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Cosmic Contributions to the Deposition of Petroleum Source Rocks: Review and Analysis

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Abstract

The development of globally distributed Phanerozoic petroleum source rocks is concentrated on time intervals, which correlate convincingly with climatic driven glaciation epochs of Earth's history, repeated every 150 million years, and during sea level high stands and maxima of global magmatism with a period of 300 million years. The 150 million year periodicity appears to be related to the path of the solar system through the spiral arms of the Milky Way and the 300 million year periodicity to changes of the spiral system. The spiral arms are preferred birth places of new stars, of which the larger ones have only smaller lifespans. Their preliminary deaths ended with explosions and selectively with the development of so-called white dwarfs, neutron stars or black holes. The times of the explosions of intermediate (sun-like) stars can be determined by measuring the present brightness of the dwarfs. Not surprisingly the last two maxima of recordable near solar system star explosions took place during the presumably spiral arms driven glacial epochs in Eocene to present and Upper Jurassic times. Such near solar system star explosions may have been the source of intense neutrino showers, cosmic rays and star dust. This dust contained all kinds of chemical elements, including phosphorus and uranium. Such cosmic phosphorus may have supported, through fertilizing, the distribution of life on Earth additionally to local phosphorus resources via bloom of biota in lakes and oceans and the enhanced growth of plants on land across all climatic zones. Subsequently it maintained the development of petroleum source rocks of all organic matter types within black shales and coals. Via the distribution of remnants of exploding stars—mainly white dwarfs, but neutron stars and black holes have to be counted as well—a cosmic contribution can therefore casually linked to the deposition of petroleum source rocks on Earth, not only purely correlatively by their contemporaneous appearances.

Keywords

Cosmic Rays, Cosmic Dust, Milky Way, Spiral Arms, Stars, Phosphorus, Uranium, Petroleum Source Rock

1. Introduction

The predictability of Earth's geological future strongly depends on the evaluation of the past. Did past geological processes increase or decrease linearly, exponentially, cyclically or with a complex combination of all? Since the Earth rotates differently modulated around the sun and the solar system itself wanders on a complex path around the center of the Milky Way galaxy, subsequent cyclic changes in the geological record should consequently occur. These changes encompass astronomically enforced processes as well as terrestrially induced intrinsic ones. Examples are the observed geodynamic periodicities of about 300 and 150 million years (**Figure 1**) of global sea level fluctuations, magmatism, orogeny, sedimentation (e.g. of organic carbon) and climate [1] [2] as well as periodicities with shorter repetition times [3] [4] [5] [6] [a.o.].

In this paper the focus lies on the 150 million year cycle (4 arm crossings lead to an orbit age of about 600 Ma around the slower rotating Milky Way structure). This cycle appears to have a strong influence on Earth's climate (**Figure 2**). An astronomical input seems obvious [9]. The astronomical input is related to the configuration of the Milky Way galaxy with its four spiral arms, exploding

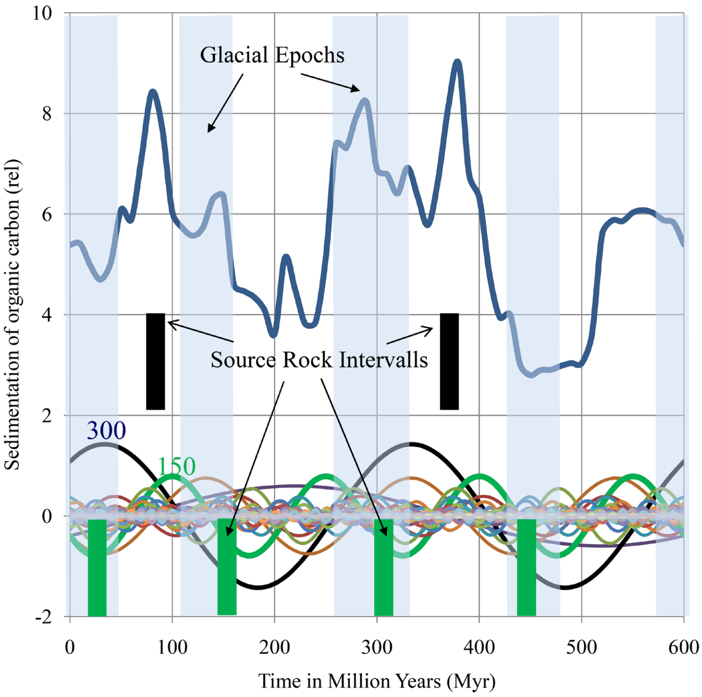


Figure 1. Fourier analysis of the sedimentation pattern of organic carbon after [7] and the dominant intervals for the sedimentation of petroleum source rocks after [8] that point to a 150 Myr (climate, Milky Way; green) and a 300 Myr cycle (sea level, magmatism, orogeny, sedimentation; black), taken from [2].

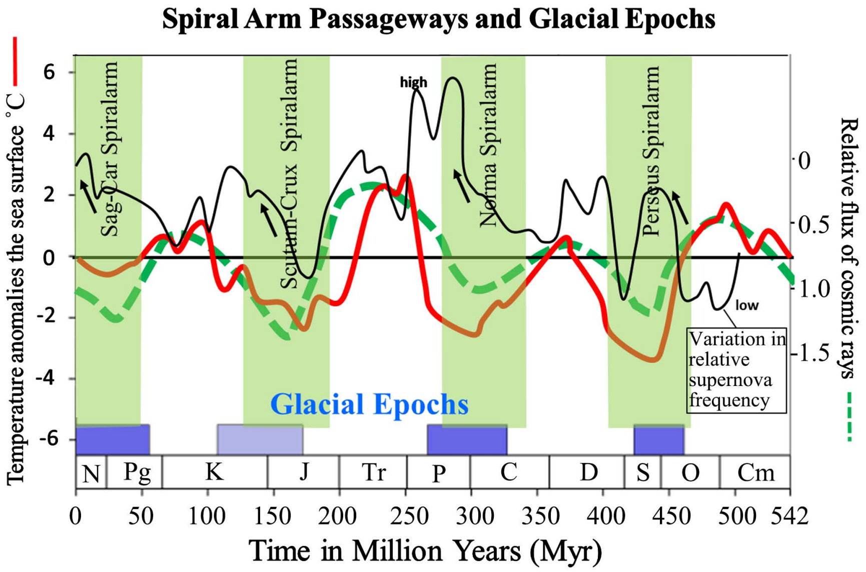


Figure 2. Phanerozoic cycles (~150 Myr) of the temperatures of the tropical sea surface (red curve) with the division of greenhouse and glacial-epochs and the flux of cosmic radiation (green shaded curve, scale inverted), that correlate with the passageways of the Earth through the spiral-arms of the Milky Way. The resulting increase in the cosmic-ray-flux enhances cloud-formation by the generation of condensation nuclei. This leads subsequently to a temperature decrease. Iron meteorites are regarded as medium of the signal for the cosmic-ray-flux [9], taken from [2]. The black curve represents the variation in relative supernova frequency presented by [11], which shows a weak graphical correlation with the other two curves. However, a generally increasing variation of supernova frequency (black arrows > derivative) may obviously correlate with the passageway of the solar system through the spiral arms of the Milky Way galaxy. For a better fit a portionwise correction through a time shift/stretch of the variation curve itself by some 10 - 30 million years backwards appears senseless.

stars of different sizes and ages and to the long geodynamic feedback system with a lunar input on Earth [1] [10]. In this sense cosmic rays and dust, cosmic isotopes at ocean floor sediments, chemical element production, supernovae and planetary nebulae as well as cosmic uranium and phosphorus have to be discussed. Phosphorus is a chemical element and very important for the bloom of life on Earth, uranium a more passive companion, deposited in larger concentrations in black shales and coals. Black shales are important petroleum source rocks, especially those of Upper Jurassic/Lower Cretaceous and Oligocene/Miocene age. Similar to black shales contemporaneously deposited Miocene coals are also important energy resources that are globally mined (e.g. as lignite).

