energy equivalent of background mass used ($E = mC^2$).
$= (2 \times 10^{33}$ g/sun)$(3 \times 10^{10}$ cm/sec$)^2 = 1.8 \times 10^{54}$ ergs

C = Gravitational potential energy from the collapse of matter
$= 6.6 \times 10^{48}$ ergs (Allen, 1981)

D = Solar Energy emitted in the 9 billion year life of the sun
$= (4 \times 10^{33}$ erg/sec$)(3.15 \times 10^7$ sec/yr$)(9 \times 10^9$ yrs$) = 1.13 \times 10^{51}$ergs

E = Solar energy reaching the earth's surface
$= (3.93 \times 10^{24}$ J/yr$)(10^7$ erg/J$)(9 \times 10^9$ yrs$) = 3.53 \times 10^{41}$ ergs

Fig. 6. An emergy evaluation of sun and earth based on the sun's share of the universe. (a) Sketch of the series of transformations evaluated; (b) bars representing the energy flows between stages.

3. The universe's emergy contribution to earth

In order to start the quantitative application of energy hierarchy concepts to space, a preliminary calculation is made in Fig. 6. Emergy flows, emergy storages and transformities are estimated for earth, the sun, and its share of the universe hierarchy. No doubt the numerical values may change as better data are obtained for the numbers used. Because this is a thermodynamic overview calculation, it is not necessary to know all the details of the many mechanisms that may be involved.

In the emergy evaluations of phenomena on earth, emergy was evaluated in units of solar insolation, which is for earth the most abundant but lowest quality energy source at the base of the earth energy networks. Emergy was evaluated in solar emjoules ($\times 10^7$ erg/J = solar emergs). The hierarchical position of energy of various processes on earth was indicated by the transformities in units of solar emjoules per joule (solar emergs/erg). In an analogous way to the calculation for the solar system, we are trying here to express everything in emergy of the most abundant, lowest quality energy, the background radiation with emergy units labeled as Universal emergs (abbreviated Uemergs). Then the more concentrated energy flows and storages in space can be characterized by universal transformities with the units Uemergs/erg. These calculations view the background radiation as part of a dynamic system that continuously draws background energy into the hierarchical network and regenerates it from the system as recycle.

To use the transformity concept to place cosmic objects in the universal hierarchy, all kinds of energy need to be expressed in emergy units of one kind. To avoid fractions, transformities are given in terms of the most abundant, lowest quality emergy, the background radiation, even though that is not the immediate source of energy for the nuclear operations at higher levels. If we are using emergy of background radiation as our base, then by definition this energy has a universal transformity of 1 Uemerg/erg.

In order to quantitatively relate the background radiation and background matter to the sun and its planet earth, let us estimate the part of the universe which has been the sun's share of low energy support. The sun is a star with about half of its supply of hydrogen for fusion used up. The calculation in Fig. 6 was made for 9 billion years, the time when the sun has completed its life cycle (twice the present age). Perhaps a billion years can be added for the total time required to collapse background resources into a sun.

Most of the sun's radiant energy results from the nuclear conversion of its matter (hydrogen used in fusion), but that process builds on the emergy in the previous accumulations and transformations. We calculated the volume the sun's mass would have if dispersed back to the concentration of the most dilute background matter (reciprocal of matter density 3×10^{31} g/cm^3, Carroll and Ostlie, p. 1228). This is the volume of the universe's low quality resources that would be required to form the sun. This volume was used to estimate the sun's share of the universal background radiation at the base of and somewhat caught up in the evolution process (Note A, Fig. 6).

The energy converted by nuclear reaction from the original dilute matter also comes from the lowest level in the universe, the dispersed hydrogen. The dispersed matter has the energy equivalence of its mass that is later converted into energy (called mass-energy after Chaisson and McMillan (1998)). Therefore, before concentration it is given the same transformity as background radiation with a value of 1 Uemergs/masserg.

The sun's share of background energy, gravitational potential, and background matter energy are shown as the bar on the left. The total output of solar radiation emitted in the sun's life is in the center bar, and the total solar insolation received in the earth's biosphere is on the right.

In the successive transformations from the dilute matter and energy to more concentrated units, the universal emergy passes from input to output, but the total quantity of transformed energy decreases. Therefore, the transformity increases as cosmic bodies form. The more processes of concentration and transformation, the higher the transformity. Transformities increase from left to right in Fig. 5. In Fig. 6 the resource emergy (A + B + C) was divided by the concentrated energy flows for the sun D and earth E, respectively, to estimate their universal transformities (center of Fig. 6). More refined calculations might include the mass expulsions during concentration pro-

cesses, the pulsed emissions of sun spots, and other details of the succession.

