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Cosmic Rays, Supernovae, Gamma-Ray Bursts, and Life

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The circumstellar habitable zone (CHZ) is usually described as a sphere surrounding a star (which translates into an annulus in the orbital plane) capable of having planets with surface water. The CHZ is necessary for the development and maintenance of complex life, but it is not sufficient. Here we address the idea that ionizing radiation also has a major determining effect for planets that are either favorable to or inhospitable to complex life as we know it. We discuss high-energy radiation and particles from the bedrock of the Earth, as well as the Sun, and cosmic rays from both Galactic and extra-galactic sources. There are two general kinds of ionizing radiation: 1) high-energy electromagnetic waves like gamma rays, X-rays, and UV radiation, and 2) particle radiation, including radioactivity, from the Earth's crust and cosmic rays. Cosmic rays include high-energy particles from the Sun, and particles from high-energy sources in the Galaxy, like novae, kilonovae, supernovae, microquasars, and gamma-ray bursts. Ultra-high energy cosmic rays originate from extra-galactic sources, like accreting black holes with jets. We discuss the various threats involving ionizing radiation and their effects on complex life. Essentially all galaxies at least as massive as the Milky Way have central supermassive black holes which may often be quiescent, but could occasionally be quite active. We focus here especially on supernovae and gamma-ray bursts, as well as the Galactic cosmic rays associated with these explosions as these are the most prevalent threats constraining complex life in the Milky Way today. We discuss the layers of biosphere protection against cosmic rays including the planet's atmosphere, the ozone layer, the planetary magnetosphere, the stellar wind and its boundary layer outside (known as the astrosphere and astropause), the Galactic magnetic field and the Galactic magnetic wind with its boundary layer (which we call the Galactosphere and Galactopause). In addition, the effects of ionizing radiation on life on Earth's surface and in shallow water are discussed. We summarize the evidence for nearby supernovae in Earth's past and the current mass extinction rates from stellar explosions. Finally, the speculation on an astrophysical cause of the homochirality of organic matter is addressed.

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1. Introduction

In 1859, the most intense solar flare ever observed occurred, called the Carrington Event. That same year, Charles Darwin published "On the Origin of the Species by Natural Selection" [1] in which he laid out his principle of evolution by natural selection. He took the variation seen in populations, for example, the variation in the beaks of finches in the Galapagos islands, combined with the idea that traits can be inherited, and visualized the slow change in a species caused by survival of the fittest by natural selection. Fitness is defined generally as the potential for an organism to produce new members of the species, which are also able to reproduce. Both natural selection and sexual selection, Darwin argued, drive evolutionary change, meaning that higher fitness organisms are more equipped to obtain food, without becoming food, and/or to compete for mates. All of this produces more high-fitness offspring, thereby improving the overall population fitness. Separate populations of the same species could then diverge and over time become an entirely new species, a process called speciation. The beaks of finches had adapted to become specialists at obtaining food from their local environment. Darwin himself pointed out a major challenge to this theory of slow evolution. Namely, that everything makes sense going backward through the fossil record, however, 538.8 million years ago animals suddenly appeared and developed into all of the forms that we know today, within about 10 million years. This geologically short period is called the Cambrian Explosion.

Just a few years later, around 1865, Gregor Mendel worked on the inherited properties of pea plants [2]. He found that genetic characteristics have alternate forms, like purple and white flowers, and are inherited from the individual's parents. Some traits were found to be dominant and some were recessive, meaning that the dominant traits would appear in the offspring, but the recessive ones would only very rarely reappear. Importantly, these genetic traits are not linked, so having one trait does not depend on having another. For example, plants could have purple or white flowers with short or long stems, as color and length are passed down independently. In 1902, Walter Sutton and Theodore Bovary independently described the underlying mechanics of Mendel's inheritance using the idea of chromosomal inheritance. But it was not until 1930 that natural selection and Mendelian inheritance were unified when Ronald Fisher published "The Genetical Theory of Natural Selection". The so-called Modern Synthesis of Evolution continued with Ernst Mayer in 1959, G. Ledyard Stebbins in 1966, and Theodosius Dobzhansky in 1974, whose synthesis all involved natural selection operating on the heritable variation supplied by mutations. In other words, mutations produce the variety on which natural selection acts. The Modern Synthesis of Evolution is shown in Figure 1 as an extension of Darwinism. The Modern Integrated Synthesis of Evolution is multivariate and its review is beyond the current scope. We emphasize only that the imperfect transfer of information due to mutations in DNA remains integral to $21^{st}-$century evolutionary theory.