2. Spiral Arms of the Milky Way Galaxy

In the Greek mythology the goddess Gaia gave birth to all life on Earth. Today we know how difficult the evolution of life must have been. It needed at least a complex network of the right galaxy, the right sun and the right moon. Right astrophysical, geophysical, geological, hydrological and meteorological conditions are required, too. The planet should have the right size and the right composition of all natural chemical elements from hydrogen to uranium. These chemical elements as well as molecules and minerals, made of them, have all distinct chemical and physical properties required for their countless applications. The planet is a comparable small rocky sphere. It is wandering on a dangerous path within the solar system through the imponderables of the Milky Way galaxy since about 4.5 billion years. As a sphere with a complex interior the Earth survived countless internal and external catastrophic events. With a time gap of about 150 million years between them it crossed the four spiral arms of the Milky Way galaxy on its path (**Figure 3**). During its residence times in spiral arms the sphere picked up, periodically enhanced, cosmic rays and dust that had apparently a significant influence on the history of the planet.

3. Cosmic Rays

Already some decades ago it has been suggested that cosmic rays may have been accountable for major climatic change and mass extinction at least in the Phanerozoic during the last ~542 million years [15] [16].

Today a scientific and political dispute is controversially ongoing whether solar variation modulates the cosmic ray flux on Earth. This variation would subsequently modify the intensity of cloud formation and could therefore be an indirect cause of global warming in times of reduced atmospheric entry of cosmic rays [17]. In opposition to the mainstream scientific assessment of global warming that human activity on Earth is the main driver, the idea of cosmic influences is also being presented by scientists. Both, main stream and opposition interpreted the ideas of the other side as ideologically biased, whereas the main stream gets currently more political support [18].

Cosmic rays are high energy particles that move through space at nearly the speed of light. Within cosmic-rays however sub-atomic particles like neutrons,

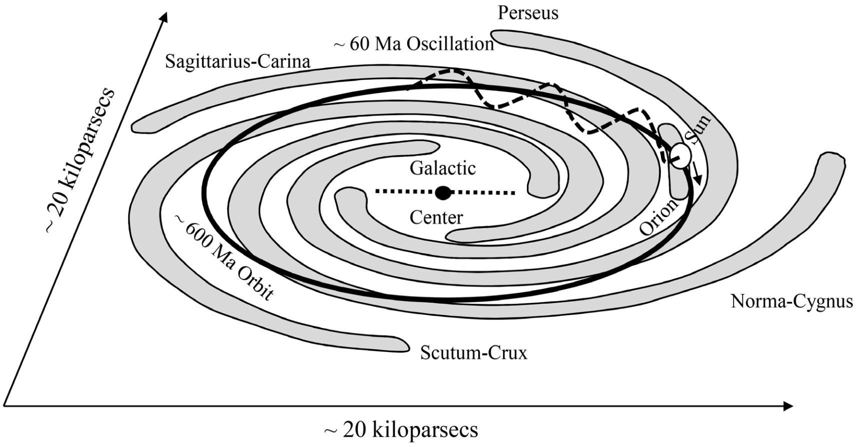


Figure 3. A depiction of the Sun's motion relative to the spiral arm pattern modified after [12] and [13], oscillations are not to scale. Perseus and Scutum-Crux should show a higher gas and dust-density, Sagittarius-Carina and Norma-Cygnus a more inferior [14]. Graph is taken from [2].

electrons and neutrinos are present as well. About 90% of the cosmic ray nuclei are hydrogen (protons), about 9% are helium (alpha particles), and all of the rest of the elements make up only 1%. Even in this one percent there are very rare elements and isotopes. All of the natural elements in the periodic table are present in cosmic rays. This includes elements lighter than iron, which are produced in stars, and heavier elements that are produced in violent conditions, such as a supernova at the end of a massive star's life. Since cosmic rays are charged—positively charged protons or nuclei, or negatively charged electrons—their paths through space can be redirected by magnetic fields. On their journey to Earth, the magnetic fields of the galaxy, the solar system, and the Earth challenge their flight paths. Most galactic cosmic rays are probably accelerated in the blast waves of supernova remnants. The remnants of the explosions—expanding clouds of gas and magnetic field—can last for thousands of years, and this is where cosmic rays are accelerated. Bouncing back and forth in the magnetic field of the remnant randomly lets some of the particles gain energy, and become cosmic rays. Eventually they build up enough speed that the remnant can no longer hold them, and they escape into the galaxy.

Cosmic rays accelerated in supernova remnants can only reach a certain maximum energy, which depends on the size of the acceleration region and the magnetic field strength. However, cosmic rays have been observed at much higher energies than supernova remnants can generate [19].

4. Cosmic Dust

Efficient producers of cosmic dust are supernovae. This is coherent with the assumption that supernovae and asymptotic giant branch stars (period of stellar evolution traversed by all low- to intermediate-mass stars (about 0.4 to 8 solar masses) late in their live) are the primary producers of dust in the universe. The cores of dust grains are known to form in the dense ejecta of supernovae (SNe) and in the slow, dense winds from evolved stars. The evolution of dust is complex and is driven by many of the key processes involved in galactic evolution. Dust grains are subsequently subject to destruction by thermal and kinetic sputtering as they escape from their source. Grains that are large enough (~0.25 μm for silicates and ~0.1 μm for carbonaceous grains) escape into the interstellar medium while smaller grains get trapped and destroyed. However, grains that reach the interstellar medium still have high velocities, and are subject to further destruction as they are slowed down.

Dust plays many essential roles in the interstellar medium (ISM) in a wide range of environments. In molecular clouds dust is important as a site for molecule formation. As a repository of metals, dust regulates the gas phase abundances and metal and non-metal transport in galaxies, inclusively phosphorus and uranium [20].

5. Cosmic Isotopes in Ocean Floor Sediments

Remnants of cosmic dust have been detected in sedimentary probes from the sea bottom, which include the radioactive isotopes ^{60}Fe (iron, half-life: 2.6 million years) and ^{244}Pu (plutonium, half-life: 80.6 million years). Due to their half-life it can be excluded that these isotope samples have survived on Earth in one way or the other since her birth. The only known processes that could contribute to the deposition of those isotopes are cosmic processes like explosions of supernovae and merger of neutron stars, respectively (see farther below). Their presence below a water column of several 1000 meters demonstrates quite well that the isotopes have undergone a complex distribution and deposition on Earth. Samples of undecayed ^{60}Fe in Antarctic snow confirm the global distribution, probes in lunar regolith and cosmic rays a source in the Milky Way galaxy. Recent explosions of at least two near-Earth supernovae have been identified as source of the mentioned radioactive isotopes [21].

The observed ^{60}Fe signals with maxima at 2.5 and 6.3 Ma confirm previous results in sediment, crust, and nodule samples. For samples between 4.2 and 5.5 Ma and for those older than 7 Ma the measured Fe level remained within the general background [22].

The ^{60}Fe profiles in deep-sea sediments allow estimating the timescale of supernova debris deposition beginning ~3 Myr ago. The best-fit ^{60}Fe pulse durations are >1.6 Myr. This timescale exceeds the $\lesssim$0.1 Myr pulse by far that would be expected if ^{60}Fe was embedded in the supernova blast wave plasma. Apparently the long signal duration can be used as evidence that ^{60}Fe arrives in the form of supernova dust, whose dynamics are separated from but coupled to the evolution of the blast plasma [21].

The observed duration in the Million years range for the arrival process of supernova ^{60}Fe isotopes on Earth (possibly about 3 - 4 million years, **Figure 4**) can also be taken as an estimate for all other accompanying supernova dust grains. Obviously, geological processes, biota and climate should have consequently gotten adapted to this long timespan. According to **Figure 4** the arrival process of "slow" dust grains and their complex delayed deposition on Earth started already 4 million years ago. This means that the first influx time of the

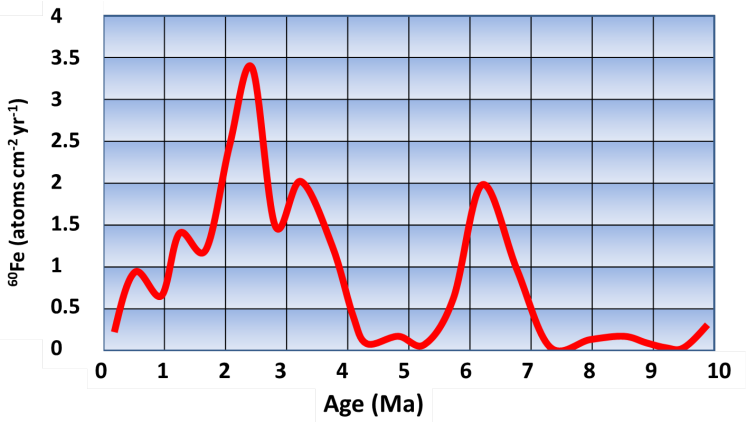


Figure 4. Influx of interstellar Fe and pulse durations. The absolute ages have an uncertainty of ~0.3 to 0.5 Myr, modified from [22].

