Advanced Track, Epoch 2

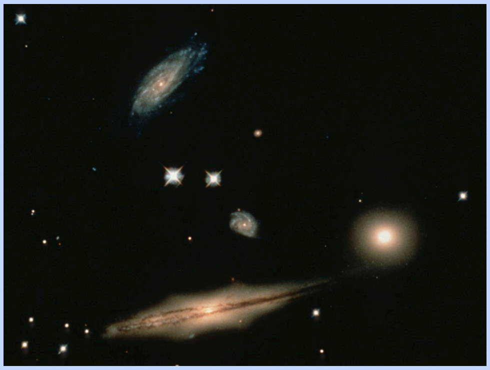
Galactic Evolution

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 downloadable at:
http://www.cfa.harvard.edu/~ejchaisson/current_research.pdf



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Cosmic Evolution

Galactic 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 second, galactic epoch, energy rate density, $\Phi_m \approx 0.01$ - 50 erg/s/g, as some of the first organized structures began emerging in the Universe.

Temporal Sequence

The proposed sequence of events in cosmic evolution—mainly galaxies, stars, planets, and life—holds as a *general* ordering of major activities across the arrow of time, from big bang to humankind. This temporal sequence pertains cleanly and clearly to those systems that gave rise specifically to us—namely, in turn, the Milky Way, then the Sun, followed by Earth, and most recently humanity—and which is thus of limited interest to "big historians." More expansively and of general interest to "cosmic evolutionists," this sequencing displays some overlap in space and time throughout the Universe that is inherently messy.

Galaxies and stars might have emerged simultaneously ("coevolved"); some of the oldest globular star clusters ("Population-II" and ~12 Gy old) are virtually as old as their parent galaxies. Conceivably, some "first stars" ("Population-III") might have preceded the galaxies, possibly becoming the building blocks of those galaxies. But in the main, since galaxies largely stopped originating (for reasons unknown) in the relatively early Universe, and since stars ("Population-I") have continued to form ever since, the epoch of galaxy formation must have mostly preceded the epoch of star formation; the stars we see today almost surely originated only after the bulk of the galaxies had taken shape.

Since the primordial "first stars" would have had pristine blends of H and He and no heavier elements, they must have been very much more massive than any stars existing today, hence very much shorter lived than any stars now known. Such pure gas, lacking in C and O that normally help clouds to cool and condense, would have needed more mass to contract than stars typically now, >10 Gy after the bang. Without those heavy-element cooling agents, the earliest protostars would have retained much of their heat from contraction, thus been unable to continue becoming genuine stars unless they accumulated more mass than stars typically do today. How much more is unknown, but if Pop-III stars really did exist, they must have contained hundreds of solar masses. No such colossal stars are seen today, the most massive star ever definitively "weighed" being ~76 $M_{\odot}$. (Repeated claims of discoveries for stars >100 $M_{\odot}$ have in all cases been shown, under higher angular resolution, to be clusters of smaller stars.)

Modern cosmology contends that the dark matter dominating galactic halos, which is typically ~6X more massive than the combination of stars, gas, and dust within the luminous parts of galaxies, is non-baryonic. Furthermore, roughly spherical accumulations of dark matter likely helped initiate galaxy formation by gravitationally trapping H gas, which is then further concentrated by dissipative interactions and angular-momentum conservation into flattened, spinning disks where most star formation has occurred during the past ~10 Gy. Both Pop-II and Pop-III stars likely formed before most galaxies had developed into less spherical and more elongated disks where nearly all Pop-I stars form today (though all three of these stellar populations may well have had some coterminous overlap). Thus far, there is no observational evidence for any stars forming earlier than the protogalaxies of mass ~ 10^{6-8} $M_{\odot}$; in fact, no evidence yet for any Pop-III stars containing zero heavy elements. On the whole, observational evidence supports the contention that the bulk of most galaxies formed prior to the formation of most (perhaps all) stars—in other words, the bulk of most galaxies had originated within the first 1-2 Gy, well before star formation began in earnest ~4-5 Gy after the big bang.

Consequently, some stars (the very earliest ones formed) likely existed during the early galaxy epoch, just as galaxies exist in the following stellar epoch; the grand epochs of the cosmos do not have hard-and-fast stops and well-defined starts. Some overlap is inevitable. Much as the later natural-history periods known as the "age of reptiles" contained mammals and the subsequent "age of mammals" also contained reptiles, the cosmic epochs in this work contain a variety of objects. The seven epochs delineated here are meant to identify the dominantly complex objects likely originating at any given time. It is in that sense, knowing that galaxy origins came forth during the first few Gy in the history of the Universe and then star formation peaked a few Gy thereafter, that we take the Galactic Epoch to precede the Stellar Epoch. Think of it as chronological bookkeeping—an attempt to impart some order and organization to the meandering sequence of events that brought forth, in turn, every known type of complex object in Nature writ large.

Chance and Necessity

Chance is surely a factor throughout all aspects of cosmic evolution. Although we now know that chance cannot be the sole instrument of change in the Universe, chance does play an integral role across the arrow of time. Even as long ago as 1692, Newton reasoned that a uniform, static cloud of gas will, naturally and of its own accord, randomly develop inhomogeneities here and there. Einstein's relativity supports this tendency of a uniform gas to fragment, even if expanding. (Einstein also though that chance played little role in Nature, but we simply think he was wrong.)

