Advanced Track, Epoch 3

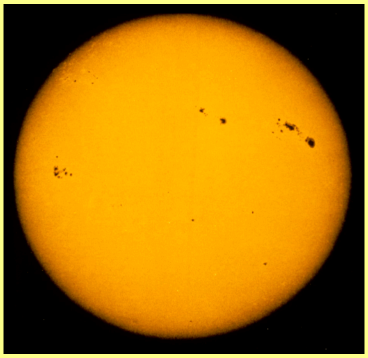
Stellar Evolution

This Advanced Track provides a technical supplement to the introductory web site on cosmic evolution, produced by Eric Chaisson and based on courses taught mainly at Harvard University for the past few decades:
http://www.cfa.harvard.edu/~ejchaisson/cosmic_evolution/docs/splash.html

Currently, this Advanced Track is abbreviated while addressing mainly the concept of energy rate density—a numerical quantity proposed as a useful complexity metric for an underlying, unifying process that guides the origin, evolution, and destiny of all organized systems across the arrow of time, from big bang to humankind. In the summer of 2014, this supplement will grow dramatically, providing much more pertinent technical material at an advanced, quantitative level (suitable for colleague scientists and graduate students) well beyond that presented in the above-linked introductory web site (which is meant for non-scientists and beginning students).

A summary of this Advanced Track is here:
http://www.cfa.harvard.edu/~ejchaisson/advanced_track_sitesum.pdf

Further material related to the subject of cosmic evolution is available at:
http://www.cfa.harvard.edu/~ejchaisson
including a collection of recent research papers easily accessed and PDF downloadable at:
http://www.cfa.harvard.edu/~ejchaisson/current_research.pdf



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Cosmic Evolution

Stellar evolution is a subset of the larger category of physical evolution, which is itself part of the grand scenario of cosmic evolution:

Cosmic evolution = **physical evolution** + biological evolution + cultural evolution.

During this third, stellar epoch, energy rate density, $\Phi_m \approx 0.1 - 1000$ erg/s/g, among a wide range of stars whose interiors grow more complex with time.

Stellar Energy Rate Densities

Changes within and among stars can be cast into the same thermodynamics context presented in the Advanced Track for the PARTICLE EPOCH. Putting aside estimates of decreasing entropy or increasing information as overly abstract and unproductive, this Advanced Track for the STELLAR EPOCH appeals to the more practical and physically meaningful quantity, Φ_m, the energy rate density characterizing open, non-equilibrium, complex systems. As with other ordered, complex systems in Nature, empirical values of Φ_m can serve as a useful gauge of stellar complexity, allowing the evolution of stars to be tracked while passing from "birth," through "middle-age," and on to "death." As stars undergo nuclear fusion that causes them to change size, color, brightness, and composition, their growing complexity can be estimated while increased energy usage drives them toward greater non-equilibrium states, eventually culminating in a return to the simplicity of equilibrium at the end of their productive "lives" as stars.

Note that astronomers usually use the term *evolution* to mean change, or development, during the lifetime of an individual star. This contrasts with the traditional meaning of the term in biology, where evolution refers to generational changes in the traits of a population of life forms. The last section of this Advanced Track suggests that populations of stars also evolve in a broad biological sense, as the overall composition of the interstellar medium and hence of each new generation of stars change gradually owing to nuclear events within stars, some of which explode as supernovae. Stars, too, can be said to evolve generally, minus any genes, inheritance or competition that comprise the essence of biological evolution affecting systems that are truly alive. None of this implies that stars are alive, a common misunderstanding of the cosmic-evolutionary scenario.

The Sun Today

Consider first the star known best, the Sun—a typical G2-type star having a current luminosity $L_\odot \approx 4\times10^{33}$ erg/s (actually 3.84×10^{33}) and a mass $M_\odot \approx 2\times10^{33}$ g (actually 1.99×10^{33}), making $\Phi_m \approx 2$ erg/s/g today. This is the average rate of the Sun's energy release per unit mass of cosmic baryons, which fuse ~10% of their H in 1 Hubble time (10 Gy). This is the energy flowing effectively *through* the star, as gravitational potential energy during star formation converts into radiation released by the mature star. Specifically, the initial gravitational energy first changed into thermal energy to heat the interior, thence nuclear energy in fusion reactions within the core, and was finally released as (mostly) visible electromagnetic energy from the mature star's surface. Such a star utilizes high-grade (undispersed) energy in the form of gravitational and nuclear events to promote greater internal organization, but only at the expense of its surrounding environment; the star emits low-grade light, which, by comparison, is highly disorganized energy scattered into wider domains well beyond its internal structure.

Perspective is crucial, however. In the case of our Sun, 8 minutes after emitting its light, life on Earth makes use of those dispersed photons, which though low-grade relative to the Sun's core are very much high-grade relative to the even lower-grade, infrared radiation that is, in turn, then re-emitted by Earth. What is waste from one process (the Sun's emission) can be a highly valued energy input for another (photosynthesis on Earth), as noted later in the Advanced Track for the BIOLOGICAL EPOCH.

The cherished principles of thermodynamics remain intact. All agrees with the 2nd law of thermodynamics, as noted earlier in the Advanced Track for the PARTICLE EPOCH. The Sun's external environment is regularly disordered, all the while order emerges, naturally and of its own accord, within the stellar system per se . . . and eventually within the planetary system that harbors life, intelligence, and society.

Normal Stars Generally

Values of Φ_m of order 1 erg/s/g hold for nearly all stars, not just for the Sun, provided they are normal, stable stars on the zero-age main sequence of the H-R diagram ("zero-age" because that's when a star starts fusing H into He, hence its "lifetime" begins). Yet as for any population—of plants, humans or stars—variations abound; there is no perfect star among physical systems, much as there is no perfect rose or perfect person among biological species or social beings. To give a few examples, all stars resembling the Sun, such as G2-type α-Centauri ($1.5L_\odot$, $1.1M_\odot$), F5-type Procyon A ($7.4L_\odot$, $1.5M_\odot$), G8-type τ Ceti ($0.5L_\odot$, $0.8M_\odot$), among myriad others in our galactic neighborhood for which their masses are known, have total (bolometric) luminosities that make their Φ_m values close to that of the Sun—in fact, for the stars just noted approximately 2.8, 9.8, and 1.3 erg/s/g, respectively.

Even much brighter, more-massive stars (still on the main sequence), such as white-hot Sirius A (A1-type) and blue-giant Vega (A0-type), have comparable energy rate densities. The former has well measured values of ~$22L_\odot$ and ~$2.1M_\odot$ and the latter ~$37L_\odot$ and ~$3M_\odot$, thus for both stars $\Phi_m \approx 25$ erg/s/g, which is roughly within a factor of 10 of our Sun's. Small but noticeable increases in complexity among these somewhat more massive stars are likely due to the nature of their fusion process. In short, these bigger stars are not fusing H→He via the p^+-p^+ cycle as does the Sun; rather, they are powered by the CNO cycle that dominates at their unavoidably higher core T owing to the their greater mass. Although the CNO cycle still yields He from H, it does so via the intermediate nuclear catalyst C and also engages O and N nuclei. The CNO cycle is more complicated than the p^+p^+ cycle since the route by which energy is processed is more convoluted and involves heavier nuclei that have greater charges, hence we should not be surprised that values of Φ_m for more massive stars are somewhat higher than for the Sun.