"faster" cosmic rays of the supernova explosion should have been a bit earlier. Those cosmic rays may have the potential to initiate extinctions on Earth. Their beginning would predate the arrival and deposition of dust. The true time shifts depend on the distances between supernovae and the solar system.

The detection of rare isotopes of iron and plutonium of exploding stars in a sedimentary environment at the bottom of the sea leads to the question: what has happened to all the other chemical elements simultaneously produced by the blast? As it will be hard to distinguish the stable isotopes of these chemical elements from the ones that have been present on Earth since the early days, however, their global distribution can be assumed, too. These include phosphorus as an essential element for life and uranium as a passive companion of biota, deposited in black shales and swamp plants that converted in course of the subsidence of sedimentary basins through the activity of microorganisms and under increasing temperature and pressure in petroleum source rocks [8] and minable coals [23]. In this sense, to take experienced astronomical support and to serve the reader, details about the evolution of stars and the origin of chemical elements will be discussed in chapter 6 and 7 as thematically required by following Greg Roberts (2013), Stanford University. Credit is given to him for his easy readable internet text on "Star Death and the Origin of Uranium", which is carefully pasted as essential portion of the two chapters, and with the original wording as requested (http://large.stanford.edu/courses/2013/ph241/roberts2/).

6. Chemical Elements and the Development of Stars

The birth material of stars is primarily hydrogen gas. This hydrogen gas will concentrate into a region through gravitational means. The fate of the star will depend almost entirely on the final mass once all of the available material has accreted into a singular spherical body. The fuel consumption process is nuclear fusion whereby the light hydrogen atoms are squeezed together to form the heavier element helium, releasing energy in the process. This energy release gives rise to very high temperatures and the star will radiate, which results in their visual appearance in the night sky. The production of elements heavier than hydrogen is broadly classified as nucleosynthesis [24].

If the initial mass of the star is less than ~0.4 M_Θ, where M_Θ is the mass of our sun, then helium will be the final product. As the star fuses hydrogen, the helium will convect away from the core and allow more hydrogen to fuse. Ultimately this will leave behind a ball of primarily helium gas. It is the gravitational mass of the star that provides compressive forces sufficient to overcome the energy barrier for a fusion process, and in this case there is simply not enough mass to continue with the process and fuse helium. The resultant star will remain fixed in composition and cool by radiating thermal energy away. This type of star is called a red dwarf and they are the most common type of star in the Milky Way galaxy, comprising ~85% of all stars. If the mass is very small, less than ~0.08 M_Θ, then the star is called a brown dwarf. Clearly these are not the kind of stars that have created the heavy elements we find on Earth [24].

If the mass of a star is in the range of 0.4 - 8 $M_{\odot}$, then further fusion processes can occur. In this case, the helium will accumulate within the core. Once the initial hydrogen fusion stops, the star will re-equilibrate its internal hydrostatic pressures by expanding its outer layers to become what is called a giant. Some of this gas will be expelled entirely, although the inner core will begin a new fusion process where now the helium is the fuel. Again due to gravitational forces, the helium will fuse together to form heavier elements such as carbon and oxygen. Over time these products can accumulate and build up a non-fusing core. This is surrounded by a shell of fusing helium, a layer of fusing hydrogen, and then an outermost region of non-fusing hydrogen gas. As the star proceeds, it will continue to hydrostatically equilibrate by expelling mass out into space. These sizes of stars can lose roughly 80% of their initial mass this way, and the gas cloud produced is called a planetary nebula. The resulting star core will be a very high temperature body of primarily carbon and oxygen, which are called white dwarfs (WD). They are roughly the size of Earth, and will no longer fuse any of their remaining atoms [24].

However, the first solids that form as a cooling white dwarf starts to crystallize are expected to be greatly enriched in actinide. The presence of actinides is somehow mysterious, since heavy elements get produced generally during supernovae explosions or similar events after all [25]. It can be estimated that the solids may evolve so enriched in actinides that they could support a fission chain reaction. This reaction could ignite carbon burning and lead to the explosion of an isolated white dwarf in a thermonuclear supernova (SN Ia).

A second mysterious observation concerning the development of near solar system white stars is their distribution along a time axis (**Figure 5**) [10] [26]. By

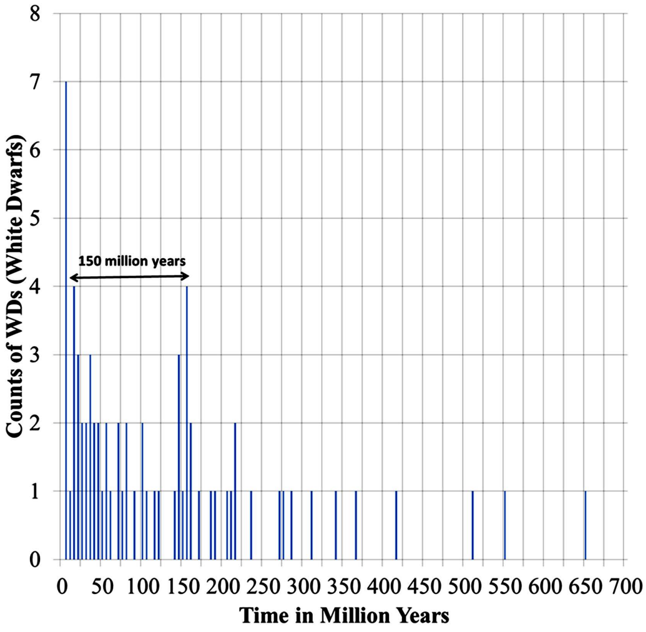


Figure 5. Counts of near earth white dwarfs per steps of 5 million years after [27], showing a 150 million years periodicity (one repetition recognizable) [10].

accompanying the solar system with an assumed similar rotation speed around the galactic center, the ages of white dwarfs show a 150 million years periodicity of maxima (at least two) along the time axis of solar passages through the spiral arms of the Milky Way (**Figure 3**). Properties of the spiral arms may therefore synchronize the white dwarf development of long lived intermediate stars either through the influence of denser cosmic rays and dust or through nearby explosions of short lived massive stars as supernovae. The contemporaneous development of white dwarfs and probable nearby supernovae within the spiral arms may link indirectly some observations concerning the effects on Earth. Despite of some mysteries white dwarfs are not yet seen as the result of real supernova explosions as occasionally stated. The huge amount of neutrinos that a supernova generates could be a speculative source for special developments inside the spiral arms. Speculatively it has already been suggested that those neutrinos could have enhanced contemporaneous magmatism on Earth, Moon and the nearby planets Venus and Mars [2].

"If a white dwarf is formed near enough to a swollen giant star" (as previously described), this binary system may undergo an interesting process. The white dwarf can accrete gas from the giant, mostly hydrogen and helium. Once the hydrogen fusion ignites, the outer layer can be blown off in an explosion called a nova. And if enough mass and fusion energy are present, the entire white dwarf may be blown apart completely. This event is called a Type Ia supernova. A Type Ia supernova is caused by increased core pressures within the white dwarf due to accumulated outer-layer gas, which then drives the fusion of carbon. This initiates then the violent explosion. The general category of carbon-fueled detonations is Type I supernova [24]. This will expel a rapid shock wave throughout the rest of the star, causing many nuclear reactions to occur on a very short timescale. Some of these reactions are classified as a rapid neutron capture, or r-process, and they are capable of producing some of the very heavy elements including uranium [27].