Solely by chance, a cloud's matter will spawn gravitational fluctuations that become the seeds for bigger things; in the early primordial gas clouds, this type of change likely led to the galaxies themselves. Such random fluctuations obey well-understood statistical laws, one of which states that the magnitude of fluctuations goes like $N^{1/2}$, where N is the average number of gas particles in a system. Thus, if the system in question is a galaxy, wherein the member atoms typically number 10^{68}, then random fluctuations house, at any given time or place, ~10^{34} atoms. And the fractional fluctuation, $N^{1/2}/N$, equals a minute 10^{-34}, which is far too small for density inhomogeneities to have grown into full-fledged galaxies within the age of the Universe. Alternatively stated, if the total number of atoms (~10^{68}) required to fashion a typical galaxy is to be accumulated exclusively by random encounters of gas particles, then we face a serious problem: A chance gathering of such a vast quantity of atoms would take several tens of billions of years, implying that few, if any, such galaxies should now exist in a Universe ~14 Gy old. The observational evidence that galaxies do in fact exist, and richly so in every direction sampled, strongly implies that chance could not have been the only factor governing the origin of these magnificent cosmic systems.

In addition to random chance that initially triggered matter fluctuations within primordial clouds, deterministic gravity also played a role in their subsequent fragmentation. Furthermore, other agents, including turbulence and shocks, and especially dark matter, likely accelerated the growth of the inhomogeneities so that myriad galaxies could have formed within a time scale shorter than the age of the Universe. In fact, the enhancement process (which is now thought to have been caused mostly by dark matter) must have been highly efficient since observations strongly imply that the bulk of all galaxies is old and thus the essence of their being originated long ago.

Galaxy-Formation Problem

Galaxy formation is not well understood; theories abound but data are crude (Peebles and Nusser, *Nature*, v465, p565, 2010). Almost all galaxies are dim and distant, and research regarding their origin and evolution remains tentative. Unlike most stars seen today, the bulk of each galaxy likely emerged long ago in time, thus far away in space now, hence their formative stages are observationally elusive—it's hard to observe and study them well. Furthermore, their evolution is strongly influenced by environmental mergers and acquisitions as galaxies collide often within their parent galaxy clusters.

Several decades ago, observations implied that virtually all galaxies are uniformly old; each seemed to have originated by means of fast (<1 Gy) monolithic events that caused the dissipative collapse of massively primordial (>10^{12} $M_{\odot}$; ~90% H, 9% He) protogalaxies in the first few Gy of the Universe (Eggen, Lynden-Bell and Sandage, *Ap J*, v136, p748, 1962). Theories, however, could not account for the rapid assembly of such huge systems; even aided by the gravity, chance alone cannot collect ~10^{68} atoms to form even a single galaxy in the entire age of the Universe, and accelerants in the earlier Universe could not then be discerned to enhance the origin of galaxies. We now also know that the Milky Way's halo harbors distinctly different populations of stars within old (>10 Gy) globular clusters, implying that galaxy construction was not likely a singular, ancient event (West, *et al, Nature*, v427, p31, 2004).

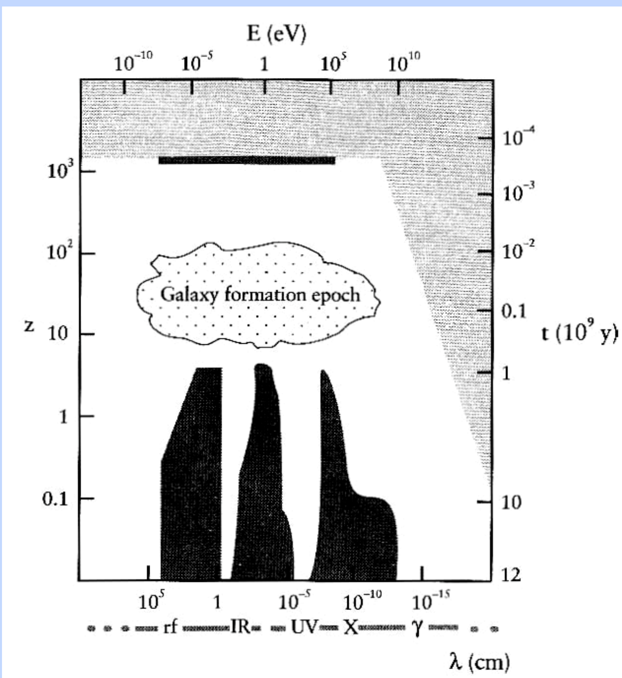
By contrast, shifting views have more recently proposed that galaxies originated much more slowly as part of a gradual, prolonged buildup over many Gy, indeed that they are now mostly still forming; hierarchical-merger scenarios became popular over the past 20 years, whereby normal galaxies were then theorized to assemble when smaller building blocks (~$10^{6\text{-}9}$ $M_{\odot}$ typical of dwarf galaxies) collided and merged frequently (Searle and Zinn, *Ap J*, v225, p357, 1978; Blumenthal, *et al, Nature*, v311, p517, 1984) while also perhaps accreting globular clusters and cold intergalactic gas (Dekel, *et al*, *Nature*, v457, p451, 2009). Current observations are generally consistent with this hierarchical model, as young galactic fragments at great distances often appear smaller in size and more irregular in shape than nearby, present-day counterparts.

