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Psychosocial Implications of Stellar Evolution?

Reframing life's cycles through the Hertzsprung-Russell diagram

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Introduction

The suggestive use of metaphors -- like the "universe of knowledge", academic "stars", "luminaries" and "stellar" careers, "heated" debate, high "visibility", "massive" support, "weighty" argument -- points to the possible value of exploring whether astrophysics offers a coherent set of metaphors to explore various kinds of psychosocial life cycle.

Use is widely made of "brilliance", whether or not associated with "stellar" or "star" in some way. The implications are typically relatively simple -- as with recognition of celebrities with the phrase "***a star is born***", or with much admiration of the stars at night. The question here is whether the insights elaborated by astrophysics regarding the nature and life cycle of stars offer means of enriching their use as a metaphor. Cause for deeper reflection is the widely-cited quotation of astrophysicist Carl Sagan:

> The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.

As discussed separately (*Generative metaphor and policy-making*, 1995), in a key paper, Donald Schon (1979) argues that:

> ... the essential difficulties in social policy have more to do with problem setting than with problem solving, more to do with ways in which we frame the purposes to be achieved than with the selection of optimal means for achieving them." For Schön "the framing of problems often depends upon metaphors underlying the stories which generate problem setting and set the direction of problem solving. (*Generative Metaphor: a perspective on problem-setting in social policy*. In: A. Ortony (Ed.), *Metaphor and Thought*, 1979, pp. 254-284)

A "generative metaphor" offers figurative descriptions of social situations, usually implicit and even semi-conscious but that shape the way problems are tackled, for example seeing a troubled inner-city neighborhood as urban "blight" and, hence, taking steps rooted in the idea of disease. The approach has been developed by Frank J. Barrett and David L. Cooperrider (*Generative Metaphor Intervention: a new approach for working with systems divided by conflict and caught in defensive perception*, Appreciative Inquiry Commons, 2001).

A valuable summary of relevance to the following argument is offered by Jozef Keulartz (*Using Metaphors in Restoring Nature*, *Nature and Culture*, 2, 2007) of the European Network of Environmental Ethics:

> Metaphors perform important cognitive functions, operating as mechanisms for the translation of something abstract into something concrete and shedding light on new and unknown phenomena through familiar ones. In short, metaphors are heuristic devices crucial for creating and conceptualizing novel ideas and new knowledge. However, metaphors are not only important cognitive tools in making sense of the world but also important discursive tools that enable communication and negotiation with others throughout the world. Metaphors then are also diplomatic devices that facilitate interaction between different disciplines and discourses (Hellsten 2002)....
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> Once it is acknowledged that the use of metaphor is inescapable and indispensable, however, we are confronted with the problem of the sheer multiplicity of metaphors. With respect to nature, Daniel J. Philippon (2004) has provided us with an extensive, although not exhaustive, list of metaphors for nature. Nature can be compared to a particular place (frontier, garden, park,

> wilderness, utopia), to a friend or family member (self, mother, father, sister, brother, wife, husband, partner), an actor (god or goddess, minister, monarch, lawyer, selective breeder, enemy), a network (web, community, tapestry), a machine (clock, engine, computer, spaceship), a state of being (virgin, harmony, balance), a mode of communication (book), a built object (bank, sink,storehouse, pharmacy, lifeboat, home), or to a contested landscape (battlefield, commons) (Philippon, 2004; see Harré et al., 1999)....
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> Taken together, the cognitive, discursive, and normative functions of metaphors determine our attitude towards entities in the world. Thus, for example, people who see nature as a divine text will be more likely to adopt a passive rather than an active attitude towards nature, while those who look at nature as a machine might stress our possibilities to control, command, and correct nature.

The approach taken here is first to note some distinct domains in which "brilliance" is recognized. **Some have been explored in other documents on this site, as noted below** (whose arguments have been partially reassembled here for convenience). The argument then introduces the Hertzsprung-Russell diagram. This is a basic mapping of the life cycle of stars, including their eventual demise. Commentary is then provided below on some details of this "map", and the variety of stars -- represented at different stage there during the course of stellar evolution.