A phenotype is the physical expression of DNA, like eye or hair color, or the purple versus white flowers of Mendel's pea plants. The genotype, on the other hand, is the chemical makeup of an organism's DNA that causes a particular phenotype. Several genotypes may produce a single phenotype. Not all traits are adaptive; to be adaptive a trait must improve the fitness of the organism. We now briefly define parts of the integrated synthesis of evolution, see Figure 1. The neutral theory of molecular evolution suggests that genetic variation in populations is mostly the result of

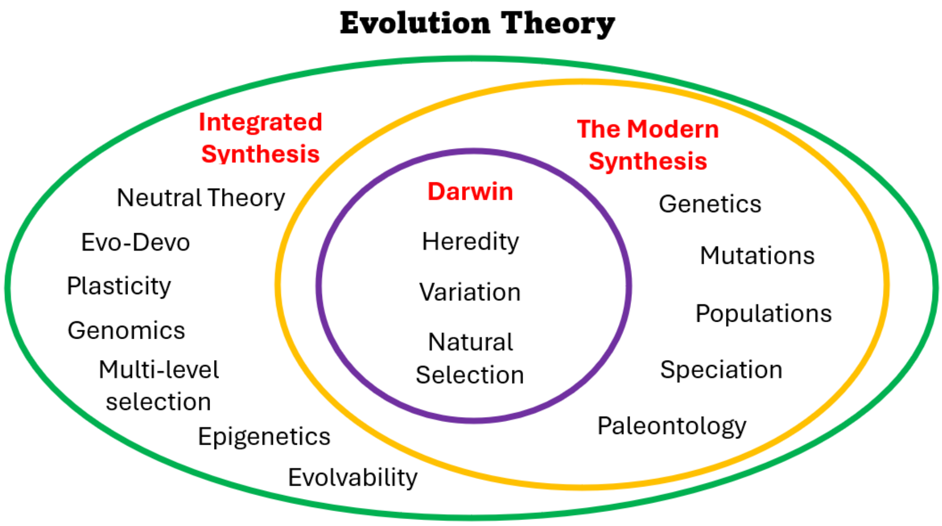

Figure 1: A Venn diagram showing the relationship and major qualities of Darwinian evolution, the Modern (20th-century) Synthesis, and the Integrated Evolutionary Biology Synthesis of the 21st-century. Darwinism remains at the center of evolutionary theory. The Modern Synthesis unified natural selection with genetic variation of populations driven by mutation. The Integrated Synthesis includes higher-order evolutionary processes, like evo-devo (evolutionary development) and epigenetics, which studies how cells control gene activity (turning genes on or off) without changing the DNA sequence.

mutation and genetic drift, rather than selection. Developmental evolutionary biology (evo–devo) is concerned with how changes in embryonic development during single generations relate to the evolutionary changes occurring between generations. Plasticity is the capacity of an individual organism to alter its behavior, physiology, gene expression, and/or morphology in response to pressure due to changing environmental conditions. Genomics focuses on the structure, function, evolution, mapping, and editing of genomes. Multi-level selection argues for the importance of selection at levels above that of single organisms in evolution, like kin, or other small group, selection. Epigenetics is the study of heritable changes in gene function not involving changes in DNA, a change in the phenotype without changing the genotype. Evolvability is the ability to produce phenotypic variation that is both heritable and adaptive.