However, the most recent findings (Mobasher *et al*, *Ap J*, v635, p832, 2005; Collins *et al, Nature*, v458, p603, 2009; Wirth, *Nature*, v430, p149, 2004; Marchesini *et al*, *Ap J*, in press, 2010) temper this scenario, reporting that many distant galaxies are already large, robust, and nearly fully formed, prompting a partial retreat to the original ideas that the bulk of each galaxy (>90% of its present being) formed quickly within the first few Gy—not necessarily by top-down collapse of a single, huge gravitating system, rather more likely by rapid bottom-up collection of many smaller ones. Emergence of the latter (each of ~$10^{6\text{-}9}$ $M_{\odot}$) are now suspected to have been aided by mostly dark matter that began as tiny quantum fluctuations in the very early Universe (~10^{-32} s), now seen imprinted as slight density inhomogeneities on maps of the 3-K cosmic microwave background radiation emitted ~400 ky after the big bang (Peebles and Nusser, *Nature*, v465, p565, 2010; Spergel *et al*, *Ap J*, v170, pS377, 2007; Busa, *Science*, v287, p69, 2000).

Such hierarchical construction events might still be underway today as a kind of evolutionary process (see next section below) that continues well after the foremost galaxy-building events began. Reality may also be somewhere in between these two grand ideas—such as the prospect, now favored in the astronomical community, that the inner core and bulge of galaxies per se formed rapidly early on, after which the major galaxies grew by accreting dwarf galaxies into their outer halos.

Only further observations will sort out the sordid details of these elusive galaxy-formation events. To date, those observations imply that the bulk of most galaxies formed at least as far back as z = 3-5 and probably more like z > 10 (*i.e.*, >12 Gya), which are some of the highest red shifts detected among the most distant galaxies and quasars. Yet, the galaxies could not have formed earlier than $z \approx 1500$, which is the time (~0.5 My) when matter began recombining and decoupling from radiation. So there are some observational bounds to what did happen long ago.

The figure below expansively sketches the status of radiation and matter as observed generally in the Universe, placing into a spacetime perspective the origin of galaxies, which probably began within z = 10-100. This grand figure clearly demonstrates how it has been so difficult to acquire good data on emerging and young galaxies that formed so long ago—namely, most of the galaxies probably originated in space and time where our current telescopes are unable to probe.



This plot of "all possible electromagnetic knowledge" depicts the extent to which the Universe can be currently explored by electromagnetic means. Red shift, z, and time, t, from the big bang are graphed vertically, whereas photon energy, E, and wavelength, λ, are plotted horizontally. (The average energy of a blackbody photon equals $2.7k_BT$ expressed in ergs, and 1 eV = 1.6×10^{-12} ergs.) The darkest shaded areas, including the horizontal bar at $z \approx 1500$, indicating the cosmic microwave background, represent the domains of current knowledge. The lightly shaded area, often called "elsewhere," cannot be directly observed, partly (at great z) because of electron scattering of primordial photons and partly (at high E) because of the opacity of nearby γ-rays due to pair production. The epoch of galaxy formation is depicted by the irregular blob at the center for which z > 10; the origin of galaxies comprises perhaps the greatest missing link in all of cosmic evolution, largely because humankind has yet to build a machine capable of imaging realms so far away and so long ago.

Galaxy Evolution

Evolution in General: Hierarchical clustering of dark-matter clumps, as noted above, provides the conceptual framework for modern studies of galaxy evolution, describing a process of upward assembly that began many Gya and continues, albeit at greatly reduced rate, to the present. Ample evidence exists that galaxies have evolved, and are still evolving, in response to external factors—usually gentle accretion of dwarf galaxies, globular clusters, and loose gas, but sometimes violent, major mergers with other regular, large galaxies long after the first protogalaxies emerged (Busa, *Science*, v287, p69, 2000). Direct imaging of irregular galaxy fragments (Conselice *et al*, *Astr J*, v126, p1183, 2003) and quasar absorption (Lyman-α) spectroscopy of intergalactic neutral H clouds (Rauch, *Ann Rev Astr&Ap*, v36, p267, 1998) reveal a multitude of galaxy building blocks (~10^9 $M_\odot$ each spread over ~3 kpc) in the earlier Universe at z > 2, or >10 Gya; bigger (~100 kpc) Lyα-emitting "blobs" are observed (Gawiser *et al*, *Ap J*, v671, p278, 2007) at even earlier epochs, $z \approx 3$, or ~11 Gya, and although all these primeval systems are near currently detectable limits, most have $(M/L)^{-1} = \Phi_m < 0.1$ erg/s/g and often much less.

Galactic encounters among such minor, oddly shaped blobs predominantly occurred long ago (>10 Gya) when the Universe was smaller and denser, subjecting the progenitors of today's massive galaxies to higher collision crossection. Computer simulations show that the extensive dark-matter halos surrounding most, if not all, galaxies predominate galaxy interactions, if only because those halos make galaxies much larger than their optical appearance implies, thereby increasing the probability of close encounters and mass assembly. That such major mergers replenish H fuel supplies while shocking and compacting loose galactic gas to make more stars, and thus probably lowering galaxies' M/L ratio (by probably only a few factors since both L and M increase, and only temporarily during brief ~10-My episodes), is evident in "starburst galaxies" specifically and in enhanced stellar birthrates observed in the Universe generally. Most stellar activity peaked during 1 < z < 3, thus between 7-11 Gya, which is probably the period in cosmic history when galaxy formation matured and galaxies' Φ_m values increased substantially (Tacconi *et al*, *Nature*, v463, p781, 2010).