The commentary itself is only presented in terms of the life cycle of communities as but one of the domains in which "brilliance" may be recognized and appreciated. The metaphor is explored there in italicized text to accompany the conventional description of the astrophysical case. With respect to other domains, that italicized description then needs to be interpreted in terms of the nature of those domains -- as suggested by the preceding references to them.

Living in the light of stellar metaphors of brilliance

Reference to the metaphor stellar evolution and the Hertzsprung-Russell diagram has been made in the following distinct contexts which each refer to the more articulated description which follows below:

- *Dynamically Gated Conceptual Communities: emergent patterns of isolation within knowledge society* (2004), in a section on *Astrophysical metaphor for evolution of gated conceptual communities*. The relevance could be extended to other collective initiatives, inten tional communities and groups
- *Going Nowhere through Not-knowing Where to Go: sustaining the process of autopoiesis through point-making* (2013), in a section on *Point-making and identity in the light of stellar evolution*
- *Towards an Astrophysics of the Knowledge Universe: from astronautics to noonautics?* (2006), in a section on *Cognitive engagement*
- *Being the Universe : a Metaphoric Frontier Co-existent Immanence of Evolutionary Phases* (1999), in a section on *Stellar evolution*
- *Openness and Closure in Pattern Language: Geometry versus Resonance* (2012), in a section on *Focus on the brightest "stars" and stellar evolution*
- *Present Moment Research: exploration of nowness* (2001) in a section on *Conceptual evolution in the "space-time" of knowledge space*

Evolution of gated conceptual communities in the light of stellar evolution (as discussed in *Dynamically Gated Conceptual Communities: emergent patterns of isolation within knowledge society*, 2004):

The appropriateness of the metaphor derives from what might be termed the physics of communication amongst the "stars" of the knowledge firmament -- and the limited number of parameters by which this could be modelled: interactivity of participants (temperature?), visibility (luminosity?), membership/connectivity (mass?), insight/inspiration/curiosity (hydrogen?), weight of facts/tradition/confirmation (gravity?).

Use of the metaphor is discussed more extensively below as a template through which the following alternative uses may be explored.

Point-making and identity in the light of stellar evolution (as discussed in *Going Nowhere through Not-knowing Where to Go: sustaining the process of autopoiesis through point-making*, 2013)**:**

Why are "light" and "brilliance" such acceptable metaphors in communication processes and the appreciation of insight? Why are celebrities in many domains termed "stars"? Why the preoccupation with "visibility" in the promotion of people and initiatives? Why the value and meaning attached to "enlightenment"? Why the ambiguity and concern relating to the "dark" (*Enlightening Endarkenment: selected web resources on the challenge to comprehension*, 2005).

Conscious life in the light of stellar evolution (as discussed in *Towards an Astrophysics of the Knowledge Universe: from astronautics to noonautics?* 2006):

How does the array of relatively simple reactions sustain the complexity and coherence of a sun? Can consciousness be understood in terms of the patterns of solar reactions through which light and heat are generated for mundane life -- in the light of *Cybernetics and Human Knowing* (*A Journal of Second Order Cybernetics, Autopoiesis and Cyber-Semiotics*) ? What then is to be understood by hydrogen and helium?

In the further course of evolution, the star may become unstable, possibly ejecting some of its mass and becoming an exploding nova or supernova or a pulsating variable star. The end phase of a star depends on its mass. A low-mass star may become a white dwarf; an intermediate-mass star may become a neutron star; and a high-mass star may undergo complete gravitational collapse and become a black hole. Are some of these patterns not reminiscent of the possible final stages of life of media personalities -- especially movie "stars", but also the geniuses of our era?