Rare, supergiant, main-sequence stars with typically thousands of solar luminosities yet hundreds of solar masses have Φ_m values within a couple orders of magnitude of the Sun's. Such larger values of Φ_m are also unsurprising for, as discussed below in the section on stellar evolution, these are the most massive stars that develop very steep thermal and elemental gradients characteristic of highly evolved and complex physical systems. Even if the blue supergiant O- and B-type stars with >10 $M_\odot$ are judged exceptions to the Φ_m trends argued throughout this research work on cosmic evolution, they are very rare exceptions given that these truly massive stars represent <0.1% of all stars on the sky; in fact, stars with >5 $M_\odot$ account for only 0.5% of all known stars, and even those with >2 $M_\odot$ still comprise only a few percent of all known stars—in fact stars in the sky obey much the same power-law distribution as do stones at the seashore where large small pebbles greatly outnumber large boulders. Giant main-sequence stars are indeed exceptionally rare in the Universe.

By contrast, on very much smaller scales yet still among main-sequence normal stars, less-massive stars such as the K2-type ε Eridani (0.3$L_\odot$, 0.8$M_\odot$) and K5-type ε Indi (0.2$L_\odot$, 0.8$M_\odot$) once again have Φ_m values comparable to the Sun's—in fact, approximately 0.8 and 0.5 erg/s/g, respectively. Extremely low-mass stars, such as the red dwarfs Proxima Centauri (M5-type, $1.7\times10^{-3}L_\odot$, 0.12$M_\odot$) and Barnard's Star (M5-type, $3.5\times10^{-3}L_\odot$, 0.15$M_\odot$), do have Φ_m values (~0.04 ers/g/s) well less than that of the Sun, but that's probably because their weak thermal and chemical gradients resemble near-equilibrium states—and at equilibrium, $\Phi_m = 0$. Although these dim stars are in fact fusing H→He, albeit just barely, they differ from the Sun (wherein convection occurs only in the outer part of its layered gaseous ball) in that they are fully convective throughout their innards, resulting in much mixing, uniform composition, and only simple differentiation. No wonder, then, that such low-mass dwarf stars have inordinately small values of energy rate density, much as expected for minimally ordered, inanimate, almost homogeneous objects.

So, a variety of stars all across the Universe currently exist on the main sequence of physical systems that process energy by fusing H → He. These stars are not all alike, just as living species have varied members (short and tall, fat and skinny, warts and all) that are not precisely the same. Again, as among life forms on Earth, variation is common within populations of stars—and those variations often have reasonable explanations for their smaller-than-solar Φ_m values. There are even occasionally, once again as within the biological world, exceptions to larger observed trends, including those for the complexity metric argued here, though those exceptions seem likely to be rare indeed.

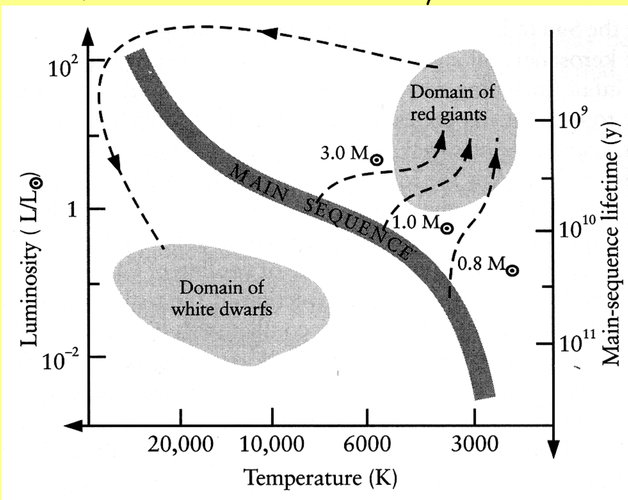
Sun's Evolution

Once the young Sun enters the main sequence and ignites H→He fusion, it remains hydrostatically balanced for ~11 Gy; its values of L and surface temperature T_s change little. Still, it is instructive to track those small changes, for they show that Φ_m does increase throughout the Sun's long lifetime, even in its relatively stable main-sequence phase.

Both theoretical inference and observational evidence reveal that our Sun currently increases its L at the rate of ~1% per 100 My. This occurs because, as the Sun fuses H→He within a central zone where the core temperature $T_c \geq 10^7$ K, the He ash accumulates and contracts, albeit slightly; much like a negative-feedback thermostat, the star continually adapts by readjusting its balance between inward gravity and outward pressure. And as the ashen core so "settles," it heats yet more to re-establish a balance against gravity, and in the process fusing additional H within an expanding 10^7-K shell overlying the core, thereby increasing its energy production rate, though again only slightly—and very slowly.

This is the so-called "faint-Sun paradox"—a paradox because it presents a puzzle regarding the apparently low T of Earth at the time that life originated several Gya (*cf*, Advanced Track for CHEMICAL EPOCH). Accordingly, the Sun must have been dimmer than it is now when it first joined the main sequence as a new star ~5 Gya. The young Sun would also then have been somewhat more massive since it regularly loses mass via its solar wind, in fact likely suffered an even greater mass loss during its youthful T-Tauri phase when its wind likely resembled more of a gale while clearing the early Solar System of formative debris. Although the Sun's early mass-loss rate is unknown, it was probably a small fraction of the star per se; today the Sun loses ~2×10^6 metric tons of particulate matter per second (*ie*, 3×10^{-14} $M_\odot$/y) and another 4.3×10^6 tons/s in equivalent radiation (*ie*, ~6×10^8 tons/s of H converted to He at a nuclear efficiency of 0.71%), but that loss hardly affects the Sun as a star, diminishing its total mass by <<0.1% to date. Computer models (Sagan and Chyba, *Science*, v276, p1217, 1997) imply that ~5 Gya the Sun was ~half as luminous yet virtually as massive, making its L value at the time ~2×10^{33} erg/s and its Φ_m value early on ~1 erg/s/g. Thus, over the past 5 Gy, Φ_m for the Sun has roughly doubled, and over the course of the next 6 Gy will nearly double again by the time its central H fusion ends.

These past and future changes in the state of the Sun can be traced on a Hertzsprung-Russell diagram, which is perhaps the most useful tool in the lexicon of a stellar evolutionist. As can be noted from the figure below, even during this quadrupling of its L, the Sun remains on or close to the main sequence—the locus of ~90% of all stars in the Universe today.