In contrast to the rare extra-luminous galaxies (for which Φ_m = 1-10 erg/s/g), some of the dimmest galaxies, such as the ultrafaint, neighboring dwarfs in Ursa Major and Bootes, apparently have the largest fractions of dark matter yet few heavy elements, raising the intriguing possibility of "dark (or ghost) galaxies" (Kormendy and Freeman, *Bull Amer Astr Soc*, v30, p1281, 1998)—a new category of very ancient, seemingly starless galactic systems, each (~10^9 $M_\odot$) composed of almost entirely (~99%) dark matter emitting hardly any detectable energy (~10^{4-6} $L_\odot$, hence $M/L \geq 10^3$, which is less than some individual stars in the Milky Way), and therefore having minute values of $\Phi_m \leq 10^{-3}$ erg/s/g. Such faintest of the dwarfs are almost surely pristine remnants of the earliest phase of galaxy formation—all of which implies that Φ_m (see below) likely increases slightly as galaxies evolve since, during infall/mergers, gravitational potential energy converts to star formation and other *in situ* galactic energies. Matter thereby acquired is spread over smaller volumes in 6-dimensional (3-space, 3-velocity) phase space and therefore less randomly distributed in real space, causing galaxies to become more ordered and organized, thus less entropic and more complex.

Evolution of Specifically the Milky Way: Here is a brief account of a widely accepted scenario for the origin and evolution of the Milky Way Galaxy, minus lingering, controversial details, yet one that explains much galactic structure observed today as well as the kinematical and chemical properties of its stellar populations (Freeman and Bland-Hawthorn, *Ann Rev Astr&Ap*, v40, p487, 2002; Chaisson and McMillan, *Astronomy Today*, 7th ed., Pearson/Addison-Wesley, London, San Francisco, 2011; Chiappini, *American Scientist*, v89, p506, 2001; Matteucci, *Chemical Evolution of the Galaxy*, Kluwer, New York, 2003; Busa, *Science*, v287, p69, 2000)—a view that supports the idea that our Galaxy is a "cannibal" that consumed at least hundreds of smaller galaxies or galactic fragments during its lifetime. Although we cannot look directly into the past and watch our own Galaxy forming and evolving, we can study other, similar systems, including their representative building blocks. The great majority of the Galaxy likely originated within the first 1-4 Gy by means of dynamic, out-of-equilibrium mergers among several smaller systems, themselves contracting pregalactic clumps of mostly dark matter having masses ~10^{7-8} $M_\odot$—comparable to the smallest dwarf galaxies and the biggest globular clusters, all of which have low heavy-element abundances that imply ancient formation from relatively unprocessed gas. Today's few-dozen dwarf galaxies in the Local Group are probably surviving remnants of those immature building blocks that have not yet merged with the Milky Way (Frebel, Kirby and Simon, *Nature*, v464, p72, 2010); and the ~160 known globular clusters in the halo may be archaic fossils (gravitationally stripped cores) of some of those dwarfs that did merge (West*, et al, Nature*, v427, p31, 2004).

Initially an irregular region ~30 kpc in diameter whose oldest stars now outline that birth, the Galaxy's baryonic gas and dust eventually settled into a thin spinning disk whose dimensions roughly match those measured today and where abundant young stars are found among others still forming. Timescales for subsequent evolution during the past ~10 Gy wherein the Galaxy's size, shape, and composition were altered are still debated, although a recently discovered thick (~2 kpc) disk containing middle-aged stars (7-10 Gy old; ~0.5% heavies) may represent an intermediate stage of star formation that occurred while the gas was still falling into the thinner plane. It also remains unclear if the original building blocks of galaxies contained already formed, even older (Population-III, 0% heavy-element) stars or if they resembled (and may still include) the dwarf galaxies seen today, some of which do have stars, others merely atomic gas.

Studies of the composition of stars in the galactic disk suggest that the infall of halo gas is still occurring today; the star-forming lifetime of a spiral disk may be prolonged by the arrival of fresh gas from the Galaxy's surroundings. However, it is unlikely that any major mergers impacted our Milky Way, otherwise its fragile thin disk would not have survived. Models of star formation and stellar nucleosynthesis imply that the fraction of heavy elements in disk stars should be significantly greater than observed, unless the gas in the disk is steadily being diluted by relatively unevolved gas arriving from the halo (or beyond) at rates of perhaps 5-10 $M_\odot$/y. Recently discovered in the galactic halo are several streams of stars with similar orbits and compositions, each thought to be remnants of dwarf galaxies torn apart by the Galaxy's tidal field and eventually "digested" by our Galaxy, much as other dwarf companion galaxies were probably "consumed" by it long ago (Belokurov *et al*, *Ap J*, v642, pL137, 2006). The small Sagittarius dwarf galaxy (~10^9 $M_\odot$), the closest member of the Local Group now approaching the center of the Milky Way's far side, has been experiencing its death throes for the past ~3 Gy and will likely be assimilated into the Milky Way within another 1 Gy (Ibata *et al, Nature*, v370, p194, 1994); simulations imply that the Magellanic Clouds will eventually meet the same fate (Newberg *et al*, *Ap J*, v569, p245, 2002). Upwards of a thousand mini-galaxies must have been likewise captured, shredded, and dissolved into the formative Milky Way long ago, their stellar inhabitants now intermingling with our Galaxy's indigenous population. Such galactic archaeology is supported by recent observations of the nearby Andromeda galaxy, where relics of past cannibalism between it and its satellite dwarf galaxies (notably filamentary streams of stars in its halo) show the hierarchical process at work (McConnachie *et al*, *Nature*, v461, p66, 2009).