Conceptual evolution in the "space-time" of knowledge space (as discussed in *Present Moment Research: exploration of nowness*, 2001):

Consideration could be given to combining the processes implicit in metaphors explored above into what amounts to an understanding of conceptual evolution in the "space-time" of knowledge space? This might be mapped by some equivalent to the astrophysicists Hertzsprung-Russell diagram -- which indicates the evolutionary pathway of stars in terms of changing mass and luminosity. What is required is a sense of the evolution of conceptual attractors in knowledge space in terms of the attraction they exert and their visibility. With respect to fascination with the origin of the physical universe, it is especially intriguing in this context to consider how analogues to its first "3 seconds" may be a characteristic of the subjective sense of the present moment.

From this perspective there are cognitive processes in the first fractions of a second of attention that continually form the universe that is then open to subsequent experience as fully made. How does "the future" relate to the space-time of cognitive space? The seemingly esoteric debates about whether the universe started with a Big Bang may be explored for their systemic significance as patterns to moment-by-moment creativity, as well as to cell division. The process of concept formation at the moment of creativity, or of cell division after conception, have structural similarities to insights into universe formation.

There may be a way in which the coherence of the moment may be experienced as a kind of standing wave phenomenon. Analogues to the formation of "heavy atoms" may be detected as the creative process meshes with reality -- suggesting a kind of periodic table of creative insight. This would help to explain the ability of traditional cultures to generate cosmologies through which their reality is structured. In particular it clarifies the perspective from which, as noted by Diana James, Australian Aboriginal cultures are able to live in a continuous present that is intimately associated with a mythical Dreamtime.

Focus on the brightest "stars" and stellar evolution (as discussed in *Openness and Closure in Pattern Language: Geometry versus Resonance*, 2012):

In contrast with insights mined from the preoccupations of fundamental physics (with the very small and short-lived), there is an irony in this respect to the significance of those borrowed from the very large and long-lived, namely from astrophysics (*Towards an Astrophysics of the Knowledge Universe? from astronautics to noonautics*, 2006).

Whether in strategic gatherings, or in gatherings of physicists, "stars" are a focus of attention -- especially the "brightest". Some topics could be said to be avoided like "black holes" or "dark matter". The "gravity" of their pronouncements may be felt -- recalling the origin of the term in *gravitas*. As noted above, the temperature of discourse may be significant -- especially in "heated" exchanges. It is of course the case that "stars" may be recognized as exploding upon the scene like supernova, whilst the visibility of others may diminish over time, perhaps imploding and becoming spent -- as with any "model", beauteous and elegant, or otherwise.

Efforts to formulate a Theory of Everything -- through such gatherings -- would treat any psychosocial processes as totally irrelevant, despite their role in the recognition of Nobel laureates. Astrophysics frames the physical processes in terms of the Hertzsprung-Russell diagram. -- a major step towards an understanding of stellar evolution or "the lives of stars". A corresponding insight is offered into the "careers" of concepts, within the strategic universe of the United Nations, by Johan Galtung (*Processes in the UN system*, 1980), as quoted separately with respect to *Meaningful opportunities and the movement of meaning* (1988):

- a fresh concept is co-opted into the system from the outside... The concept is broad, unspecified, full of promises because of its (as yet) virgin character, capable of instilling some enthusiasm in people who do not suffer too much from a feeling of dé-vu having been through a number of concept life cycles already....
- the organization receives the concept and it is built into preambles of resolutions; drafters and secretaries get dexterity in handling it.... The concept thus moves from birth via adolescence to maturity, meaning that it has been changed sufficiently to become structure and culture compatible....
- from maturity to senescence and death is but a short step: the concept thus emasculated can no longer serve the purpose of renewal as what was new has largely been taken a away and what was old has been added in its place - except, possibly, the term itself....
- a fresh concept is co-opted into the system from the outside, e.g. one that has already been through its life cycle in another part of the UN system. For the rest read the story once more.