The subject of stellar evolution—one of the 7 major epochs of cosmic evolution—is fortunate to have a single graph that encapsulates many of the salient changes experienced by stars. The Hertzsprung-Russell diagram organizes stars by luminosity and surface temperature, making several patterns and groups evident: Most normal stars lie on the main sequence (darkly shaded curve across center), while red-giant stars are found at upper right and white-dwarf stars at lower left. Our Sun is currently near the middle of the main sequence, at 1 $L_\odot$ (or $4x10^{33}$ erg/s) and ~5800 K. The dashed lines depict the evolutionary tracks of 0.8, 1.0, and 3.0 $M_\odot$ stars, thereby dating the ages of the star clusters depending upon their turnoff coordinates (marked in years at right) in the H-R diagram. (Adapted from Chaisson and McMillan, Astronomy Today*, Pearson, 2011.)*

When the Sun does leave the main sequence in ~6 Gy, it will experience a significant increase in Φ_m, for by then it will begin to evolve and complexify more dramatically. Post-main-sequence evolutionary changes accelerate in every way: Its L will increase substantially, its color will change noticeably, its internal gradients will grow greatly, and its value of Φ_m will rise much more rapidly than in its first 11 Gy. What follows are some numerical details of this evolutionary scenario, averaged over many models, noting that until nearly the star's demise M remains practically constant all the while L and therefore Φ_m increase (Sackmann *et al, Astrophys J*, v418, p457, 1993; Kaler, *Cambridge Encycl Stars*, Camb U Pr, 2006):

In ~6.2 Gy, the Sun's extremities will expand while exhausting H gas at its core, yet still fusing it within the surrounding layers. Its L will first become nearly twice larger (in addition to its already main-sequence doubled value of L today), making then $L_\odot \approx 10^{34}$ erg/s—the result of a bloated object fluxing its energy through a larger surface area as our future Sun enters the so-called subgiant branch of the H-R diagram (see previous figure). By then, its energy output will have increased because its core T_c will have risen with the continued conversion of ever-more gravitational to thermal energy; He ash accumulating in the core will contract substantially, thus producing more heat, which once again stabilizes the star against collapse. By contrast, its surface T_s will then have decreased as with any distended object from ~6000 K to ~4500 K, making its previous (as current) external color of yellow more orange. At this point, the star will have become a convoluted object—its envelope expanded past the size of Mercury's orbit while receding into interstellar space and its core contracted to the size of Earth while approaching the quantum state of e^- degeneracy. As its He-ashen core then continues compacting under the relentless pull of gravity, its T_c will approach the 10^8 K needed to fuse He, all the while its T_s will have lowered further to ~4000 K and also become redder as the aged star inflates further.

Additional complications will become manifest since, although H→He fusion occurs throughout the more voluminous intermediate layers, that process will have switched from the simpler p^+-p^+ cycle to the more elaborate CNO cycle (wherein those heavy nuclei, especially C, act as nuclear catalysts) mainly because the overlying layers will be then heated to higher T from the even hotter underlying core. Eventually, ~0.7 Gy after leaving the main sequence, and following an extremely short period of unstable, explosive He fusion when it first ignites (or "flashes" ferociously for a few hours according to computer models), the star will attain a more stable state on the horizontal branch (see the 1-$M_\odot$ track plotted on the more detailed H-R diagram in the next section), where it fuses He→C and thence displays $L \approx 50L_\odot$, but only for ~100 My more—the classic late stage of a red-giant star near "death."

Throughout this period of post-main-sequence evolution, the Sun's internal thermal, density, and elemental gradients will have markedly steepened; its mass will have decreased to ~0.8 $M_\odot$ owing to strong winds and serious mass-loss caused by its larger size

(~100 $R_\odot$) and reduced surface gravity; and its core, once laden with mostly H fusing into He will have become mostly He fusing into C, all of which means a more differentiated internal constitution—a clear sign of an evolved physical system that has become decidedly more complex, as are all red-giant stars.

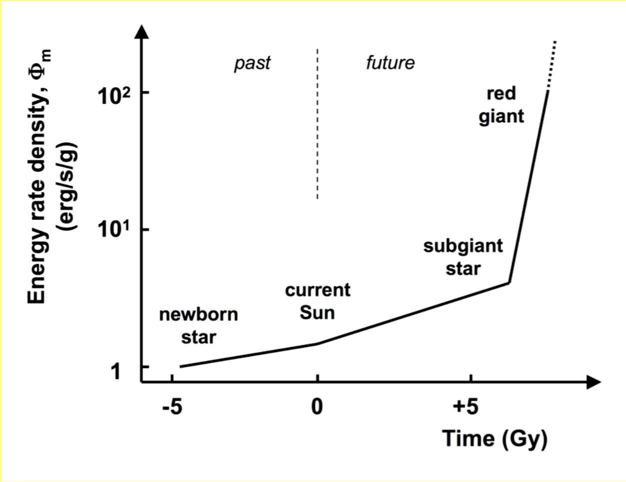
Ultimately and for a much shorter period of time (<10 My) as He is consumed and C accumulates in its core, the elderly Sun will likely swell still more and lose more M while transitioning deeper into the giant domain, where its values of L and hence Φ_m probably increase by roughly another order of magnitude. As sketched in the more detailed H-R diagram in the next section below, the future Sun will most likely negotiate these changes by moving back up along the so-called asymptotic giant branch (AGB) typical of the brightest red giants. Multiple shells of H and He will then fuse internally, but its total mass is too small to allow appreciably its core to reach 6×10^8 K needed to fuse C→O, thus its central fires will extinguish without synthesizing heavier nuclei. While nearing its end fate, the Sun's constitution will have become more complicated than when it first began fusing as a homogeneous sphere of mostly H gas ~5 Gya. The future Sun will be unable to survive the changing environmental conditions. It is destined for deletion from—that is, it will be naturally selected out of—the local population of stars.

The progressively increased complexity described here for a 1-$M_\odot$ star is well reflected in its increased Φ_m values throughout its stellar evolutionary journey—much as expected for any open, non-equilibrated system both evolving and complexifying. The Sun, in particular, has, and will have, increased its Φ_m values throughout its lifetime while repeatedly adapting to its environmental circumstances. Here is a summary of its principal changes, which are also tabulated in the next table and plotted in the next figure:

- ~1 erg/s/g when the newborn Sun arrived on the main sequence ~5 Gya
- 1-4 erg/s/g while evolving on the main sequence for ~11 Gy and thereafter reaching the subgiant branch
- ~120 erg/s/g when the future Sun (by then ~80 $L_\odot$ and ~0.8 $M_\odot$) becomes a red giant in its final ~0.5 Gy
- ~1000 erg/s/g (maybe) as the Sun terminates as an AGB star in its last ~0.1 Gy.
- 0 erg/s/g, as its nuclear fires cease, its envelope dissipates, its core shrivels and cools, and its whole being fades to equilibrated blackness—but not for a long, long time greater than the current age of the Universe.

Energy Rate Densities for the Sun

Stellar type	Time (Gy)	Φ_m (erg/s/g)
AGB star	+ 7	~2000
red giant	+ 6.9	120
subgiant star	+ 6.2	4
current Sun	0	2
newborn star	- 5	1



The value of Φ_m for the Sun increases gradually while fusing H→He throughout >95% of its total ~12-Gy lifetime (on the left side of the vertical dash to the present and on the right side into the future). Even while on the main sequence, the Sun approximately quadrupled its luminosity and hence its energy rate density while steadily, yet very slowly, growing more complex. Only toward the end of its tenure as a nuclear-burning star does the Sun's core contract enough to trigger He→C fusion, to escalate its internal organization, and to cause a rapid rise in Φ_m by about an order of magnitude.

Rising Φ_m well characterizes the Sun as it becomes more structurally complex while physically evolving—but only while fusing as a genuine star. Its ultimate destiny is two-fold: a slowly receding outer envelope that gradually disorders by dispersing into the surrounding interstellar medium, and a small, dense, hot core remnant whose C embers glow solely due to its stored heat. These latter, white dwarfs are not white-dwarf stars per se (in contrast to red-giant stars that really are stars while still fusing nuclei); there is actually nothing stellar about white dwarfs since no nuclear fusion occurs within such relatively homogenized spheres of C that are supported only by a sea of e^- obeying the Pauli exclusion principle. Such an end-fate for the Sun is not very complex—and not very surprising either, since such a dead star, as with any object—animate or inanimate—has an energy flow well below optimum (*cf.*, section below on white dwarfs that have Φ_m nearing 0).