If the initial star mass is in the range of 8 - 25 $M_\odot$, a series of similar fusion reactions will be initiated, although the fate of the core is different. As in the lesser mass stars, a core of carbon and oxygen build up as nuclear fusion products. In this case, however, the mass of the surrounding layers, mostly helium and hydrogen, is large enough to cause the core to collapse and drive even more nucleosynthesis. Here, carbon will fuse to form neon and magnesium, and the oxygen can fuse to produce sulfur, silicon and phosphorus. This process will continue until ultimately an iron (Fe) core is the final fusion product residue [24].

It is here worth noting the uniqueness of the element iron. Within this element, there is a packaging of the nucleon particles, neutrons and protons that is optimally stable. As a result it is thermodynamically the most favorable fusion product. The fusion of the very light elements results in an increase in the product's binding energy, up to an atomic mass number of 26 for iron. Similarly, the nuclear fission (dissociation) of heavy elements like uranium creates daughter particles with higher binding energy as well, and hence this process too is thermodynamically favorable. Within a star, every reaction that fuses two atoms into a particle the size of iron or smaller will release some amount of energy. This energy manifests itself as a temperature rise within the star. Subsequently the available thermal energy has the potential to help drive further fusion reactions, until iron has been produced, and the sequence stops. Its fusion would require more energy than can be provided by the rise in temperature [27]. It is for this reason that every element with an atomic number greater than iron is referred to as “heavy”.

During the lifetime of these massive stars (~8 to 25 $M_{\odot}$), layers of various elements fusing together release photons that apply pressure to the outer gas layers, causing the size of the star to expand and become a supergiant. The core of the star builds up with iron until a threshold is reached. At this point, the iron atoms are so close that every available electron energy state is occupied, and the Columbic repulsive forces are at their maximum. This is referred to electron degeneracy pressure. It is an extremely strong force, although gravitational force may overcome this, causing the star to collapse and detonate as a Type II supernova. This reaction is powerful enough to initiate the rapid neutron capture process as well, and provides a means for creating uranium and other heavy elements [24].

The remnant of this very violent explosion is a neutron star. This object is comprised of roughly 10% to 20% of the star’s initial mass within a volume that is incredibly small. Additionally, due to the conservation of momentum, they often are born with extremely high spin rates, on the order of 10 to 100 rotations per second. It is the nutation of their spin axis that creates very regular pulses of radio waves, which are detectable. Fast-rotating neutron stars are called pulsars [24].

Lastly, it is mentioned that stars with a mass greater than ~25 $M_{\odot}$ follow a similar lifecycle, however their interiors are compressed to such an extent that the repulsive forces between adjacent neutrons are insufficient. As a result a black hole is formed (**Figure 6**) [24].

7. Supernovae and Heavy Elements

In order for heavy elements like uranium to be formed (Periodic Table of the Elements, see **Figure 7**), a rapid supply of energetic neutrons must be made available. This is what a supernova explosion is capable of providing. The explosion is initiated by an excessive pressure build up about the iron core, and rapid compression ensues. The gravitational force overcomes the electron degeneracy pressure and begins to drive endothermic (energy consuming) reactions. A process occurs where protons in the nuclei capture electrons and become a neutron. This happens until a sufficient core of neutrons has been built up, reaching a state of neutron degeneracy. The compression wave then bounces off of the neutron core and reflects back as an outward propagating shockwave, travelling at a significant fraction of the speed of light [26].

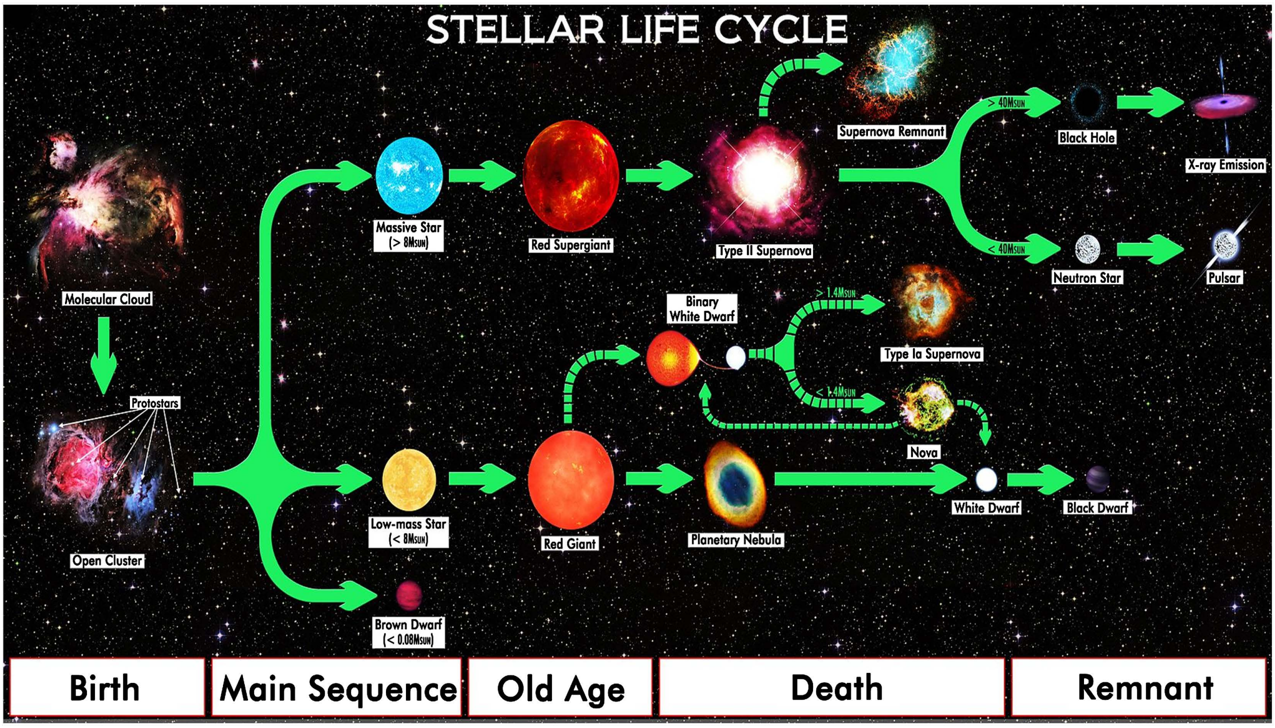
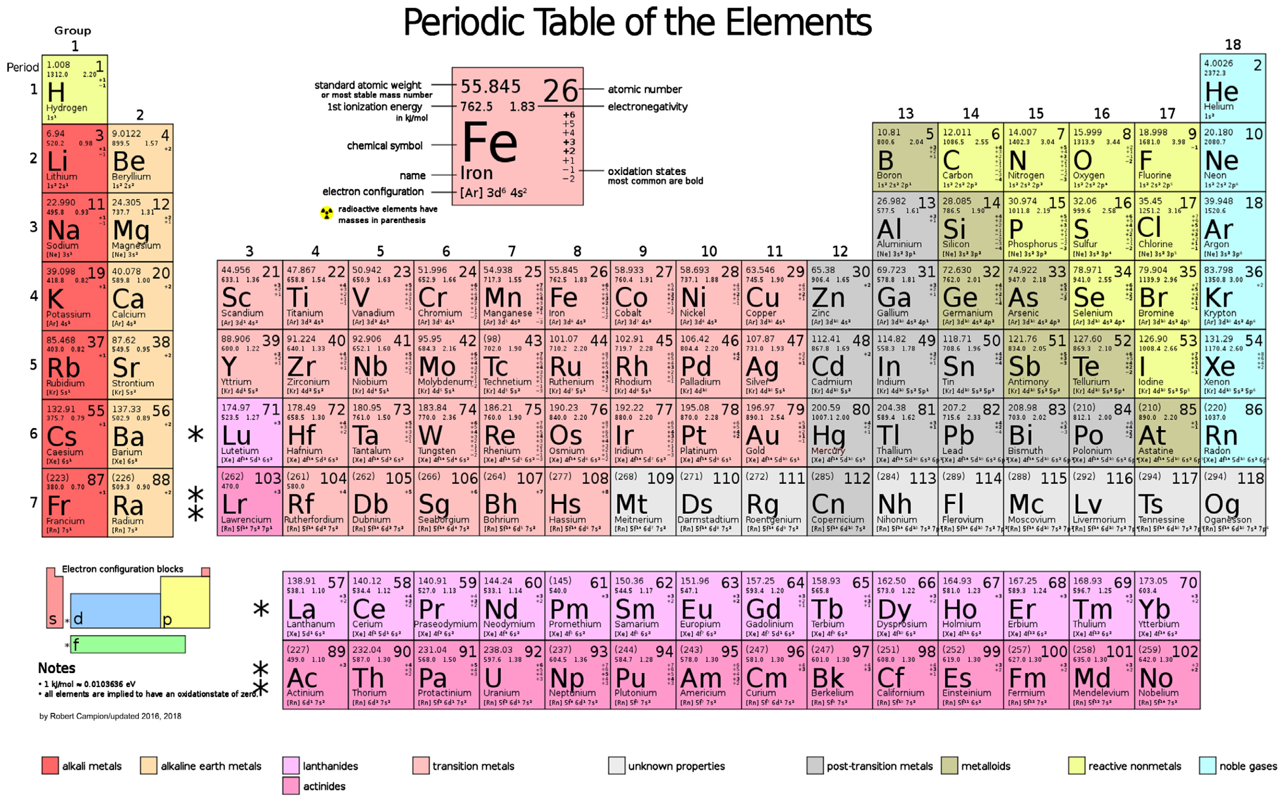