If such a strategic concept is understood to be a "point" in knowledge space, mixing metaphors in the light of Galtung's comment, it might be asked whether attention should be given to the "half-life" of any strategic point -- especially those recognized as "hot topics". The question also relates to the extensive research on anomalies by Charles Fort, widely quoted to the effect that: *I conceive of nothing, in religion, science or philosophy, that is more than the proper thing to wear, for a while.*

Hertzsprung-Russell Diagram as a generative metaphor

A good point of departure is the famed Hertzsprung-Russell Diagram, pioneered independently by Elnar Hertzsprung (1911) and Henry Norris Russell (1913). It is recognized as one of the greatest observational syntheses in astronomy and astrophysics. The diagram plots the luminosity of stars as a function of their temperature. The luminosity, or absolute magnitude, increases upwards on the vertical axis; the temperature (or some temperature-dependent characteristic such as spectral class or color) decreases to the right on the horizontal axis. From this it is readily apparent that stars preferentially fall into certain regions of the diagram along a curving diagonal line called the "main sequence", although there are other regions where other types of stars (red giants, supergiants, white dwarfs, super novae, pulsars, flare stars) also fall [more].

The suggestion is that conceptually gated communities (and various kinds of social group) emerge and live out their lives in a way that could be represented on an analogous diagram. In public relations terms, there is already a familiarity with the visibility of a group (its "luminosity") and a sense of whether it is "hot" or "cool". The analogue to temperature may be more meaningfully understood as degree of communication interactivity amongst members of the community -- especially since temperature is associated with interactivity between atoms. Following from work of B W Tuckman (*Developmental Sequence in Small Groups*, 1963) the stages of Forming / Storming / Norming / Performing (see also R B Lacoursiere. T*he Life Cycle of Groups: Group Developmental Stage Theory*, 1980; Stan Davis, *The Life Cycle of Organizations*, 1990). A sense of the knowledge exchange processes is usefully explored by Martha G. Russell and Kaisa Still (*Engines Driving Knowledge-based Technology Transfer in Business Incubators and Their Companies*, 1999).

In the case of religious groups, the life cycle has for example been characterized by David Moberg (*The Church as Social Institution*, 1984) in phases:

1. Energy, charisma, community, fluidity, no tradition and few rules;
2. Comes as the pioneers are dying out or moving on, accompanied by appeals from the second generation ("help us preserve the past"; "write things down"; "train us to do what you have done"; "let us build in some structures to make sure nothing changes");
3. Good or bad, with renewal or fossilization. Either the spirit of the original movement wins or the rules and the structure win. Either the life is renewed and flows through the structures, or the structures stifle the life. [more]

Seemingly analogous to the H-R diagram, Lawrence Cada et al. (*Shaping the Coming Age of Religious Life*, 1979), identified a "vitality curve" in the light of a historical study of the life cycle of religious institutions. As discussed by Mary V. Maher (*Between Imagination and Doubt: Religious Life in Postmodern Culture*, 2003), Cada distinguishes five separate stages of a religious movement's history:

1. Founding: usually by a strong and visionary leader who has been forced out or has chosen to leave a comfortable mainline institution.
2. Expansion: how far and how fast depends on the culture and the historical situation. This phase usually has two ingredients: a passionate sense of the vision of the founder; and endless energy to communicate that vision.
3. Stabilization or settled-downness: the movement becomes affirmed by society and is legitimatized as mainstream.
4. Breakdown of the structures and systems that the founder had brought forth and that had worked during the expansion phase: This is a time of fervent activity to "fix" the problem, through new structures, systems, and regulations. It is a time of increased polarization between those who want to return literally to the founder's words and policies and those who want to translate them into new realities. Bureaucratic survival of agencies and their leaders means that more financial demands are placed on individual members and congregations, but standards of belief and behavior are lessened. Hence, a loss of attachment to the institution and loss of a sense of connectedness. Most important of all, there is a loss of identity and loss of a sense of a future. Change becomes unbearable for many.
5. Crisis: this has two possible paths: continued decline, paralysis, and eventual demise; or re-founding through transformation. Change and transformation are not the same. Change is reaction to cultural realities and happens at a point in time. Transformation happens intentionally over time. Change comes from broken functions and structures. Transformation begins at the center of a movement's collective soul. Mere change can be only directionless motion and energy. Transformation re-forms. [more]