Contemporaneous with Darwin, many discoveries were beginning to revolutionize experimental physics. In 1858, Julius Plücker installed two electrodes inside a vacuum tube and discovered so-called cathode rays traveling from one electrode (the cathode) to the other electrode (the anode). Although not understood at the time, this was the beginning of particle physics. Before this, it was thought that matter could emit radiation only if heated, if a high voltage was applied, or if light was shone upon it (in the rare case of fluorescence). Much later, in 1895, Wilhem Röntgen, in another experiment with cathode ray tubes found [3], by accidentally having left photographic materials nearby, that they were exposed to some mysterious radiation that he called X-rays (because of their unknown nature). Because they are capable of penetrating materials, including flesh, the medical use of X-rays was quickly exploited. In 1896, Henri Becquerel discovered strange 'rays' [4] coming from uranium (U). In 1897, J.J. Thompson experimented with cathode ray tubes and showed that

X-rays can ionize gas. He also discovered that cathode rays were electrons because their direction would bend the same way in the presence of a magnetic field, indicating that they were charged particles [5]. Pierre Curie and Marie Curie discovered, in 1898, that radiation from uranium (coined radioactivity by Marie Curie [6]: see Figure 2) also radiated from the elements polonium (Po) and radium (Ra). Radium was named by Marie Curie based on its especially high-intensity radiation. The radioactivity of Thorium (Th) was discovered by Gerhard Schmidt in 1898. On Earth, there is a lot of radium (Ra) and radon (Rn) as ^{226}Ra and ^{222}Rn are both produced as part of the ^{238}U (4.5 Gyr half-life) and ^{232}Th (14 Gyr half-life) decay chains. Radon levels in homes, especially basements, should be checked as thousands of cancer deaths, caused by Radon, occur each year in the United States alone, according to the Environmental Protection Agency, see Figure 3. Ernest Rutherford, with Thomas Royds, experimented with radioactivity and shielding material of varying thickness and found that radioactivity produced two types of radiation [7]. The alpha (α) rays did not penetrate materials deeply, while the beta (β) rays were able to penetrate deeply. He established the compact nature of the nucleus and determined that the α particles have charge +2, which turned out to be the nuclei of helium atoms. Further experiments showed that β particles (cathode rays) are deflected by electric or magnetic fields and come in two types, negative electrons and positively charged positrons (anti-electrons). The radioactive element Radon emits a third type of ray (Figure 2) that is not deflected by a magnetic field and is very penetrating. Rutherford called them gamma (γ) rays and they are electromagnetic waves that are higher energy than X-rays. Figure 2 shows a schematic diagram of α, β, and γ radioactive decay. In 1904, Rutherford proposed the (incorrect) idea that the radioactive decay of elements in the Sun might resolve the tension between Lord Kelvin's estimate of a relatively short solar age and the slow evolutionary change required by Darwin. From radioactive dating, we now know that the Earth is 4.5 Gyr old, rather than the 24 - 400 Myr proposed by Kelvin in 1863. Today, we know the Sun lives on Hydrogen turning into Helium, and so it will live about another five billion years.

2. Ionizing Radiation

Ionizing radiation is a form of energy that, upon interacting with matter, removes electrons from atoms or molecules. The resulting atoms become positively charged due to the loss of one or more negatively charged electrons. Ionizing radiation comes in two very different forms: 1) high-energy electromagnetic radiation and 2) particle radiation. The highest energy photons, namely the Ultraviolet (UV), X-rays, and γ-rays (gamma rays) are capable of ionizing water and other materials. Likewise, cosmic ray particles: protons, neutrons, electrons and so on, often have enough energy to ionize atoms.

On Earth, the sources of ionizing radiation include high-energy electromagnetic radiation from the Sun, solar particle radiation - such as energetic solar particles (SEPs); cosmic rays accelerated by Galactic and even some extra-galactic sources; and natural radioactivity. Today, the latter supplies the highest dose of ionizing radiation to animals. Cosmic ray particles include protons, neutrons, electrons, positrons, muons, the nuclei of helium atoms as well as the nuclei of heavier atoms.