Figure 6. Life cycle of stars from birth to remnant stages. Credit: R.N. Bailey, 2017, this file is licensed under the creative commons attribution 4.0 International license in Wikipedia.



Periodic Table of the Elements

55.845 26 — standard atomic weight or most stable mass number; atomic number
762.5 1.83 — 1st ionization energy in kJ/mol; electronegativity
Fe — chemical symbol
+6 +5 +4 **+3** **+2** +1 −1 −2 — oxidation states most common are bold
Iron — name
[Ar] 3d⁶ 4s² — electron configuration

radioactive elements have masses in parenthesis

Group

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1.008 1 1312.0 2.20 H Hydrogen																	4.0026 2 2372.3 He Helium
2	6.94 3 520.2 0.98 Li Lithium	9.0122 4 899.5 1.57 Be Beryllium											10.81 5 800.6 2.04 B Boron	12.011 6 1086.5 2.55 C Carbon	14.007 7 1402.3 3.04 N Nitrogen	15.999 8 1313.9 3.44 O Oxygen	18.998 9 1681.0 3.98 F Fluorine	20.180 10 2080.7 Ne Neon
3	22.990 11 495.8 0.93 Na Sodium	24.305 12 737.7 1.31 Mg Magnesium											26.982 13 577.5 1.61 Al Aluminium	28.085 14 786.5 1.90 Si Silicon	30.974 15 1011.8 2.19 P Phosphorus	32.06 16 999.6 2.58 S Sulfur	35.45 17 1251.2 3.16 Cl Chlorine	39.948 18 1520.6 Ar Argon
4	39.098 19 418.8 0.82 K Potassium	40.078 20 589.8 1.00 Ca Calcium	44.956 21 633.1 1.36 Sc Scandium	47.867 22 658.8 1.54 Ti Titanium	50.942 23 650.9 1.63 V Vanadium	51.996 24 652.9 1.66 Cr Chromium	54.938 25 717.3 1.55 Mn Manganese	55.845 26 762.5 1.83 Fe Iron	58.933 27 760.4 1.91 Co Cobalt	58.693 28 737.1 1.88 Ni Nickel	63.546 29 745.5 1.90 Cu Copper	65.38 30 906.4 1.65 Zn Zinc	69.723 31 578.8 1.81 Ga Gallium	72.630 32 762.0 2.01 Ge Germanium	74.922 33 947.0 2.18 As Arsenic	78.971 34 941.0 2.55 Se Selenium	79.904 35 1139.9 2.96 Br Bromine	83.798 36 1350.8 3.00 Kr Krypton
5	85.468 37 403.0 0.82 Rb Rubidium	87.62 38 549.5 0.95 Sr Strontium	88.906 39 600.0 1.22 Y Yttrium	91.224 40 640.1 1.33 Zr Zirconium	92.906 41 652.1 1.60 Nb Niobium	95.95 42 684.3 2.16 Mo Molybdenum	(98) 43 702.0 1.90 Tc Technetium	101.07 44 710.2 2.20 Ru Ruthenium	102.91 45 719.7 2.28 Rh Rhodium	106.42 46 804.4 2.20 Pd Palladium	107.87 47 731.0 1.93 Ag Silver	112.41 48 867.8 1.69 Cd Cadmium	114.82 49 558.3 1.78 In Indium	118.71 50 708.6 1.96 Sn Tin	121.76 51 834.0 2.05 Sb Antimony	127.60 52 869.3 2.10 Te Tellurium	126.90 53 1008.4 2.66 I Iodine	131.29 54 1170.4 2.60 Xe Xenon
6	132.91 55 375.7 0.79 Cs Caesium	137.33 56 502.9 0.89 Ba Barium	* 174.97 71 523.5 1.27 Lu Lutetium	178.49 72 658.5 1.30 Hf Hafnium	180.95 73 761.0 1.50 Ta Tantalum	183.84 74 770.0 2.36 W Tungsten	186.21 75 760.0 1.90 Re Rhenium	190.23 76 840.0 2.20 Os Osmium	192.22 77 880.0 2.20 Ir Iridium	195.08 78 870.0 2.28 Pt Platinum	196.97 79 890.1 2.54 Au Gold	200.59 80 1007.1 2.00 Hg Mercury	204.38 81 589.4 1.62 Tl Thallium	207.2 82 715.6 2.33 Pb Lead	208.98 83 703.0 2.02 Bi Bismuth	(210) 84 812.1 2.00 Po Polonium	(210) 85 890.0 2.20 At Astatine	(220) 86 1037.0 Rn Radon
7	(223) 87 380.0 0.70 Fr Francium	(226) 88 509.3 0.90 Ra Radium	** (262) 103 470.0 Lr Lawrencium	(261) 104 580.0 Rf Rutherfordium	(262) 105 Db Dubnium	(266) 106 Sg Seaborgium	(264) 107 Bh Bohrium	(277) 108 Hs Hassium	(268) 109 Mt Meitnerium	(271) 110 Ds Darmstadtium	(272) 111 Rg Roentgenium	(285) 112 Cn Copernicium	(284) 113 Nh Nihonium	(289) 114 Fl Flerovium	(288) 115 Mc Moscovium	(292) 116 Lv Livermorium	(294) 117 Ts Tennessine	(294) 118 Og Oganesson

*	138.91 57 538.1 1.10 La Lanthanum	140.12 58 534.4 1.12 Ce Cerium	140.91 59 527.0 1.13 Pr Praseodymium	144.24 60 533.1 1.14 Nd Neodymium	(145) 61 540.0 Pm Promethium	150.36 62 544.5 1.17 Sm Samarium	151.96 63 547.1 Eu Europium	157.25 64 593.4 1.20 Gd Gadolinium	158.93 65 565.8 Tb Terbium	162.50 66 573.0 1.22 Dy Dysprosium	164.93 67 581.0 1.23 Ho Holmium	167.25 68 589.3 1.24 Er Erbium	168.93 69 596.7 1.25 Tm Thulium	173.05 70 603.4 Yb Ytterbium
**	(227) 89 499.0 1.10 Ac Actinium	232.04 90 587.0 1.30 Th Thorium	231.04 91 568.0 1.50 Pa Protactinium	238.03 92 597.6 1.38 U Uranium	(237) 93 604.5 1.36 Np Neptunium	(244) 94 584.7 1.28 Pu Plutonium	(243) 95 578.0 1.30 Am Americium	(247) 96 581.0 1.30 Cm Curium	(247) 97 601.0 1.30 Bk Berkelium	(251) 98 608.0 1.30 Cf Californium	(252) 99 619.0 1.30 Es Einsteinium	(257) 100 627.0 1.30 Fm Fermium	(258) 101 635.0 1.30 Md Mendelevium	(259) 102 642.0 1.30 No Nobelium

Electron configuration blocks
s *d p
*f

Notes
- 1 kJ/mol ≈ 0.0103636 eV
- all elements are implied to have an oxidationstate of zero.

by Robert Campion/updated 2016, 2018

🟥 alkali metals
🟧 alkaline earth metals
🟪 lanthanides
🟪 actinides
🟥 transition metals
⬜ unknown properties
⬜ post-transition metals
🟫 metalloids
🟨 reactive nonmetals
🟦 noble gases

Figure 7. Periodic table, source: https://commons.wikimedia.org/wiki/File:Periodic_table_large.svg#/media/File:Periodic_table_large.svg. This file is licensed under the creative commons attribution 3.0 Unported license.