Stellar evolution as a generative metaphor

As noted by Tim Thompson: "*A star is not a static thing, it changes with time. The process of aging in stars is called stellar evolution. As a star ages, it goes through changes reminiscent of the life cycles of living things, the details of which depend on the star's overall mass. Massive stars live short but exciting lives, whereas small stars live long, quiescent lives.*" [more]

The H-R diagram is considered to be a useful way to follow the changes that take place as a star evolves [more]. Its regularity is an indication that definite laws govern stellar structure and stellar evolution. Building mathematical models of stars, based on straight forward physics, and allowing those models to evolve naturally in time as a star ages, recreates the H-R diagram as it is observed -- with a surprising degree of fidelity of agreement between theory and observation that is of great interest in astrophysics. The ability of the theory of stellar evolution to explain the H-R diagram in its finest details, singles out stellar evolution as one of the most successful and productive of scientific theories. Most stars lie on the main sequence, burning hydrogen to helium through nuclear reactions. As they live out their lives, changes in the structure of the star are reflected in changes in stars' temperatures, sizes and luminosities -- causing them to move in tracks across the diagram.

Is there a case for recognizing that the life of community is determined by the rate at which its initial unifying and energizing inspiration (with a propensity to enter successfully into explanatory bonds) is converted into a polarized and essentially neutral or sterile perspective? Are such possibilities suggested by explorations such as that of Ilanit Tof (*Modern Cosmology as Psychological Metaphor*, 1996)?

Stellar evolution is not studied by observing the life cycle of a single star; rather, by observing numerous stars, each at a different point in its life cycle, and running computer models that simulate stellar structure. Following the Wikipedia description of such evolution, phases to be distinguished are:

Giant molecular interstellar cloud: This initial stage is distinguished by its very low density and large size. *It might usefully be equated to some movements of opinion in their very first phases.* The cloud is stable, its constituent molecules being too widely spaced for gravity to draw them closer

Protostar: The next stage results when the cloud is destabilized, such as by a supernova sending out a shockwave of successive compression and rarefaction (analogous to a soundwave travelling through air), knots of matter are formed -- cores of greater density. *Diffuse movements of opinion may similarly be stimulated to coalesce -- such as by shocks like 9/11.* When the density exceeds a certain threshold, gravity takes over, and the region begins to collapse into a protostar (each dense core producing anywhere from 1 protostar to tens of thousands). *As exchanges increase, between those attracted to the particular perspective, the force of attraction increases -- a centre of gravity effectively becomes defined.* The atoms gain speed in their fall toward the center, providing the protostar with heat (heat is defined as particle motion), a weak infrared glow, and rotation. *The movement transforms into a loose organization, exchanges may become heated, the community becomes faintly visible, and its members may be understood as acquiring orientation.* The lowest mass stars are classified as red dwarf stars, but even red dwarfs are massive enough to trigger hydrogen fusion in their cores to sustain their feeble starlight. If the collapse of the fragmenting interstellar cloud results in an object of less than about 0.08 solar masses, the central temperature and density of the protostar will never get high enough that hydrogen fusion can take place in a sustained, controlled manner. Such an object is a brown dwarf. These can shine only briefly as their central temperatures are too low to utilize hydrogen as nuclear fuel. Contraction remains the only source of energy; they die away slowly, over hundreds of billions of years. As it collapses, the brown dwarf will shine because it converts its gravitational energy through contraction into luminosity -- being heated by gravitational contraction up to 15 million degrees Kelvin, stripping the electrons from their parent atoms, creating a plasma.