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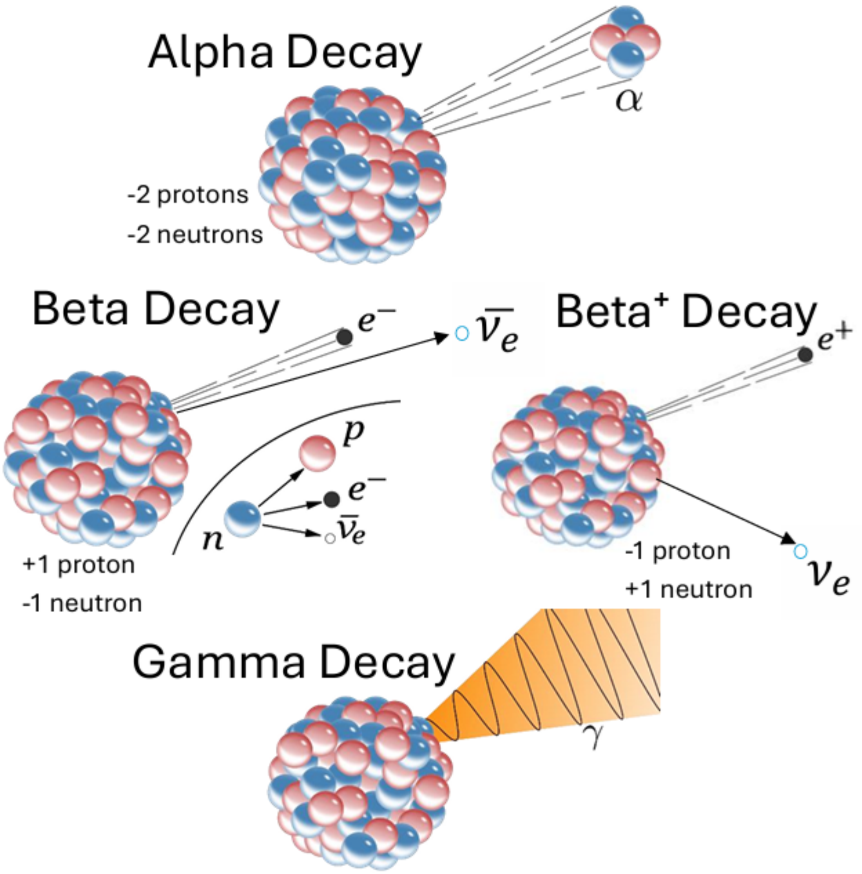

Figure 2: Three types of radioactivity are shown schematically. The α-rays, top, are nuclei of helium atoms with a charge of +2. The β-rays (also called cathode rays) are electrons with a charge of -1 (middle left) or positrons (β+ decay) with a charge of +1 (middle right). An (electron) neutrino, ν_e, or antineutrino is also emitted during β decay. The γ-rays, bottom, are neutral high-energy electromagnetic radiation. The change in the nucleus is shown in each case. A free neutron undergoing β decay is shown inset. Credit: Adapted from public domain images.

2.1 Natural Radioactivity

Natural radionuclides occurring in significant quantities in the soil, water, and air, include potassium ^{40}K, Uranium ^{238}U, and Thorium ^{232}Th. Through the process of differentiation and plate tectonics, the vast majority of the more massive elements including radioactive Th and U have been depleted from the crust because heavier elements sink downward in the mantle preferably compared to the lighter elements, for example silicon, which rises due to gravitational differentiation. In this way, the core contains most of the iron (Fe), as well as most of the radioactive elements, in the Earth. The crust became rich in silicon (Si) and magnesium (Mg) and their compounds. Of course, the differentiation of the materials inside the Earth was most active during its formation, as the crust had yet to form and the surface was covered by iron-rich molten lava.

During early Earth, the asteroid and comet bombardment frequency was many orders of magnitude higher than it is today. Not only did these comets and asteroids bring new materials