As the shockwave moves outward, it passes through various layers: first a dense neutron gas, then the equilibrated iron region, followed by a number of still fusing layers of silicon burning, carbon and oxygen burning, helium burning, and hydrogen burning. The outermost layer is still primarily non-fusing hydrogen. Through each layer that the shock wave interacts, a host of nuclear reactions occur, most notably the rapid neutron capture process.

The r-process is called rapid with respect to the decay mechanisms available to heavy, unstable nuclei. Specifically, it is referenced to the time over which beta minus decay occurs, in which a neutron within the nucleus converts into a proton and emits an electron (and a neutrino). This allows very large nuclei to accumulate in number. The r-process is contrasted with the s-process, a slow neutron capture mechanism, which does not require a supernova explosion to initiate. This process is capable of producing heavy elements up to lead and bismuth, roughly four times the mass of iron. However, the very heavy elements like uranium require the r-process to be formed [27].

The result of a supernova explosion is that heavy elements are ejected out into space, and are available material for the formation of other celestial objects. Through the natural decay rates of heavy elements, time scales can be estimated for when supernova events may have happened. A few particularly useful elements have half-life decay times on the order of 10^8 to 10^{10} years, and they are used in a method called cosmochronology. The useful isotopes for dating nucleosynthesis events that created Earth's material are U-235 and U-238, which have half-lives of 7.13×10^8 and 4.51×10^9 years, respectively. The present day ratio of these two isotopes is roughly U-235/U-238 = 0.007. Given their decay rates, the abundance of these elements at the time the solar system formed (roughly some billion years ago) should have been about 0.3. Within a supernova explosion, models predict that the production ratio should be approximately 1.5. Thus, depending on how many supernova explosions contributed to the abundance of uranium isotopes we see today, the time of their occurrence is estimated to be from 2 billion years ago (if only a single supernova) to 10 billion years ago [24]. Given the timescales discussed above, it is interesting to ponder with respect to the present understanding for the age of the visible universe, which is ~13.77 billion years [28].

However, the rapid neutron-capture process needed to build up many of the elements heavier than iron seems to take place primarily in more seldom neutron-star mergers, not supernova explosions, as stated by some authors [29].

8. Life Span of Stars

An important issue of cosmic star building processes is the final life span of the stars. At the end of the life of long lived intermediate and short lived massive stars they either convert selectively into white dwarfs, neutron stars or black holes. Assuming that an intermediate star lives one thousand times longer than a massive star, according roughly to a log-log distribution (see **Table 1**) [30], and that their relationship remained constant through the history of the Milky Way

Table 1. Representative lifetimes of stars as a function of their masses after [30].

Mass (solar masses)	Time (years)
60	3 million
30	11 million
10	32 million
3	370 million
1.5	3 billion
1	10 billion (sun)
0.1	1000s billions

(theoretically), then the birth rate of massive stars could have been really high once by counterbalancing their high death rate, fertilizing subsequently the interstellar medium, especially the spiral arms of the Milky Way galaxy with a large amount of heavy chemical elements. However, by taking the fraction values of sun-like stars (7.6%) and of massive stars larger than 16 $M_{\odot}$ (~0.00003%) (**Table 2**) and calculating a proportion of about 253,000, the general birth rate of massive stars may have been comparable low.

According to **Table 1** the largest intermediate stars that convert to white dwarfs may live only estimated 50 million years. After their birth they may already explode on their path before leaving the spiral arm and distribute their chemical elements to the local cosmic dust cloud through the development of short living planetary nebulae (about 50,000 years) in course of their death. In this case the energy output during the explosion could be close to the one of a supernova. A larger portion of short living intermediate stars with their closeness to massive stars could also be the cause of a higher white dwarf count as obviously recognized (**Figure 5**). This could enlarge the probability of a contemporaneous development of massive stars and their following death as supernovae. In this sense **Table 2** encompasses some properties and frequencies of so-called main sequence stars. White dwarfs and all giants as residues are excluded. About 23% of the main sequence stars are low- to intermediate-mass stars (~0.4/0.45 to 8 $M_{\odot}$) and the important source from which the abundant white dwarfs develop. Following these observations the number of supernovae related neutron stars and black holes should be comparable small, depending on the real birth rate of massive stars. The investigation of cosmic isotopes at the bottom of the sea delivered a time gap of about 4 million years between assumed supernovae explosions of massive stars within an effective vicinity to the solar system [22], leading to the assumption that the time gap between exploding intermediate-mass stars inside the same region of the Milky Way galaxy must be significantly shorter. Their total contribution of chemical elements to the cosmic dust entering the Earth is certainly of great importance as well, and may interfere with the contributions of supernovae. This may also be true for the arrival of cosmic rays that are related to intermediate star explosions, including accompanying Earth penetrating neutrinos.

Table 2. Properties and frequencies of main sequence stars, white dwarfs and all kinds of giants excluded. 23% of these stars are low- to intermediate-mass stars, and the important source, from which the white dwarfs develop (~0.4/0.45 to 8 $M_{\odot}$). Modified from [https://en.wikiversity.org/wiki/Stars/Astronomy].

Class	Temperature K	Conventional color	Mass (solar masses, $M_{\odot}$)	Radius (solar radii, R)	Fraction of all main sequence stars
O	≥33,000 K	blue	≥16	≥6.6	~0.00003%
B	10,000 - 33,000 K	blue to blue white	2.1 - 16	1.8 - 6.6	0.13%
A	7500 - 10,000 K	white	1.4 - 2.1	1.4 - 1.8	0.6%
F	6000 - 7500 K	yellowish white	1.04 - 1.4	1.15 - 1.4	3%
G	5200 - 6000 K	yellow	0.8 - 1.04	0.96 - 1.15	7.6%
K	3700 - 5200 K	orange	0.45 - 0.8	0.7 - 0.96	12.1%
M	≤3700 K	red	≤0.45	≤0.7	76.45%

9. Phosphorus for Life

On Earth, there have always been several essential components for the promotion of life, and the slow evolutionary route from Microorganisms to Humans. Water is certainly one of them. But one important ingredient that has always been rare, and whose geochemical cycle leads to separated forms that are not readily available to biota, is phosphorus. When Earth formed 4.5 billion years ago, any phosphorus that was present likely sank into the molten core because of the element's distinct chemical properties. The Earth never started off with much of this element. The average crustal concentrations of phosphorus are about 0.1 wt. percent. Apparently, the only source of phosphorus to the global biosphere appeared to be the chemical weathering of minerals exposed in continental rocks. As long as the planet has been oxygenated, much of the phosphorus made available by continental weathering is promptly caught by iron oxidation. As a pure "water world" planet without plate tectonics, concealed totally by ocean with no opportunity of terrestrial supply of phosphorus, the evolution of life on Earth would have been dramatically hampered. Without exposed land mass for weathering, there is not a viable mechanism for nutrient delivery and possible climate stabilization [31].

Phosphorus is one of just six chemical elements on which Earth organisms depend. As already mentioned above, almost all chemical elements have been made by nucleosynthetic reactions in various kinds of stars and have been collected along our cosmic history. Phosphorus is found in DNA, RNA, and other important biological molecules. It is crucial to the compound adenosine triphosphate, which cells use to store and transfer energy. However, since the supply of phosphorus from internal subsurface sources appears to be somehow limited, additional external sources may play a crucial role. Phosphorus that made life possible could have been delivered to Earth's surface from extraterrestrial origins, and previous studies have proposed meteorites as potential sources. Based on a recently published analysis [32] much smaller extraterrestrial particles known as cosmic dust—as already mentioned above—may also deliver phosphorus to Earth's atmosphere. The availability of cosmic dust is certainly dependent on the location of the solar system on its path through the dusty spiral arms of the Milky Way galaxy. A series of chemical reactions convert then the phosphorus into biologically useful forms like metal phosphites and phosphates that eventually fertilize, periodically Milky Way driven, Earth's surface. The ablation of phosphorus from interplanetary dust particles entering the Earth's atmosphere is a potentially significant source of this key bioelement. The estimated current global mean P (phosphorus) deposition flux, in the form of submicron-sized MSPs (meteoric smoke particles as metal phosphites and phosphates, respectively), is 1×10^{-8} $g \cdot m^{-2} \cdot yr^{-1}$, with a maximum of $\sim 5 \times 10^{-8}$ $g \cdot m^{-2} \cdot yr^{-1}$ (northern Rockies, Himalayas, and southern Andes). The fraction of phosphorus creating bioavailable metal phosphites is estimated to be 11% [33].