Maturity: A new star emerges at a specific point on the main sequence of the H-R diagram. New stars come in a variety of sizes and colors. Stars range from blue to red, from less than half the size of our Sun to over 20 times its size. The brightness and color of a star depend on its surface temperature, which depends on its mass. *According to its nature and size, a conceptually gated community may also be understood as emerging at a specific point in a "main sequence". The community may even be distinguished by "colour": blue, red, green, brown, black (as explored in the UNU GPID project).* The star will rest there for a period of years: millions (for the biggest and hottest stars); billions (for mid-sized stars like the Sun); tens or hundreds of billions (for red dwarfs). During this time it expends most of the hydrogen in its core. Eventually the supply of hydrogen runs out and the star enters a new phase of its life. *The community may remain in the "main sequence" for an extensive period of time, until its supply of "inspiration" and "vision" runs out and it enters a new phase of existence.* During this period of maturity the star's existence is a tug of war between gravity, which wants to crush the star into a point, and the fusion going on inside, which wants to explode the star and send pieces of it hurtling through the universe. *For the community, this period of existence is a tug of war between the force pulling the community into a one-pointed "integral" or "unified" perspective (most evident in the case of fundamentalism) and the tendency to explode throughout society (again most evident in the missionary impulse of religious and ideological groups).*

Beginning of the end: Once the supply of hydrogen in the star's core is depleted, nuclear processes there cease. *A conceptually gated community is also faced with the prospect of cessation of the core processes sustained by its inspiration.* Without the outward pressure generated by these reactions to counteract the force of gravity, the outer layers of the star begin to collapse inward, toward the core. *The community then tends to collapse in upon itself -- it becomes increasingly inward looking.* The temperature and pressure increase as during formation, but now to even higher levels, until helium fusion begins. *During the process of collapse of a community the dynamics become increasingly heated -- associated with furious increase in self-righteousness, self-justification and pressures to conform.* The newly generated heat temporarily counteracts the force of gravity, and the outer layers of the star are now pushed outward; the star becomes as much as 100 times larger than it ever was during its maturity. It is now a red giant. The mass has not increased, so its density is much lower (except in the inner core, where the density is higher than during the hydrogen fusion phase). *In the case of a community, this might be understood as a final missionary phase through which adherents are widely dispersed outward from its headquarters.*

End of stellar lifecycle: The final phases of stellar evolution depend on the star's mass. *Similarly the final phases of evolution of a conceptually gated community depend on the extent to which it is mass movement. Is there a degree of equivalence to be found with the pattern of social collapse identified by Jared Diamond.* (*Collapse: How Societies Choose to Fail or Succeed*, 2004)?

- **Low mass stars**:
  - **Red dwarfs**: A star with less than about half a solar mass will never be able to fuse helium, even after the core ceases hydrogen fusion. There simply isn't a stellar envelope massive enough to bear down enough pressure on the core. These red dwarf stars which live for hundreds of billions of years. When nuclear reactions eventually ceases in their cores, they will continue to glow weakly in the infrared and microwave part of the spectrum for many billions of years. The lowest mass stars are classified as red dwarf stars, but even red dwarfs are massive enough to trigger hydrogen fusion in their cores to sustain their feeble starlight.
  - **Brown dwarfs**: Slightly less massive objects, known as brown dwarfs, can shine only briefly as their central temperatures are too low to utilize hydrogen as nuclear fuel. In the case of a brown dwarf, as contraction continues, the speed of the atomic nuclei eventually becomes great enough to overcome the electrical repulsion keeping them apart and nuclear fusion occurs [more]. Eventually, its collapse will be halted by electron degeneracy.
  - **Black dwarfs**: Because it has no additional sources of energy, the brown dwarf will continue to radiate its internal heat until it fades out of view to become a black dwarf. A black dwarf is the remains of a Sun-sized star which has evolved to a white dwarf and subsequently cooled down such that it no longer gives out radiation. White dwarfs are so dim because they are small and not because they are cool. A more appropriate name for white dwarfs is degenerate dwarf. None exist in the universe, as the time taken for a white dwarf to cool to such a degree is longer than the lifespan of the universe to date.
- **Medium mass stars**:
  - **Red giant**: Once a medium-size star (0.4 to 3.4 times the mass of our Sun) has reached the red giant phase, its outer layers continue to expand, the core contracts inward, and core-dwelling helium atoms fuse into carbon. The fusion releases energy, granting the star a temporary reprieve. In a Sun-sized star, this process will take approximately one billion years. The atomic structure of carbon is too strong to be further compressed by the mass of the surrounding material. No more fusion can happen. The core is stabilized and the end is near. The star now begins to shed its outer layers as a diffuse cloud called a planetary nebula.
  - **White dwarf**: Eventually, only about 20% of the star's initial mass remains and it spends the rest of its days cooling and shrinking until it is only a few thousand miles in diameter. The star has become a white dwarf. White dwarfs are stable