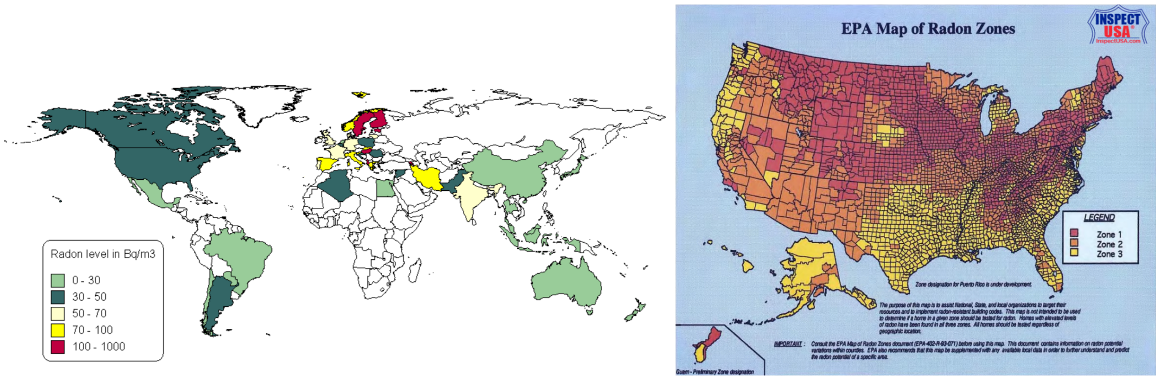

Figure 3: Left: Radon exposure is shown in countries for which adequate data is available. **Right:** Radon levels are broken down by county in the USA. To compare the two plots note that the units on the left are Bqm^{-3} and on the right zone 3 is less than 74 Bqm^{-3}, zone 2 is between 47 and 148 Bqm^{-3}, and zone 1 is above 148 Bqm^{-3}. Regions like Australia, Brazil, and the southeastern USA are relatively safe; while areas in Scandinavia and the Rocky Mountains, for example, have potentially dangerous radon levels. Credits: United Nations, the U. S. Environmental Protection Agency (EPA), and InspectUSA.com.

to the surface, the impacts also brought a lot of kinetic energy, causing frequent melting and breaking of a nascent crust. They brought with them undifferentiated raw materials from which the planets originally formed including rocks, metals, and water. And possibly, comets brought organic molecules to early Earth [8].

Short-lived radioactive nuclei present during the formation of the Earth have long since decayed into stable forms. However, three massive radioactive isotopes: ^{232}Th, with a 14.1 Gyr half-life, ^{235}U, with a 700 Myr half-life, and ^{238}U, with a 4.5 Gyr half-life, each decay through a complex series of alpha and beta decays. Each daughter nucleus in the series has a different half-life and ends with the stable nuclei ^{208}Pb, ^{207}Pb, and ^{206}Pb respectively. Lead is the most massive non-radioactive element and only the relatively rare isotope (2% of the lead on Earth) ^{204}Pb does not originate from the decay of heavier nuclei, so most of the lead near the Earth's surface was once a heavier element like Th or U. The age of the Earth is estimated to be 4.54 Gyr based on the ratio of uranium to lead present in rocks on Earth today [9]. Radon (^{222}Rn), with a half-life of 3.8 days, is an intermediate product of the ^{238}U decay series and is a significant source of background ionizing radiation on Earth, depending on the location, see Figure 3.

The effects of an exoplanet having radioactive abundances that are different than Earth's are not well understood, but a few things seem clear. A planet with fewer radioactive elements than the Earth will have a shorter geophysical lifetime, implying that the magnetic dynamo would slow down prematurely, weakening the dipole magnetic field and the protection it provides against SEPs from the Sun and cosmic rays. Having some radioactive elements is essential for developing a living planet, as radioactivity in the core and mantle substantially slows the inexorable cooling of rocky planets. Today about one-half of the Earth's internal heat comes from radioactive decay and the other half remains from the Earth's formation [10].

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2.2 Magnetic Activity of Planet Host-Stars

Stars are formed as hot balls of plasma spinning very fast; this engenders magnetic fields. Note that when gas is very hot, some or all of the electrons are removed from atoms and the ionized gas is called a plasma, composed of ions and electrons, but neutral in net charge density. Stars are made of plasma except for the cooler outermost layer exposed to space. Stellar rotation always implies differential rotation as rotation acts quite differently towards the equator than near the poles. This effect is apparent on the surface of the Sun by observing the location and motion of sunspots. Differential rotation results in circulations of plasma (called von Zeipel currents); similarly, circulations occur in convective zones in a rotating star: all these circulations enhance magnetic fields in a process called the magnetic dynamo. These currents enhance existing magnetic fields, called seed fields which must exist, since in any rotating star, surfaces of constant pressure and constant density do not coincide, so driving weak electric currents. These currents provide the seed field, which gets enhanced, all the way to equipartition, when instabilities can occur limiting further strengthening.