Evolving Stars Generally

Much as a range of Φ_m values pertain for populations of normal stars all along the main sequence, a similar range of variation is apparent for stars that have evolved away from the main sequence. As for the Sun discussed above, increasing Φ_m for aged stars can be considered a measure of their ongoing stellar evolution and growing internal complexity. Indeed, it is the increased energy flow fostered by stars' growing complexity that causes them to evolve away from the main sequence. Consider a few representative examples of well-known stars at different stages in their evolutionary cycles, and compare and contrast them to where the Sun is headed—energetically speaking.

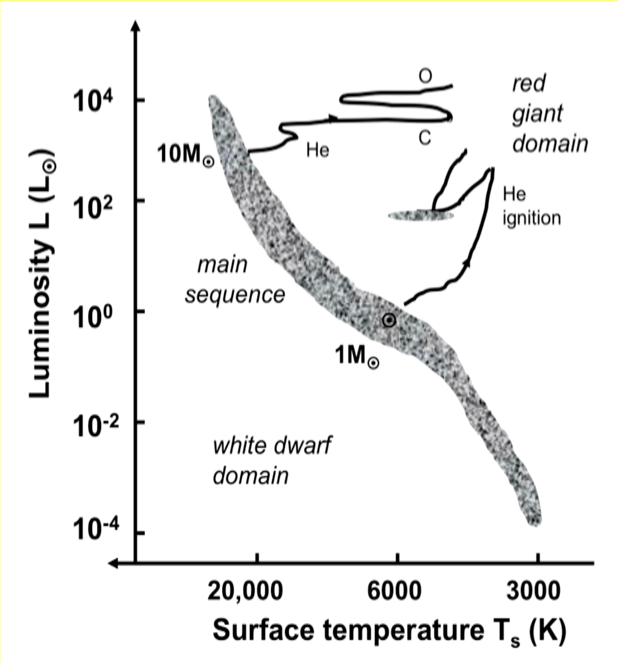
As noted in the previous section, ~5.5 Gy from now the Sun will swell to become an ordinary red giant, much like the prominent K2-type star Arcturus (the giant bright star comprising the Herdsman's foot in the constellation Boötes), which has already achieved such a substantially evolved, hence moderately complex, state. With $L \approx 180\ L_\odot$ and $M \approx 1.5\ M_\odot$, Arcturus' $\Phi_m \approx 240$ erg/s/g. Likewise, K5-type Aldebaran (a red giant that forms the "eye of the bull" in the constellation Taurus) has ~330 $L_\odot$ and ~2.5 $M_\odot$, thus $\Phi_m \approx 265$ erg/s/g. (These stars' mass values already account for their serious ejection losses as red giants.) Once again, Φ_m rises as these red-giant stars pass through more advanced evolutionary stages in their lifecycles, much as expected on the basis of the above discussion for the Sun. Given their status as elderly, massive stars, their internal thermal and elemental gradients grow large as their T_c approaches 10^9 K yet T_s remains low, ~4000 K—all of this change amidst a complexifying array of organized heavy-element shells from H near their surfaces to at least C and possibly O in their cores. Evolved, complex systems indeed.

Nearly all stars pass through the red-giant domain (the only exceptions being the smallest of the red dwarfs having <0.2 $M_\odot$, which proceed directly to become black dwarfs). At the core of every relatively low-mass (≤8 $M_\odot$) red-giant star is a white-dwarf star—the end-fate of all low-mass stars—typically having the crossection of the Earth yet the mass of the Sun. Hundreds of such dwarfs have been spotted in our galactic neighborhood, such as Procyon B ($6\times10^{-4}\ L_\odot$, 0.6 $M_\odot$) and Sirius B (0.02 $L_\odot$, 1.1 $M_\odot$), their red-giant envelopes having long receded into interstellar space (sometimes displaying so-called planetary nebulae). They thus typically have $\Phi_m = 10^{-2}$-10^{-3} erg/g/s, much as for all white dwarfs detected in the Milky Way, on their way to becoming black dwarfs in ~10^{12} y when $\Phi_m = 0$. The theory of stellar evolution implies that the cores of all low-mass stars (including our Sun) are destined to become such a white dwarf, a very dense (~10^7 g/cm^3) ball of mostly C embers whose electrons virtually touch one another. As its mass is inadequate to generate higher T_c and hence further nuclear fusion, the center of a white dwarf compresses its constituent ions as much as possible, ripping electrons from their atomic orbitals. The resulting sea of e^-, held buoyant not by heat but by the Pauli exclusion principle and known technically as a degenerate Fermi gas, is no longer fusing, no longer ordering, no longer evolving or complexifying.

Stars much more massive (≥8 $M_\odot$) than the Sun perhaps best demonstrate increasing complexity, evolution, and energy rate densities. These are the stars that eventually develop great thermal and chemical gradients between their cores and surfaces, thereby reaching impressive levels of (physical) complexity—and consequently higher values of Φ_m than for any stars like the Sun. These big stars don't last long, however, for their added mass overwhelmingly bears down on their interiors, accelerating the conversion of gravitational PE to heat, and ultimately engendering energy flows and complexity states. They do so in a sequence of steps that periodically cause ash to accumulate in their cores, central fusion to stop, and their cores to contract to ever-higher ρ under the relentless compression of gravity, which in turn causes T_c to rise enough for fusion to reignite among steadily heavier nuclei, where the ash of each burning stage becomes the fuel for the next stage—H near the relatively cool periphery of the core, He, C and O at lower, intermediate layers, and Ne, Mg, Si, among other heavies deeper down—each of which type individually arrays in a series of onion-like layers overlying the core, and all of which together enhance thermal and elemental gradients, thus creating progressively higher degrees of complexity.

High-mass stars evolve much faster than their low-mass counterparts. In fact, all evolutionary changes happen much more rapidly for the bigger stars than for the Sun because their large mass and stronger gravity generate more heat, speeding up *all* phases of stellar evolution. For example, in a 20-$M_\odot$ star, H burns for ~10^7 y, He for ~10^6 y, C for ~10^3 y, O for ~1 y, and Si for ~1 week; the Fe core grows for <1 day.

The figure below is a more detailed H-R diagram than the previous one, here showing the evolutionary tracks of a representative very massive star that lives fast and dies young. Note that He fusion proceeds so quickly that high-mass stars have a very different evolutionary track than for the Sun. Their envelopes swell and cool while becoming supergiant stars. What makes their paths on the H-R to loop back and forth as shown in the figure? It's not entirely clear conceptually, other than the computer models show it to be a common feature for very massive stars. The turnarounds in their evolutionary paths are apparently related to the Eddington limit—the L at which radiation pressure acting on myriad e^- effectively balances the inward gravitational pull. Regardless of the devilish details that even experts lack, at each step in the process of synthesizing the heavy elements needed for the cosmic-evolutionary story to continue, these massive stars seem to grow evermore complex.