Nonetheless, the intergalactic debris now seen within major galaxies such as the Milky Way are minor additions to already mature galaxies. Dwarf galaxies are analogous to interplanetary asteroids and meteoroids that continually impact Earth long after the bulk of our planet formed 4.6 Gya; the current terrestrial infall rate of ~40 kton/y = 3.6×10^7 kg/y, or an accumulated amount roughly equaling 2×10^{17} kg over 4.6 Gy, is negligible compared to the mature Earth totaling 6×10^{24} kg. Geologists do not consider our planet to have been forming throughout the past many billion years, rather that the bulk of Earth originated 4.6 Gya and has grown in small ways ever since. Most galaxy development is now over, if not yet entirely done, as building-block acquisitions continue to add <<1% of total mass per encounter—much of it providing fuel for continued galaxy evolution as assimilated galaxies, regardless of their small relative masses, bring in new stars, gas, and dark matter that occasionally trigger waves of star formation.

Φ_m for Galaxies

The Milky Way: Our Galaxy (conventionally written with a capital "G" to distinguish our own such system, the Milky Way, from myriad others) displays a 2-4-arm spiral configuration, probably with a linear bar through its center, and visually measuring ~30 kpc (1 pc ≈ 3.26 light-years) across a differentially rotating, circular disk of thickness ~0.5 kpc. The entire system has been observationally estimated to contain ~10^{11} stars, of which our Sun is one of the great majority within the disk and ~8 kpc from its center. Visual inspection of stars and radio observation of nebulae show that our Galaxy's rotation remains constant to a radial distance of at least 15 kpc, implying that the mass of the system within this radius is ~2 $\times10^{11}$ $M_\odot$ (where $M_\odot \approx 2\times10^{33}$ g), an extent delineated by its spiral arms comprising stars as well as much low-density interstellar matter. The integrated luminosity, L, or net energy flow in the Galaxy, measured at all wavelengths across the electromagnetic spectrum and including contributions from interstellar gas and dust, cosmic rays, and magnetic fields, as well as stars, is ~3×10^{10} $L_\odot$ (or ~10^{37} W, where $L_\odot \approx 4\times10^{33}$ erg/s) within 15 kpc and very low surface brightness (if any luminosity at all) beyond (Flynn et al, *Mon Not Roy Astr Soc*, v372, p1149, 2006). Thus, *prima facie*, for the Milky Way, the inverse of the astronomers' standard mass-to-light ratio, $(M/L)^{-1} \approx (7\ M_\odot/L_\odot)^{-1} = \Phi_m \approx 0.3$ erg/s/g.

The above estimates for M and thus for Φ_m do not include dark matter, an enigmatic ingredient of the cosmos that currently troubles much of modern astrophysics. If Newtonian gravity binds our Galaxy, then such dark matter, which is probably mostly non-baryonic in nature, is needed to keep it from rotational dispersal; angular velocities of interstellar clouds in the Galaxy's extremities remain high far (~40 kpc) from the galactic center, the implication being that this huge physical system is even bigger and more massive, containing at least as much dark matter as luminous matter. Observations (Alcock, *Science*, v287, p74, 2000) imply a diffuse spherical halo at least 10 times larger diameter (~300 kpc) than the disk, thus a Galaxy several times as massive as that given above (*i.e.*, ~10^{12} $M_\odot$), and a consequent Φ_m value equal to at most a third of that derived above, or ~0.1 erg/s/g. This is the energy-rate-density value listed in the final table and graph of the penultimate section of the Advanced Track for the PARTICLE EPOCH.

Here, we are concerned neither with the composition of the dark matter (the leading contenders for which are faint, massive compact halo objects [MACHOs] and invisible, weakly interacting elementary particles [WIMPs]), nor with the ongoing puzzle that this peculiar substance has so far escaped observational detection at any wavelength. Suffice it to say that an invisible halo apparently engulfs the inner domain of stars, gas, and dust once thought to represent the full dimension of our Galaxy, and that the dark matter has much M yet little L, which then affect estimates of Φ_m, hence system complexity (*cf.*, last section below).

Other Normal Galaxies: These above values of M, L, and Φ_m for the Milky Way Galaxy are typical of many normal galaxies observed throughout the Universe, namely those whose principal constituents are vast quantities of thermally emitting and baryonically constructed stars distributed in spiral or elliptical structures (Faber and Gallagher, *Ann Rev Astr&Ap*, v17, p135, 1979; Schneider, *Extragalactic Astronomy and Cosmology*, Springer, Berlin, 2006).