3.1. Life and the biosphere

At first thought, it might seem strange to find the cool, low energy planet earth at a higher level of energy quality and transformity than the intense energy of the sun. However, the earth is an information center with very high solar transformity of life, estimated earlier as 10^{32} solar insolation emjoules/J (Odum, 1996 p. 229). Life required the planet, its appropriate orbit, its appropriate star, and the large quantities of matter and energy processed over time for its development. Expressed as emergy of universal background in Fig. 6, life may have a universal transformity of 5.1×10^{44} Uemerg/erg, obtained by multiplying the universal emergy per erg of earth insolation 5.1×10^{12} Uemerg/solar erg by 10^{32} solar erg/life erg.

4. Summary and conclusion

The concepts of energy hierarchy developed for many scales on earth are consistent with many of the observed phenomena of the universe. An energy systems model with hierarchical networks helps explain how energy and matter can be produced and recycled through each level in a cycle of evolution and pulsing. If the cosmos includes units at different stages of the cycle, the energy hierarchy organization is compatible with a universe in steady state, although concepts are not inconsistent with the self organization after a big bang. Recognizing the pulsing paradigm that is part of the energy hierarchy theory, we often describe the spatial pattern of energy hierarchy on earth as a Christmas tree with flashing lights, an analogy that may be appropriate in a universe with many areas of alternating effluorescence.

The transformity concept can be extended to the universe by dividing the required emergy of background energy and mass-energy by the energy of processes and storages of heavenly bodies. A tentative calculation of emergy and transformity of the solar system and the earth provides a numerical example. In principle at least, the example shows how to put the solar transformities calculated for earth environment and economy on a universal basis.

Acknowledgements

Work on this paper was aided by suggestions and criticism in collaborative discussion with Dr. Dolores Krausche, Florida Center for Engineering Education, Gainesville, FL.

References

Brillouin, L., 1962. Science and Information Theory, 2nd ed. Academic Press, New York, 351 pp.
Carroll, B.W., Ostlie, D.A., 1996. An Introduction to Modern Astrophysics. Addison-Wesley, Reading, MA.
Chaisson, E., McMillan, S., 1998. Astronomy, 3rd ed. Prentice-Hall, Upper Saddle River, NJ, 470 pp.
Henry, R.C., 1999. Diffuse background radiation. Astrophys. J. 516, L49–L52.
Hoyle, F.G.B., Narlikar, J.V., 2000. A Different Approach to Cosmology. Cambridge University Press, New York, 357 pp.
Jastrow, R., 1969. Red Giants and White Dwarf. New American Library, Signet, 241 pp.
Kolb, E.W., Turner, M.S., 1986. The Early Universe. Addison-Wesley, Reading, Massachusetts.
Kragh, H., 1999. Cosmology and Controversy, The Historical Development of Two Theories of the Universe. Princeton University Press, Princeton, New Jersey, 500 pp.
Lerner, E.J., 1991. The Big Bang Never Happened. Times Books, Random House, New York, 466 pp.
Lotka, A.J., 1922a. Contribution to the energetics of evolution. Proc. Natl. Acad. Sci. 8, 147–151.
Lotka, A.J., 1922b. Natural selection as a physical principle. Proc. Natl. Acad. Sci. 8, 151–154.
Odum, H.T., 1967. Biological circuits and the marine systems of Texas. In: Olson, T.A., Burgess, F.J. (Eds.), Pollution and Marine Ecology. Interscience, Wiley, New York, pp. 99–157.
Odum H.T., 1971 Environment, Power and Society. Wiley, New York, 331 pp.
Odum, H.T., 1976. Energy quality and carrying capacity of the earth. Trop. Ecol. 16 (1), 1–8.
Odum, H.T., 1983. Systems Ecology. Wiley, New York, 644 pp.
Odum, H.T., 1988. Self organization, transformity, and information. Science 242, 1132–1139.
Odum, H.T., 1995. Self organization and maximum power. In: Hall, C.A.S. (Ed.), Maximum Power. University Press of Colorado, Boulder, pp. 311–364.
Odum, H.T., 1996. Environmental Accounting, Emergy and Decision Maxing. Wiley, New York, 373 pp.
Odum, H.T., 2001. An energy hierarchy law for biogeochemical cycles. In: Brown, M.T. (Ed.), Emergy Synthesis, Proceedings of the Emergy Conference of 1999, Center for Environmental Policy, University of Florida, Gainesville, pp. 235–248.
Schilling, G., 1999. Watching the universe's second biggest bang. Science 283, 2003–2004.
Zwicky, F., 1929. On the red shift of spectral lines through interstellar space. Proc. Natl. Acad. Sci. 15, 773–779.