Evolutionary tracks for stars of 1 and 10 $M_\odot$ show how stars with much greater than the Sun's mass track more horizontally across the H-R diagram from the main sequence into the red-giant region. Some points are labeled with the type of nucleus that has just started fusing in the inner core—resembling bifurcating transitions into each new burning stage (see next figure). The lower evolutionary track graphed here traces a 1-$M_\odot$ star (such as the Sun) leaving the main sequence and ascending the red-giant branch as its core shrinks and envelop expands. Eventually, with higher core T_c , nuclear fusion ignites He→C as the aged star becomes a red giant. The upper track represents more massive stars (in this case, 10 $M_\odot$) that undergo repeated upgrades in their fusion cycles at accelerated rates, looping back (to the left with renewed nuclear ignition) and forth (with core contraction) while fusing He, C, and O.

Note that, in contrast to the Sun whose complexity increases only modestly for much of its lifetime, more massive stars demonstrate more strongly a correlation among evolution, complexity, and Φ_m. To give one example, owing to its greater gravity, a 10-$M_\odot$ star lives fast and dies young (~50 My lifetime) while developing huge thermal, density, and elemental gradients between its core and surface as it fuses progressively heavy nuclei within ordered, concentric shells—a repetitive process that engenders ever-increased energy flows and complexity states. In fact, it is the growing complexity fostered by such stars' rising energy flow that causes them to quickly evolve away from the main sequence toward the supergiant domain, as sketched by the higher, looping track in the previous figure, where for each cycle that yields heavier nuclei, the value of Φ_m rises still more (Vanbeveren, *et al*, *Astr&Astrophys Rev*, v9, p63, 1998; Kaler, *Cambridge Encycl Stars*, Camb U Pr, 2006). Numerically, for the specific case shown in the figure, $\Phi_m \approx$ 600, 1800, 2600, and 4000 erg/s/g while fusing H, He, C, and O, respectively—enhanced energy flows that will eventually synthesize up to Fe nuclei, exceed optimum values, and explode the star into disordered pieces during a violent supernova. Both Rigel and Betelgeuse, exceptionally luminous members of the constellation Orion, are good examples of such stars now evolving toward this disastrous fate.

Note also from the previous figure that evolution proceeds so rapidly in the 10-$M_\odot$ case that the star doesn't even reach the red-giant region before He-fusion begins. As each element is burned to depletion at the star's center, its core contracts and heats up, thus fusion starts anew. In a series of steps that resemble a bifurcation graph discussed earlier in the Advanced Track for the PARTICLE EPOCH and regraphed in the figure below, such high-mass stars produce ever-heavier nuclei and at ever-faster pace.

Gravity is the culprit, causing a non-burning stellar core to contract and heat up at virtually every step of the way; that infall continues until it is halted either by e^- degeneracy pressure or by the onset of a new round of nuclear fusion. The more massive the star, the more repetitions occur before the star finally expires. A good example of a notable star within this stage in its career is the post-main-sequence blue supergiant Rigel in the constellation Orion. With ~$6x10^4$ $L_\odot$ and ~17 $M_\odot$, its $\Phi_m \approx 7.1x10^3$ erg/s/g. Its bright rival in Orion, the red supergiant star Betelgeuse has ~$8x10^4$ $L_\odot$ (much of it in the IR) and ~19 $M_\odot$, thus $\Phi_m \approx 8.4x10^3$ erg/s/g. Both these stars are at advanced stages in their nuclear-fusing cycles (especially the latter), probably already fusing C→O and possibly O→Ne at their cores. They seem destined to explode as supernovae in a My or so—and may have already done so, their spectacular, radiant demise now racing across the sky toward us.

To rationalize the claim that as stars evolve they grow more complex, consider first the track of a 4-$M_\odot$ star, which would take a trek on the above H-R diagram intermediate between the 1-$M_\odot$ and 10-$M_\odot$ stars. While evolving away from the main sequence, this star has the following vital statistics and complexity metrics:

- on the main sequence while fusing H, the star has ~ 10^2 $L_\odot$, thus $\Phi_m \approx 50$ erg/s/g
- at He fusion, the star has increased to ~200 $L_\odot$ and $\Phi_m \approx 100$ erg/s/g
- at C fusion, it has ~10^3 $L_\odot$ and $\Phi_m \approx 500$ erg/s/g.

Now consider the track of a 10-M star, which is even more impressive in its complexity rise:

- at H fusion, ~$3x10^3$ $L_\odot$ and $\Phi_m \approx 600$ erg/s/g
- at He fusion, ~$9x10^3$ $L_\odot$ and $\Phi_m \approx 1.8x10^3$
- at C fusion, ~$1.2x10^4$ $L_\odot$ and $\Phi_m \approx 2.4x10^3$
- at O fusion, ~$8x10^4$ $L_\odot$ and $\Phi_m \approx 1.6x10^4$.

Not only does Φ_m increase as massive stars evolve away from the main sequence, but also the more massive the star the greater the increase in Φ_m at each and every step of the fusion cycles that produce the heavy elements.

In making these calculations, approximate mass-loss rates were accounted for. As noted earlier for the case of the Sun, that rate was small— ~10^{-14} $M_\odot$/y—in fact, so small as to have no effect on the Sun as a star (though often a real effect on any attendant planets). The most massive stars, however, are more active systems and have greater mass-loss rates—some of them as large as 10^{-6} $M_\odot$/y, thus they can loose up to a full $M_\odot$ in a mere My. Even so, since these biggest stars endure for much shorter times than the Sun—some as short as a few My from birth to death—these huge loss rates will still not much affect the stars as they evolve, likely robbing the stars of hardly more than $^1/_3$ of their total mass during their lifetimes. (There are exceptions—as always in Nature, it seems—such as Wolf-Rayet stars, which are flaring stars mostly devoid of H, and eruptive variables whose mass-loss rates are extraordinary, and this activity might influence the way those rare stars evolve.) Accordingly, the values for Φ_m given in the above paragraph are altered only moderately by mass escaping the big stars, thus preserving the empirical trend connecting evolution and complexity for the remarkable physical systems that are stars.

Exotic End States

When stars' internal T_c reaches ~$3x10^9$ K and their composition becomes mostly Fe within their inner cores (yet still only within a volume about the size of Earth), they catastrophically implode and then rapidly (possibly within seconds) explode as supernovae. The most recent such event nearby (~50 kpc away in the Large Magellanic Cloud), and the best-studied (Type-II) supernova in history, was the core collapse of the B3-type, 15-$M_\odot$ supergiant star, SK-69°202, whose intense flash of light first reached Earth in 1987. Now known as SN1987A, its internal complexity was presumably maximized (for a normal star) just prior to detonation when this ~10^5 $L_\odot$-object would have had $\Phi_m \approx 1.3x10^4$ erg/s/g—in reasonable agreement with the value of Φ_m for the end-state of a 10-$M_\odot$ star just computed two paragraphs above. The detection of a mere 11 neutrinos at Earth—just the number expected despite ~10^{57} of them launched by the supernova—a few hours prior to the optical flash (as it would have taken that amount of time for the shock wave to propagate out of the detonated star, thus revealing the ejected debris) is good confirmation—essentially proof—that core collapse of very massive stars actually do occur in Nature. However, there is as yet no observational evidence for the n° star that theory says might have been left behind.