Generalizing to other galaxies (Roberts and Haynes, *Ann Rev Astr&Ap*, v32, p115, 1994), most normal, mature galaxies display Φ_m = 0.01-1 erg/s/g—values comparable to or a little less than those of normal stars (*cf*, Advanced Track for STELLAR EPOCH). This is not surprising since, when examined *in toto*, galaxies are hardly more than huge collections of emitting stars plus non-emitting dark matter. Despite their majestic splendor and blue-rich (youthful) color, spiral galaxies as physical systems are not overly complex compared to many other forms of organized matter, especially biological and cultural systems (*cf,* Advanced Track for BIOLOGICAL and CULTURAL EPOCHS). Nor is it surprising that reddened (aged) elliptical galaxies—huge balls of myriad old stars yet without much interstellar matter or internal structure—typically have the largest values of M/L among normal galaxies, thus the smallest values of Φ_m = 0.02-0.05 erg/s/g; elliptical galaxies, as open, non-equilibrated, thermodynamic systems, illustrate relative simplicity, in fact resemble vast collections of chaotic constituents high in entropy. Ellipticals, often termed "red and dead" galaxies owing to their abundant red giant stars, may be examples of the ultimate fate of our Milky Way, especially since Andromeda and the Milky Way seem destined in several Gy to experience a close encounter, possibly merge, and trigger another round of starburst activity likely to transform these two grand spirals into an elliptical system near astronomical death (Cox and Loeb, *Mon Not Roy Astr Soc*, v386, p461, 2007).

Dwarf Galaxies: Our Galaxy is part of an extended celestial neighborhood called the Local Group, which spans ~2 Mpc in diameter (van den Bergh, *Astr&Ap Rev*, v19, p273, 1999). As surveyed to date, this minor galaxy cluster contains 3 big, normal galaxies and ~50 smaller, or dwarf, galaxies; none of the dominant systems, including the Milky Way and the Andromeda (M31) galaxy ~800 kpc away, resides at the dynamical nucleus of this cluster. Andromeda has much the same vital statistics as our Milky Way: Its mass within its observed disk out to ~20 kpc from its core is ~3.4×10^{11} $M_\odot$, and with an integrated L ≈ 5×10^{10} $L_\odot$, M31's value of Φ_m would normally be ~0.3 erg/s/g; but rotation-curve analysis of its outlying stars and gas clouds well into its halo implies that its total mass, including dark matter, is ~2×10^{12} $M_\odot$, decreasing its Φ_m value to ~0.05 erg/s/g. And so it is for nearly all normal galaxies: Φ_m ≈ 0.5 erg/s/g without dark matter, and as much as an order of magnitude smaller with dark matter included.

The irregular and dwarf galaxies of the Local Group are different, given that their observed stellar velocity dispersions imply that these smaller systems are even more dark-matter dominated than the normal galaxies. Prominent among our Galaxy's ~30 satellites (most with remarkably similar 10^{6-8} $M_\odot$ within ~0.3 kpc [Strigari, *et al, Nature*, v454, p1096, 2008; Wadepuhl and Springel, *Mon Not Roy Astr Soc*, arXiv:1004.3217v3, 2011]) are the Large and Small Magellanic Clouds, satellite irregular galaxies (of masses ~10^{10} and 5×10^9 $M_\odot$, sizes ~4 and 2 kpc, and distances ~50 and 60 kpc, respectively); it is unclear if these Clouds are beyond the Galaxy or within its extended, nearly spherical halo, which is a remnant of an earlier evolutionary stage where old Population-II stars with low heavy-element (>He) abundances (~0.1% by mass) predate the younger, higher-elemental-abundance (~1% as in the Sun), Population-I stars in the galactic disk.

Computer simulations of the early Universe that includes cold, non-relativistic dark matter ("ΛCDM standard cosmology" model [White and Rees, *Mon Not Roy Astr Soc*, v183, p341, 1978]) predict that >10^3 dwarf galaxies should now inhabit the Local Group, but only ~50 have been found thus far [Klypin, et al, *Ap J*, v522, p82, 1999]. Most of these dwarfs are extremely faint (10^{4-6} $L_\odot$; M/L ≈ 10^2 $M_\odot/L_\odot$ [Kleyna, *et al, Astr J*, v117, p1275, 1999]), implying that others might not be missing but merely yet undetected substructures of dark matter having even lower L. Given the observed underabundance of heavy elements within the dwarf galaxies having high dark-matter density, these and other mini-galactic systems are widely considered to be ancient vestiges of an earlier era in cosmic history when stellar evolution had not yet produced many elements >He. Estimates of Φ_m vary from 0.02-0.1 erg/s/g for the Milky Way's well-known dwarf galaxies to 10^{-3}-10^{-2} erg/s/g for the newest such fainter objects found (Mateo, *Ann Rev Astr&Ap* v36, p435, 1998; Belokurov, *et al*, *Ap J*, v654, p897, 2007); the purported unseen dwarfs, in turn, must be among the least luminous galaxies in the Universe with $M/L > 10^3\ M_\odot/L_\odot$ and thus $\Phi_m < 10^{-3}$ erg/s/g.