10. Petroleum Source Rocks

Source rocks are rocks which have generated petroleum (oil and gas) or which would be able to generate those hydrocarbons. They are organic-rich sediments (e.g. black shales) that may have been deposited under a range of environmental conditions including deltaic, lacustrine and marine. Nutrient availability was certainly a key driver for the necessary bloom of biota ahead of the deposition of organic carbon and the supply with phosphorus was crucial for this process. Therefore the deposition of source rocks may have additionally to geological conditions a galactic component.

Source rocks are characterized through the types of biotic matter that they contain:

- Type I source rocks are created with remains of algal mats deposited under anoxic conditions in deep sweet water lakes.
- Type II source rocks are made from marine bacterial and planktonic relics conserved under anoxic conditions in marine environments.
- Type III source rocks are produced from terrestrial plant material that has been disintegrated by bacteria and fungi under oxic or sub-oxic conditions. Most coals and coaly shales are Type III source rocks.

Source rocks of six stratigraphic levels generated more than 90% of original recoverable petroleum reserves in the world: 1) Silurian (9%), 2) Upper Devonian-Tournaisian (8%), 3) Pennsylvanian-Lower Permian (8%), 4) Upper Jurassic (25%), 5) middle Cretaceous (29%), and 6) Oligocene-Miocene (12.5%).

Apparently the concentration of source rocks does not follow a distinct mechanism because the areal distribution, point of origin in specific structural forms, and actually the geochemical character of them altered from one interval to another. The geologic age and the evolution of biota played an important role as well.

Certain source rocks are referred to as "world class" with very high quality, a large thickness and of wide geographical distribution. Examples include:

The Upper Jurassic marine Kimmeridge Clay or its stratigraphic equivalents generated most of the oil found in the North Sea and the Norwegian Sea (**Figure 8**) [8]. The laminated carbonate-rich upper Jurassic Hanifa Formation sourced the giant Ghawar field in Saudi Arabia with oil. Both geological layers may represent Mesozoic high quality source rocks. The most important change in the character of source rocks during the Phanerozoic was the evolution of source rocks based on type III kerogen and coal. The effectiveness of these source rocks achieved its optimum in the Oligocene-Miocene (**Figure 9**) [8].

The worldwide distributions of these two world class source rocks of Mesozoic and Tertiary age, which were deposited across all climatic zones between the equator and the poles, and across all different geological circumstances, are shown in **Figure 8** and **Figure 9**. This demonstrates clearly that severe global processes must have been very active, independent from the climatic conditions with their Milky Way driven periodicity of 150 million years. Climate may therefore be only of secondary order for biotic blooms. Contemporaneous life supporting global availabilities of phosphorus as an important portion of necessary nutrients may have fertilized worldwide deltas, lakes and oceans. A cosmic source of phosphorus appears likely. Since black shales and coals show generally higher uranium concentrations than usual sediments, an additional cosmic source of this heavy element may have also been effective, contemporaneously with the possible entry of cosmic phosphorus to the surface of the Earth.

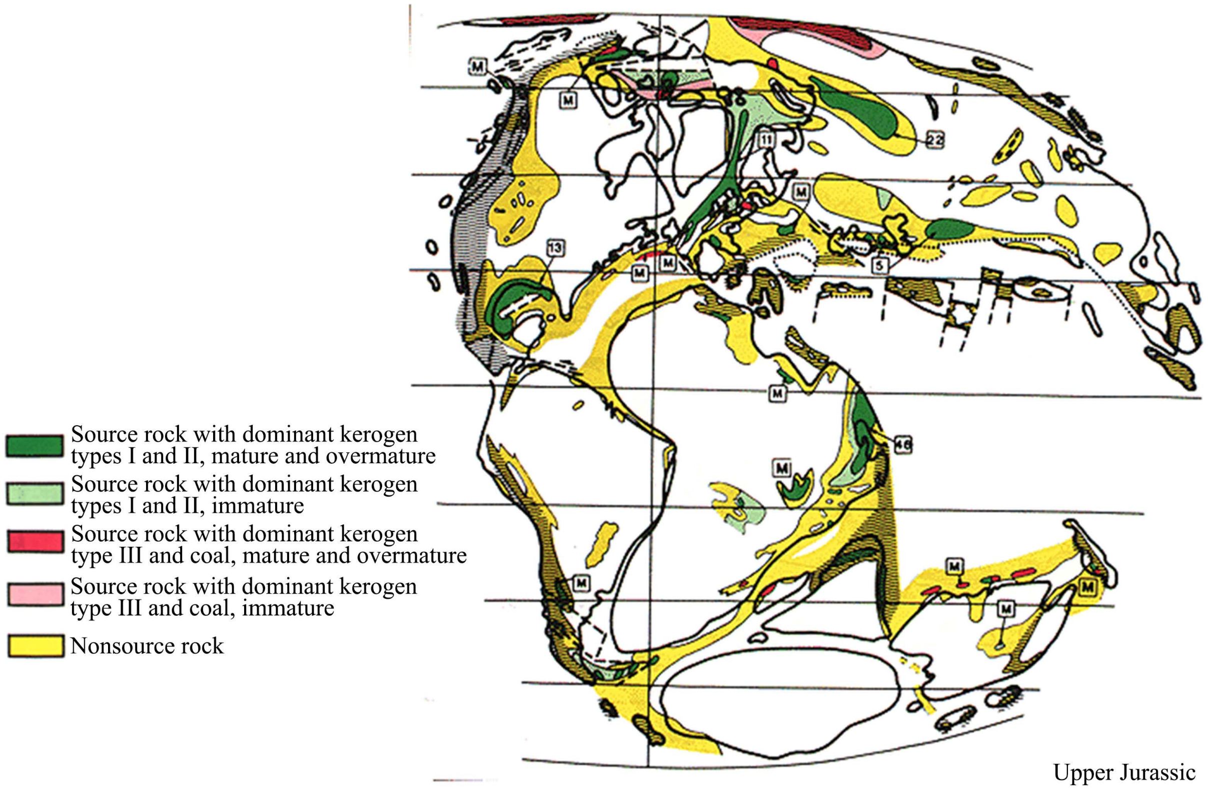


Figure 8. Paleogeography of the Upper Jurassic source rock distribution [8], across all climatic zones between the equator and the poles, and across all different geological circumstances.