This is not to say that indefinitely higher values of Φ_m produce evermore complexity. Examples abound in Nature where too much energy flow triggers just the opposite—namely, open systems that suffer disruption, disorder, and breakdown, diminishing systems' complexity and often returning them to equilibrium. Toward the end of the Advanced Track for the PARTICLE EPOCH, we noted how flames, bombs, and other destructive energy sources effectively reverse the evolutionary process. A supernova event is another such case, wherein at the moment of explosion Φ_m is so large (>>10^6 erg/s/g) as to reduce the previously ordered star to disordered chaos. Such a violent event does in fact resemble a detonated bomb; although the scales are vastly different, the values of Φ_m are similar and both results—for bomb and supernova—catastrophic. A 1-Megaton nuclear device, for example, has a huge $\Phi_m \approx 10^{11}$ erg/s/g, which explains its utter destructiveness. Such a bomb is uncontrolled chaos—quite the opposite of organized order—but someday when humankind masters nuclear fusion we might be able to control for positive evolutionary purposes such huge values of Φ_m, as is the nearly case already on smaller scales for computers and aircraft among other technological devices, as noted in the Advanced Track of the CULTURAL EPOCH.

Even more peculiar states of inanimate matter are expected to survive the compressed kernels of neutron stars, those rotating remnants (pulsars) of massive stars that occasionally survive supernova explosions. These small, perhaps still hot objects of extreme density—mere tens of km across yet with huge $\rho \sim 10^{13}$ g/cm^3—comprise virtually pure neutrons, the remnants' electrons having collided with protons to yield a highly ordered neutron sea that effectively competes with gravity. Here, for stellar cores >1.4 $M_\odot$ (the "Chandrasekhar limit"), the onslaught of gravity is enough to overwhelm the Pauli principle for electrons but not that for neutrons, thereby causing the core to collapse to even smaller size and greater density than for a white dwarf. Again ironically, such an uncommonly ordered neutron star, having a density comparable to an atomic nucleus, might well resemble a superconducting fluid like that displayed by liquid helium at some of the lowest T (~10^{-3} K) attainable in the laboratory (Careri, *Order and Disorder in Matter*, Benjamin/Cummings, 1984).

Ponder one more point regarding open, self-gravitating systems—which, by the way, stars are. Such a "gas without walls" is nonetheless quite unlike any isolated system in a laboratory. Stars, among other members of the cosmic hierarchy of material clusters, do not readily relax toward a state of thermodynamic equilibrium with their surroundings. Even the terminal phase of many stars may not be, at first, an equilibrium state. Instead, their fate is probably one of free gravitational infall. For when a very massive star (>2.5 $M_\odot$, the "Landau-Oppenheimer limit," a lower limit in the absence of rotation) loses its previously maintained hydrostatic equilibrium between gravity and pressure, it collapses catastrophically toward the bizarre configuration known as a black hole. If black holes ultimately trap all matter, with the increasing areas of their widening event horizons proportional to thermodynamic entropy, S (Thorne, *Black Holes and Time Warps*, WWNorton, 1994), then they too can be said to tend toward an obligate equilibrium as Nature's premier state of maximum S for any given space. Even if black holes evaporate—though no observational evidence yet supports that idea—while radiating away their insides over eons of time, they become Nature's final S producers (Hawking, *Nature*, v248, p30, 1974). Eventually—but only in the very remote future, perhaps of order 10^{70} y [sic!]—thermodynamics becomes the victor, not gravity.

To be sure, approaching gravitational equilibrium (in addition to thermal and chemical uniformity) would mean a Universe full of black holes. At the start of all things—the α-point of spacetime—perfect equilibrium prevailed for non-gravitational forces, while essentially maximum disequilibrium characterized gravity, for there were then no structures whatsoever. As implied by the discussion of gravitational S in the Advanced Track for the PARTICLE EPOCH, the trends are quite opposite for gravity as for thermal and chemical effects; gravity has counter-thermodynamic tendencies. An initially regular, low-S gravitational state is destined to evolve into a subsequently irregular, high-S one at the end of all things—the Ω-point of spacetime—indeed, unavoidably one that maximizes all actually entropies and approximates the "heat death" long postulated by classical physics.

Generational Stellar Change

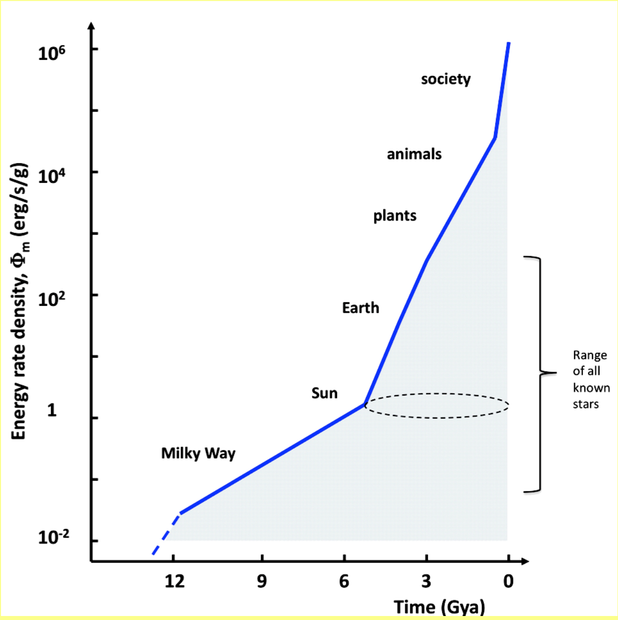
Stars do not merely increase their Φ_m values while developing during a single generation of change. They also, in a truer sense of the word *evolution*, display increased Φ_m as 2nd, 3rd, and Nth-generation stars emerge in turn from the debris of earlier generations of stars. Much akin to changes within populations of plants and animals over many generations of life forms, populations of stars do also basically alter as the composition and heterogeneity of interstellar space (and hence of each new stellar generation) changes over exceedingly long durations of time—minus, of course, any system functionality, genetic inheritance, or species competition, for these are the value-added qualities of genuine biological evolution that go well beyond the evolution of physical systems. Sometimes such stellar changes are hard to grasp because the changes are so very slow and the times so very great.

Stars endure for periods that depend largely on their mass. None of the least massive stars (<0.5 $M_\odot$) could have existed for more than a single generation, since these slow-fusing stars would not have had time to move through their evolutionary paces even once; the old, red dwarfs in the globular clusters of our Milky Way are surely ancient, Population-II stars having relatively low (~1%) heavy-element abundances. By contrast, sunlike stars endure roughly for the full age of the Galaxy (~12 Gy), and some could well have formed early in its history, run out their entire ~10-Gy lifetime, and now be expired. Stars with >3 $M_\odot$ would have experienced well more than one generation since they last for ≤1 Gy; several generations of these bigger stars must have come and gone in the history of our Galaxy—as typified by the young, blue, Population-I stars having higher (~2%) heavy-element abundances. And stars with ≥10 $M_\odot$ that fuse for merely ≤50 My, must have participated in many generations of heavy-element-production. Statistically, within only the first 1 Gy of the Milky Way's history, all stars >5 $M_\odot$ had already scattered into interstellar space new elements produced by ~5×10^8 supernovae.