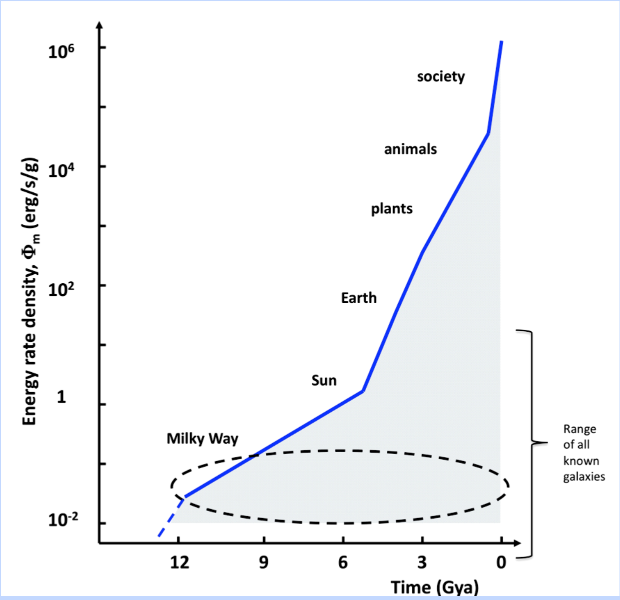
Active Galaxies: In contrast to normal galaxies, some active counterparts, such as anomalously massive ($>10^{12}\ M_\odot$) radio galaxies or quasars, have $L \approx 10^{38-40}$ W, hence values of Φ_m as much as ~50 erg/s/g, but almost certainly for only relatively short periods of a few tens of My. There is a selection effect occurring here: Such transient systems are predominantly noticed on the sky when they are most energetic and thus more observable. Accordingly, active galaxies probably resemble active metabolisms among biological systems, such as horses while racing, birds while flying, or humans while marathoning when Φ_m can increase by an order of magnitude or more above their basal, or normal, energy rates, but again only for relatively short periods of time (*cf*, Advanced Track for BIOLOGICAL EPOCH).

Throughout all of Nature, values of Φ_m display considerable variation within any given type of organized system, depending upon the degree of activity and requiring care when using Φ_m as a complexity diagnostic.

That Φ_m does not increase greatly and indefinitely for galaxies is probably dictated by core supermassive black holes (~$10^9\ M_\odot$) whose jets and winds assert negative feedback that tends to resist further accumulation of matter and quench additional star formation, thus limiting growth of L and hence Φ_m. (In the case of our Galaxy, its central black hole is massively irrelevant at only ~$4\times10^6\ M_\odot$, currently dormant, and apparently not a major player in the evolution of the Milky Way).

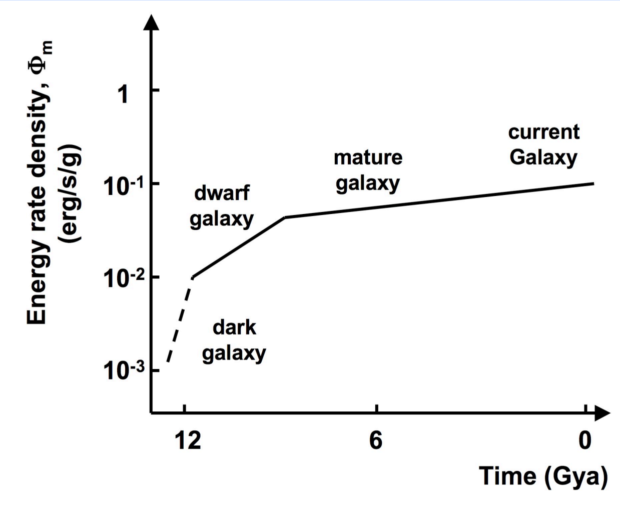
Galaxies in Perspective

The graphs below numerically summarize the above discussion, plotting estimates of Φ_m against time. The first graph is semi-logarithmic, placing galaxies into the larger scheme of all complex systems over the course of cosmic history. The specific value of Φ_m plotted for galaxies along the rising blue curve is that for our Milky Way, dating back to its origin ~12 Gya. The dashed oval includes the likely changes in Φ_m experienced by our Galaxy while evolving during this long time interval; this range is expanded for easier viewing in the next figure. The general range of values of Φ_m for all galaxies typically extends over an order of magnitude less for dwarf galaxies and perhaps two orders of magnitude more for active galaxies; this full range for all possible values of Φ_m for all known galaxies extends throughout the dotted rectangle, which is nonetheless confined to only the bottom part of this graph.



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 Milky Way Galaxy while evolving over the past ~12 Gy, and whose values of Φ_m are plotted in more detail in the next figure. All galaxies—whether normal, dwarf, or active—inhabit the lower part of this graph; their Φ_m values reside within the wider range outlined by the bracket at right.

The second graph below is also plotted semi-logarithmically, but for a much smaller range of the previous graph (that within the dashed oval), thus showing more clearly the temporal change of Φ_m during our Galaxy probably evolution. This graph does not show sharp spikes of increased Φ_m that might have occurred during relatively brief (ten-to-hundred-My) episodes of enhanced star formation caused by significant (although not major) collisions with neighboring dwarf galaxies—events that would have increased both M and especially L, thus potentially yet temporarily raising Φ_m by a few factors during the Galaxy's long mature phase. There is probably no way to reconstruct the past in the detail needed to specify those periods when star-bursts would have briefly, though dramatically, enhanced Φ_m during our Galaxy's evolution.



The growing complexity of the Milky Way Galaxy, expressed in terms of Φ_m (plotted only within the dashed oval of the previous figure), is shown here in greater detail rising slightly over its ~12 Gy existence to date during the physical-evolutionary phase of cosmic evolution. According to the hierarchical theory of galaxy construction, dwarf galaxies and pregalactic clumps of gas merged relatively rapidly in the earlier Universe, such that within several Gy after the big bang our Galaxy had matured to nearly its present size and scale. The value of Φ_m for the Galaxy has continued rising ever since and will likely continue doing so, though only slightly, slowly, and episodically, as more galaxies (mostly dwarfs) collide and merge with our parent Galaxy.