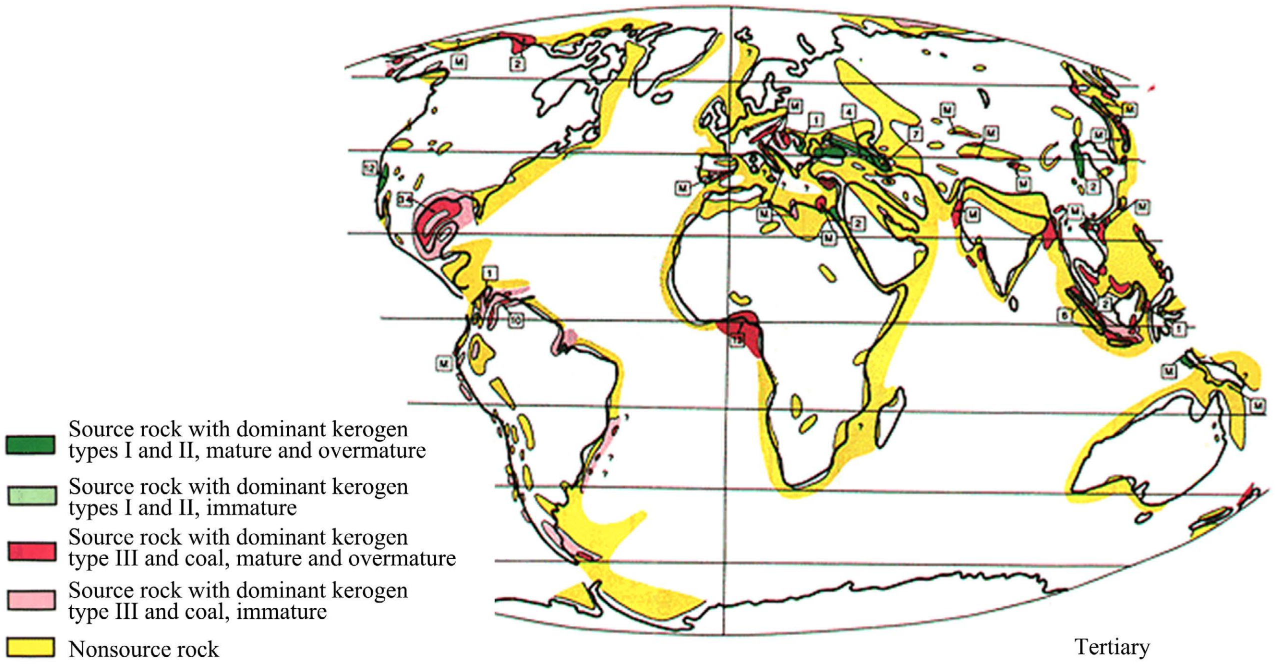


Figure 9. Paleogeography of the Oligocene—Miocene source rock distribution [8], across all climatic zones between the equator and the poles, and across all different geological circumstances.

11. Cosmic Uranium?

At least the observation that globally significant resources of uranium have been mineralized in the near surface environment involving meteoric water during Upper Jurassic and Miocene times simultaneously with the deposition of remains of blooming biota and the concentration of uranium therein, a cosmic contribution appears to be a realistic assumption.

More than 4000 sandstone-hosted uranium occurrences host over 0.54 Million tons of mined and in situ U^3O^8 (uranium-oxide) throughout the Colorado Plateau/USA (**Figures 10-12**). This is about 30% of the world endowment of tabular and basal channelsandstone-hosted deposits. Most of the resources are in two distinct mineral systems with deposits hosted in the Triassic Chinle and Upper Jurassic Morrison Formations. In the Chinle mineral system, base metal sulfides typically accompany mineralization. However, the dominant Morrison mineral system represents about 80% of the regional resources. As uranium source volcanic ash preserved as bentonitic mudstones within the Morrison Formation, and lithic volcanic clasts, ash shards and bentonitic clay in the lower part of the Chinle Formation have been currently suggested. Transport in both systems was likely in groundwater through the more permeable sandstones and conglomerate units. The first comprehensive examination of paleoclimate, paleotopography, and subsurface structure of aquifers coupled with analysis of the geochronology of deposits suggests that there were distinct pulses of uranium mineralization/redistribution during the period from about 259 Ma to 12 Ma with a significant maximum during the Upper Jurassic when oxidized mineralizing

Figure 10. Erosional topography of Monument valley on the Colorado Plateau/USA.

Figure 11. Grand Canyon, cutting through the uranium bearing Colorado Plateau/USA.

Figure 12. Colorado River as transport way for the eroded rock grains of the uplifted Colorado Plateau/USA, making uranium resources—mainly with Upper-Jurassic mineralization age—available for mining.

fluids were intermittently rejuvenated in the Plateau in response to changes in tectonic regime and climate. Multiple lines of evidence indicate that deposits formed at ambient temperatures of about 25˚C to no greater than about 140˚C. In both systems, deposits formed where groundwater flow slowed and was subject to evaporative concentration [34].

During Upper Jurassic and Miocene, especially in the USA and China (**Figure 13**), the formation and/or preservation of sandstone-style uranium deposits appears to be partly controlled by tectonic uplift events, especially those generated in an open system by the infiltration of meteoritic water. In general, modern landforms were shaped by diverse global tectonic events that began in the Middle and Late Miocene. This includes the formation of continental-scale orogens, including the uplift of the three broadly contemporaneous ranges, the Alpine-Himalayan Belt, the Cordillera, and the East African Rift. Studies on sandstone-style uranium deposits report that though their stratigraphic ages extend from the Proterozoic to the Cenozoic, they remarkably occur from the Late Jurassic to the Neogene. Uranium mineralization ages during the Tertiary are concentrated between 20 and 0.1 Ma, clustering mainly in the Miocene although remobilizations are known to have occurred afterwards, some even in the Holocene. Global tectonics in the Miocene, between 20 and 5 Ma, resulting in the regional uplift of mountain ranges, may have applied substantial control over the migration directions of uranium-bearing fluids that formed these sandstone-style uranium deposits. The near surface mineralization systems may indicate that the entry of uranium via rain from atmospheric clouds containing cosmic dust as condensation nuclei could have been an additional source [35].

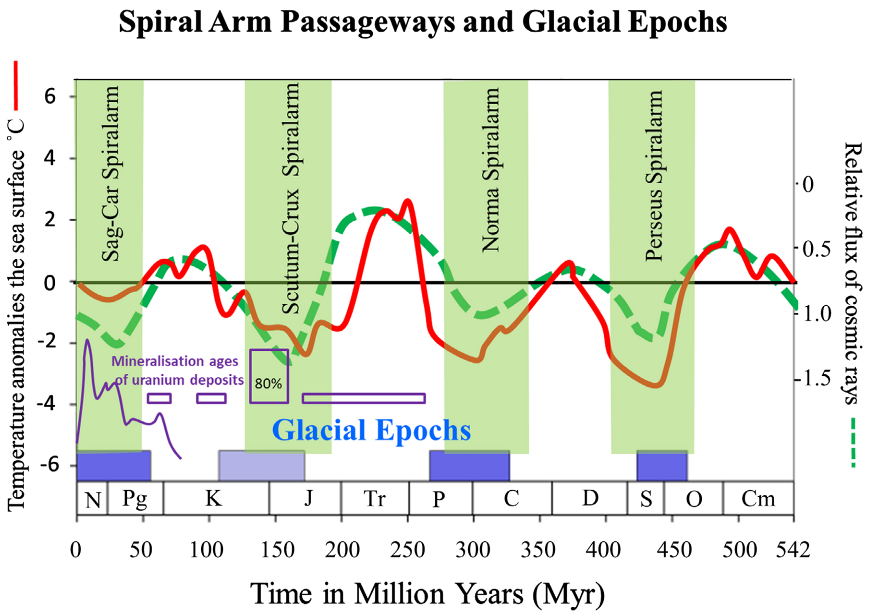


Figure 13. Global sandstone-style uranium mineralization ages, many of them occur in the Miocene (China) and later (violet curve) [35], and ages of mineralization of the Colorado Plateau/USA (violet boxes) [34], presented by using **Figure 2**. Not to scale.

12. Conclusion

By combining astrophysical, geophysical, geological, meteorological and biological data for a timespan of several 100 million years the evolution of the Earth appears continuously and strongly related to properties of the Milky Way galaxy. This encompasses, coming from backwards, the deposition of energy resources like oil and coal, the bloom of biota ahead of that, the entry of cosmic dust in our atmosphere from the interstellar medium containing phosphorus and uranium among other elements, the detonation of long lived intermediate and short lived massive stars and the related production of heavy elements mainly within the spiral arms of the Milky Way galaxy, the wandering of the solar system through these spiral arms along a path around the Milky Way center, and the subsequent long term climatic effects on Earth with a 150 million year periodicity. According to this evaluation, leaving the current spiral arm by the solar system in the near geological future (millions of years), the climate on Earth may get warmer, the ice-caps at the poles vanish, the sea level rises, and the height of the orogens shrinks due to erosion of their peaks and metamorphism of their roots with a related crystal water release. The reduction of the phosphorus input may lead to a decrease of biota growth on land and in sea with all the problems that may follow for all then living species. In addition to the primordial Earth inside the habitable zone of the sun the overall adjacent and ever-changing cosmic space with all its periodically/episodically varying ingredients appears to be a further pillar of life on Earth, subterraneously archived and globally and repeatedly represented through the buried fossil remains.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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