All 1st-generation, Population-III stars fused via the p^+-p^+ cycle; regardless of their mass, they had no heavy nuclei, hence had to use H exclusively. Once that initial generation of massive stars had run its course, their expelled heavies enriched galactic space where supernova concussions mixed the heavies with much loose H. Some of those newly formed stars with high enough T_c then began fusing via the more involved CNO cycle noted above. And given the way the CNO energy-generation physics operates, a 2nd-generation star of, say, 10 $M_\odot$, would fuse with a distinctly higher Φ_m value than any 1st-generation star that had no heavies and had to use the p^+-p^+ cycle regardless of its T_c. And as heavy-elements abundances increased over the course of generation upon generation of stars, Φ_m for enriched stars of given mass would also have necessarily increased. (In this way, the spectra of the youngest stars that show the most heavy elements enables researchers to estimate the ages of stars even when found isolated in space.) The result is that Nth-generation stars grow evermore complex with time. Our Sun, with its rich complement of heavies that could not have been produced within it, is a product of many such prior generations.

Given that stars are demonstrable energy (and entropy) converters, they thus represent relatively localized sites of growing complexity—first, because stars also *radiate* entropy (as well as energy) into their surrounding environment and, second, because the gravitational agents tending to enhance stellar gradients usually overwhelm the opposing, non-gravitational agents (like heat) tending to diminish them. In essence, stars are islands of increasing negentropy in a universal sea of rising chaos, and much like most other ordered structures, they obey, within a wide range and variation, the proposed criterion of energy rate density as a measure of order, flow, and complexity in the material world.

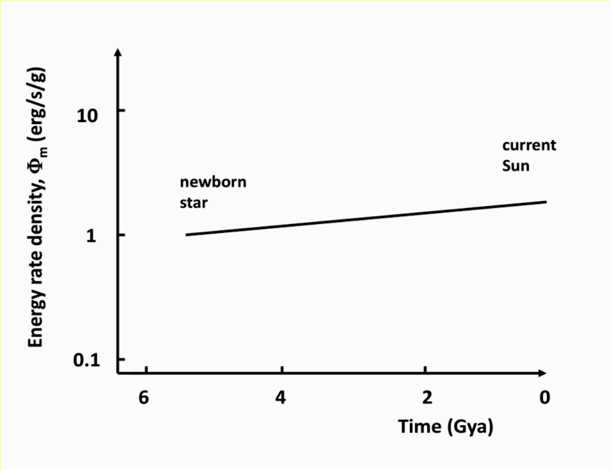
The figure below broadly summarizes our recent discussion about stars and their evolution. It includes values of Φ_m for a spectrum of complex systems, placing into perspective specifically the case of our Sun today. The dashed oval outlines the range of changes in Φ_m for the Sun over the past ~5 Gy. The bracket at right spans the full range of Φ_m for all known stars at various stages of the physical-evolutionary phase of cosmic evolution. All things considered, energy rate density is a useful way to quantify the rise of complexity during stellar evolution, much as done elsewhere in this work for other open, complex systems scattered all about Nature.



This graph repeats the essence of an earlier one (cf, end of Advanced Track for PARTICLE EPOCH), suggesting Φ_m as a measure of rising complexity over all historical time. The dashed oval includes the range of changes likely experienced by our Sun while evolving over the past ~5 Gy, and whose values of Φ_m are plotted in more detail in the next figure. All stars—

whether normal (main-sequence), dwarf, or giant, among others—range widely over the bottom-to-middle part of this graph; their Φ_m values reside within the wider range outlined by the bracket at right.

The next figure plots only the values of Φ_m as the Sun evolved over the course of the past ~5 Gy, from newborn star to the present day. This is just the range noted within the dashed oval of the previous figure.



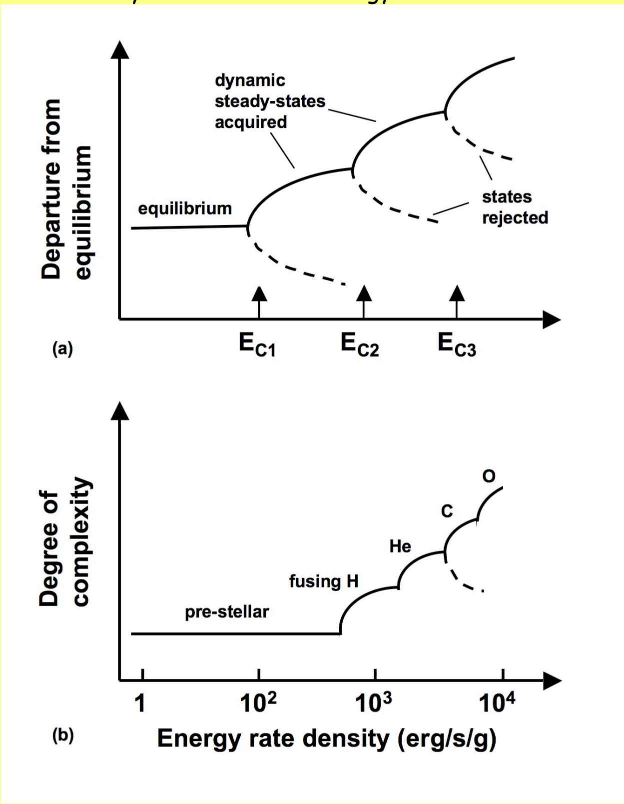
While on the main sequence, the Sun approximately quadrupled its luminosity and hence its energy rate density while steadily, yet extremely slowly, growing more complex, as noted above in the section on the Sun's Evolution (see also the graph two figures prior). What is shown here is only the change in Φ_m within the dashed oval of the previous figure.

Selection Among the Stars

The above arguments describe, at the least, developmental change within stellar evolution—the kind of change termed by some biologists (Mayr, *This is Biology*, Harvard U Pr, 1997) *transformational evolution*—mostly gradual (and occasionally episodic) alterations among objects quite apart from any generational selectivity. Mountains sprouting in response to tectonic forces, fertilized eggs developing into mature adults, and normal stars swelling to become red giants are all examples of transformational evolution. Virtually all changes in the inanimate Universe, among many also in the living world, are minimally of this kind.

Selection arguably works alongside the flow of resources into and out of all open systems, not just life forms. Moreover, systems of any degree of complexity seem selected partly for their ability to command energy. Energy flow and natural selection likely operate in tandem as systems evolve—the former utilized by those systems advantageously suited to their randomly changing environments, and the latter non-randomly eliminating those unable to do so. Conceivably, energy drives systems beyond equilibrium while selection aids the emergence of greater complexity for those systems able to manage the increased energy flow per unit mass. In other words, normalized energy flow rate may itself be the trait most often selected by successful systems of the same kind.

The following figure helps to visualize such an energy-selection mechanism at work, where part (a) depicts the general case of a system experiencing repeated opportunities to survive or terminate. Wherever and whenever optimum energy is available, systems capable of drawing power competitively, thereby building structures or functions able to utilize those energies, are favored; selection from among many energy-based choices rewards and nurtures dynamic steady-states that create pathways capable of optimizing power per unit mass. Those systems using energy either too much, too rapidly, too little or too slowly are rejected and destroyed—the former two cases because systems would burn, the latter two because they lack threshold energy.