Galaxy Complexity

We might expect that normal galaxies would have values of Φ_m comparable to that of normal stars largely because, when examined in bulk, galaxies visually seem hardly more than gargantuan collections of stars. Yet galaxies harbor much dark matter whereas stars do not. Since Φ_m is, effectively, an energy *density*, this quantity scales inversely as the mass of the entire galaxy housing those stars. As a result, galaxies typically have Φ_m values (0.01-50 erg/s/g) somewhat smaller than for most stars (2-1000 erg/s/g), yet there is some overlap among the most active galaxies (see above) and the dimmest stars (*cf*, Advanced Track for STELLAR EPOCH).

Since galaxies, in the main and in bulk, preceded stars, and since their values of Φ_m are somewhat less than that for stars, does that mean that galaxies are simpler than stars? And what about the oft-heard statement that all life forms are more complex than any star or galaxy? The latter derives not only from knowing that more information is needed to describe any living thing, but also that life forms express intricate function as well as maintain structure. As a general proposition, physical systems display less functional complication, thus are likely simpler—though I formerly thought the opposite and once stated in print that galaxies are complex objects (Chaisson, p34, in *The Universe*, Price and Fraknoi, eds., Bantam, 1987), but I now realize that by claiming that our Galaxy resembles a "galactic ecosystem . . . as complex as that of life in a tide pool or a tropical forest," I was parsing mere words and turning a literary phrase to describe a subjective impression. In fact, galaxies *are* complex systems, yet their degree of complexity is unequivocally less than that of life and probably less than most stars as well.

That galaxies are simpler than expected at first glance is not surprising from a systems perspective, for once we examine their whole systems globally within their extended environments, galaxies are recognized to contain hardly more than $10^{9\text{-}12}$ relatively unordered stars. Ellipticals are the epitome of chaotically swarming stars; even spirals are ragged and misshapen when examined at high resolution—the disordered traces of a violent past. The many ongoing collisions, mergers, and acquisitions experienced by galaxies likely prevent them from growing too complex; when they do collide the result is a mess, not some new order, much as when cars crash creating a wreck of simplified debris rather than a better, more ordered car.

Furthermore, the hierarchical model of galaxy formation, which holds that galaxies are assembled by chaotic merging of smaller pieces, implies that the properties of individual galaxies should be controlled by six independent parameters, including mass, size, spin, age, gas content, as well as the surrounding environment. But observational surveys of a wide variety of many normal galaxies suggest that all these parameters are correlated with each other, and that in reality galaxy morphology may be dominantly regulated by a single such parameter—namely, current mass (Disney, *et al, Nature*, v455, p1082, 2008; van den Bergh, *Nature*, v455, p1049, 2008).

Nor should we be surprised that the energy rate density, Φ_m , occasionally overlaps for stars and galaxies, much as it sometimes does for plants and animals or for society and its tools (*cf*, Advanced Tracks for BIOLOGICAL and CULTURAL EPOCHS); overlaps, though rare, exist for comparably complex systems in an imperfect Universe.

Sweeping spiral arms adorning some galaxies, as well as their cores, bulges, disks, and halos, are not likely more complex than the many different components of stars—core, convection zone, photosphere, corona, as well as irregular spots and flares on stellar surfaces—indeed stars too are judged relatively simple based on Φ_m measures (1-10^3 erg/s/g; cf. Advanced Track for STELLAR EPOCH). All such physical systems are relatively simple, at least compared to more complex systems that originated and evolved later in time.

This is not to claim that galaxy evolution is driven solely by gravity and the energy flows that result from conversion of gravitational potential energy, which can be readily modeled in coarse-grain N-body simulations; a suite of convoluted "gastrophysical" processes at regional levels within galaxies, including cooling and accretion of interstellar gas, transformation of that gas into stars, as well as feedback of energy and momentum from stars back into the gas, all comprise fine-grain, local-level, nature-nurture bookkeeping too disordered to currently simulate (Bromm, *et al, Nature*, v459, p49, 2009). The formation, development, and evolution of galaxies, as minimally understood today from observations of different objects of different ages in different places, does display, *en masse*, simplicity transforming into complexity—the utter simplicity of the early primordial Universe giving way naturally to one in which matter clumped, structured, and ordered. But complexity is a relative word; some organized matter that came after the onset of galaxies is even more complex, and progressively so—and that is what the term Φ_m seeks to quantify as a uniform, consistent, and general complexity metric for all ordered systems.

In Sum

Galaxies of all types, including those of dwarf, normal, and active status, have derived Φ_m values that are among the lowest of known organized systems—typically in the range 0.01-50 erg/s/g, with most normal galaxies displaying plus or minus a few factors times 0.1 erg/s/g. In the specific case of our Milky Way Galaxy, its Φ_m rose while hierarchically clustering:

- from protogalactic blobs >12 Gya ($\Phi_m \approx 10^{-3}$ erg/s/g)
- to widespread dwarf galaxies (~10^{-2})
- to mature, normal status ~10 Gya (~0.05)
- to our galaxy's current state (~0.1).

Although of lesser complexity and longer duration, the Milky Way is nearly as adaptive and metabolic as any life form—transacting energy while forming new stars, cannibalizing dwarf galaxies, and dissolving older components. By the quantitative measure promoted here—energy rate density—galaxies are then judged, despite their oft-claimed majestic splendor, to be not overly complex compared to many other forms of organized matter—indeed unequivocally simpler than intricately structured and exquisitely functioning life forms.