because the inward pull of gravity is balanced by the degeneracy pressure of the star's electrons. (This should not be confused with the electrical repulsion of electrons, but is a consequence of the Pauli exclusion principle.). No white dwarf more massive than 1.4 solar masses can exist; electron degeneracy pressure isn't strong enough. Consider what we know about novae: Matter is accreted around and onto a white dwarf until it gets hot enough to fuse, and fuses explosively. If the white dwarf's mass is tipped over the Chandrasekhar limit (1.4 solar masses; named for the physicist who discovered it) then electron degeneracy pressure fails and the star collapses. This causes the white dwarf to be blasted clean apart in a supernova event known as a type-I supernova. These supernovae may be many times more powerful than the death of a massive star (a type-II supernova).

  - **Black dwarfs**: With no fuel left to burn, the white dwarf radiates its remaining heat into icy space for many millions of years. In the end, there is just a cold dark mass sometimes called a black dwarf. The universe is not old enough for any black dwarf stars to exist.

- **Massive stars**:
  - **Red supergiants**: Fate has something very different -- and very dramatic -- in store for stars more than 5 times as massive as our Sun. After the outer layers of the star have swollen into a red supergiant (a very big red giant), the core begins to yield to gravity and starts to shrink. As it shrinks, it grows hotter and denser, and a new series of nuclear reactions begins to occur, creating and expending progressively heavier elements, temporarily halting the collapse of the core. Eventually, several more stops down the periodic table, silicon fuses to iron-56. Until now, the star has been maintained by these energy-liberating fusion reactions, but iron cannot fuse.
  - **Supernova**: There is suddenly no energy outflow to counteract the enormous force of gravity, and the star collapses. What happens next is not clearly understood. But whatever it is can cause a supernova explosion in less than a fraction of a second, one of the most spectacular displays of power in the Universe. The accompanying surge of neutrinos starts a shock wave, while the continuing jets of neutrinos blast much of the star's accumulated material -- the so-called seed elements, lighter than and including iron -- into space. As some of the escaping mass is bombarded by the neutrinos, its atoms capture them, creating a spectrum of heavier-than-iron material including the radioactive elements up to uranium. Without supernovae, no elements heavier than iron would exist. The shock wave and jets of neutrinos continue to propel the material away from the dying star, off into interstellar space. Then, streaming through space, the material from the supernova may collide with other cosmic debris, perhaps to form new stars, or planets and moons, or to serve as raw materials for a vast variety of living things. So what, if anything, remains of the core of the original star? Because we do not have a good understanding of the actual explosion mechanism, it's not entirely clear.
  - **Neutron stars**: But it is known that in some supernovae, the intense gravity inside the supergiant forces the electrons into the atomic nuclei, where they combine with the protons to form neutrons. The electromagnetic forces keeping separate nuclei apart are gone (proportionally, if nuclei were the size of dust motes, atoms would be as large as football stadiums), and the entire core of the star becomes nothing but a dense ball of contiguous neutrons, a single atomic nucleus the size of Manhattan. This is a neutron star. It is still an open question whether or not all supernovae do form neutron stars, however. It is believed that if the stellar mass is high enough, the neutrons themselves will be crushed and the star will collapse until its radius is smaller than the Schwarzschild radius and it becomes a black hole. However, our understanding of stellar collapse is not good enough to tell us whether it is possible to collapse directly to a black hole without a supernova, if there are supernovae which then form black holes, or what the exact relationship is between the initial mass of the star and the final object that remains.

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