Natural selection diagrams schematically illustrate how, at certain critical energies, labeled here variously E_C, systems can spontaneously change, or bifurcate (vertical arrows), into new, non-equilibrium, dynamic steady-states. Chance affects the opportunities that arise, but necessity determines which fork systems select, namely which structures and functions are acquired (solid, rising curve) and which become extinct (dashed curves), thus the result is inherently unpredictable as with all of evolution. Such energy-selection diagrams can be drawn for any physical, biological, or cultural system successfully able to adapt and take advantage of increased energy while further complexifying. (b) For the case of the 10-$M_\odot$ star noted earlier, its degree of complexity rises substantially while Φ_m increases and the star evolves through several fusion cycles (solid curves). By contrast, the Sun will never succeed in fusing much C, hence will never acquire enough Φ_m to become overly complex; it is destined to terminate and thus be naturally selected out of the population of stars (dashed curve).

Interpretations of such energy-selection diagrams are straightforward for living systems, such as plants that provide familiar examples of biological selection among a wide assortment of wondrous life forms adorning Nature. Here selection—that's genuine neo-Darwinism—is clearly at work, making use of energy rate densities well in excess of those for galaxies, stars, and planets. As sketched in part (a) of the above figure, energy-flow diagnostics display increased complexity for a variety of steady-states among plants that, following the solid curve, evade locally and temporarily the usual entropy process. As noted later in the Advanced Track for the BIOLOGICAL EPOCH, photosynthesis operates more effectively in flowering angiosperms than in gymnosperms and, in turn, even more effectively in more organized, cultivated (C_4) crops such as maize and sugarcane. Similar trends are also evident for animals, yet with typically even higher energy rate densities along a broad evolutionary sequence spanning prokaryotes, ectotherms, and endotherms. All this agrees with standard arguments in ecology that highly metabolizing opportunists enjoy advantages during periods of change.

It is worth stressing two probable, general guidelines governing the use of energy, not only for life forms but also apparently for all open, complex structures: Energy is likely a necessary, but not necessarily sufficient, condition for the growth, maintenance, and evolution of ordered systems—much as, for example, in the case of plant growth, CO_2 and H_2O are also needed. Furthermore, optimum ranges of energy use apparently exist for all ordered systems—as here for plants for which not too much, yet not too little, energy is required for photosynthesis, just as plants enjoy optimal ranges in heating and watering, lest they either desiccate or drown.

We need not dwell on the concept of selection operating throughout the bush of life, for the process is well accepted among biologists today. Yet, natural selection likely pertains to physical and cultural events as well—for whether stars, life or society as discussed throughout these Advanced Tracks, we encounter the same *general* trend found all across the living world: The greater the perceived complexity of the system, the greater the flow of energy density through that system—either to build it, or to maintain it, or both.

But is there any selection occurring among the stars—any non-random elimination, as argued in the Advanced Track for the BIOLOGICAL EPOCH to be the best interpretation of all natural selection in Nature? In short, is there any *differential evolution* for physical systems, akin to traditional neo-Darwinism whereby biological systems able to survive change are the ones best adapted to varying conditions? Perhaps there is, for only stars with sufficiently high values of Φ_m achieve states of substantial complexity; only those massive main-sequence stars having roughly $\Phi_m \geq 100$ erg/s/g manage to create considerable order in concentric nuclear layering, their internal step-wise functions of core contraction, enhanced heating, and renewed fusion resembling the general bifurcations of part (a) of the figure above, where the specific values in part (b) of that figure for a high-mass star are derived from the upper track of the previous H-R diagram for a 10-$M_\odot$ object. By contrast, our Sun, with $\Phi_m \approx 2$ erg/s/g currently, will in ~7 Gy never evolve beyond a rudimentary red giant and never become selected for much greater complexity. Its energy rate density will not likely ever reach those critical values needed for the natural emergence of greater stellar complexity. The Sun will eventually be non-randomly eliminated from its population of stars.

Much as for biological evolution among living species (*cf*, Advanced Track for BIOLOGICAL EPOCH), the process of selection, generally considered, also seems operative in the physical evolution of non-living systems (although selective pressures for the latter are likely partly internal and autocatalytic). Wherever energy flows are available, living systems develop in ways capable of drawing power competitively, and they build whatever structures are needed to optimally process those energies. Selection is a process that tends to reward a system for actions that are reinforced and retained. Similar processes pertain to inanimate objects, even in the absence of genetic replication. Whenever suitable energy flow is present, selection from among many energy-based choices rewards and nurtures those systems that engender pathways capable of drawing and utilizing more power per unit mass—up to a point beyond which too much power can destroy a system.

At least as regards ubiquitous energy flow, external environmental interaction, and internal structural modification while experiencing change, stars have much in common with life—provided that stars are examined broadly, dynamically, and over extremely long periods of time.

None of the above claims that stars are alive, nor do stars evolve in the strict and limited biological sense. Yet close parallels are apparent, including stellar populations, variations, adaptation, selection, and perhaps even a kind of crude replication among the stars—a generational activity—reminiscent of the following scenario that draws upon Darwin's Malthusian-inspired principle of natural selection—but here a more simplified physical selection minus the sophistication of biological evolution:

Galactic clouds spawn clusters of stars, only a few of which (the most massive ones unlike the Sun) enable other, subsequent groups of stars to emerge in turn, with each generation's offspring showing slight variations, especially among the heavy elements contained within. Waves of sequential star formation are observed (Elmegreen and Lada, *Astrophys J*, v214, p725, 1977) to propagate through many such interstellar clouds like slow-motion chain reactions over eons of time—shocks from the death of old stars triggering the birth of new ones—neither one kind of star displaying a dramatic increase in number nor the process of regeneration ever being perfect. Those massive stars selected by Nature to endure the heat needed to produce heavy elements are in fact the very same stars that often produce supernova blasts that then create new populations of stars, thereby episodically, gradually, and repeatedly enriching the interstellar medium with greater elemental complexity on timescales measured in millions of millennia. As always, the necessary though perhaps not sufficient conditions for the growth of complexity depend on the environmental circumstances and on the availability of energy flows in such (here, stellar) environments.

In Sum

On and on, the cycles churn; build up, break down, change. Stars adjust their states while evolving during one or more generations, their energy flows (per unit mass) and their Φ_m values rising while they complexify with time. In the case of the Sun:

- from early protostar ~5 Gya ($\Phi_m \approx 1$ erg/s/g)
- to the main-sequence Sun currently (~2)
- to subgiant status ~6 Gy in the future (~4)
- to aged red-giant near termination (~10^2).

Stellar interiors undergo cycles of nuclear fusion that foster greater thermal and chemical gradients, resulting in increasingly differentiated layers of heavy elements within highly evolved stars. Our Sun is the product of many such cycles. We ourselves are another. Without the elements synthesized in the hearts of stars, neither Earth nor the life it harbors would exist. Roughly speaking, low-mass stars are responsible for most of the C, N, and O that make life on Earth possible. High-mass stars produce the Fe and Si that comprise the bulk of Earth itself, as well as the heavier elements on which much of our technology is based.

Growing complexity can serve as an indicator of stellar aging—akin to developmental processes—allowing stars to be tracked on H-R diagrams, while their interiors undergo cycles of nuclear fusion, thereby causing them to change in size, color, brightness, and composition while passing from "birth" to "maturity" to "death." Complexity can also be seen over even longer times—akin to evolutionary processes—as stars change over many generations in space. Such changes slowly alter the structure of every star, including the Sun, which will eventually be selected out of the population of neighboring stars. At least as regards energy flow, material resources, and structural integrity while experiencing change, adaptation, and selection, stars have much in common with life.