The magnetic activity of the Sun, and other stars, produces X-rays, UV radiation, and magnetized stellar winds. The high-energy radiation and winds erode the atmospheres of planets in the circumstellar habitable zone. Stellar winds carry particles and magnetic fields, along with their angular momentum, away from the star and out into the interstellar medium. This causes stars to slowly lose angular momentum, which causes their rotation to slow. Since the magnetic activity depends on the star's rotation rate, stellar magnetic activity reduces over time. So the X-ray and UV radiation fluxes and the solar/stellar winds go down with age. This is not to be confused with blackbody radiation from the star which is used to determine the habitable zone and the UV habitable zone around the Sun and other stars. A major difference is that the magnetic activity has the majority of its effect within the first 1-2 Gyr after the star is formed. If we go down to really low mass stars, for example late M-type stars, the fraction of their lifetime that they are active increases for lower mass. That means that, given the age of the universe, really low mass stars are all active.

The emission from a solar-like star is well approximated by a blackbody, with a slowly changing surface temperature; plus X-ray and UV radiation due to the magnetic activity. The latter source of high-energy radiation varies with an 11-year period - the solar cycle, as well as having a long-term decline due to the decrease in magnetic activity resulting from slowing rotation. This occurs while the surface temperature and optical luminosity of the star slowly increase, at an even lower rate for Sun-like stars, due to the conversion of hydrogen into helium in the core during main sequence stellar evolution.

2.2.1 High Energy Electromagnetic Radiation

High-energy electromagnetic radiation in our context includes ultraviolet (UV) light, X-rays, and gamma rays. The removal of planetary atmospheres by UV and X-rays from active host stars is significant in some cases [11,12]. High-energy electromagnetic radiation from the Sun would be a major source of ionizing radiation for life on Earth if it were not for the ozone layer. UV light disassociates ozone, UV + $O_3 \rightarrow O_2$ + O. Therefore, the creation of atmospheric ozone must exceed its destruction by UV light for an ozone layer, and the protection it provides, to persist. The formation of ozone depends on the oxygen content of the atmosphere, which was negligible until

2.4 Gyr ago when the Great Oxygenation Event (GOE) occurred. During the GOE, photosynthetic organisms, at first cyanobacteria and later algae, began dramatically transforming the atmospheric content. Today, ozone absorbs about 98% of the UV light that would otherwise impact life on the surface and in shallow waters. Recall that, 2.5 Gyr ago, the Sun was about 90% as bright as it is now, and it was a bit cooler, but the solar UV flux was significantly higher than it is today [13]. Likewise, the Sun will continue to increase in luminosity in the future, making it impossible for life on Earth (at 1 AU) in about 1 Gyr or less, ultimately becoming a red giant in ~5 Gyr. Life on Earth dramatically changed due to the rise of oxygen levels. On the one hand, O_2 was toxic to many organisms resulting in the collapse of ecosystems and ultimately mass extinction. On the other hand, O_2 provided the currency for a new high energy-consuming type of life.

2.2.2 The Solar Wind and Solar Energetic Particles (SEPs)

In addition to light from across the electromagnetic spectrum, including radio to gamma rays, the Sun and the other stars emit particles, collectively called the solar or stellar wind respectively. The solar wind was discovered by Ludwig Biermann in 1951 [14], based on the ion tails of comets. As noted, some of these wind particles are called solar or stellar energetic particles (SEPs) as they are likely accelerated to high energies by magnetic fields. The main mechanism to generate magnetic fields is also due to L. Biermann, who showed, with Arnulf Schlüter, that when the surfaces of constant pressure and constant density do not coincide, and they never do in a rotating star, electrodynamic forces drive an electric current [15,16]. Electric currents lead to magnetic fields. The resulting magnetic fields can be enhanced by the dynamo mechanism, to near equipartition with the plasma motions. Motivated by the discovery of the solar wind, a model was introduced by Eugene Parker in 1958 [17] and studied further by Edmund Weber and Leverett Davis [18] whereby stars with about the mass of the Sun and lower, which have outer convection zones, allow for a magnetic dynamo to be generated. The dynamo mechanism is due to Fritz Krause and Max Steenbeck, starting in 1965 [19] and in parallel to Parker, starting in 1969 [20]. Consequently a stellar/solar corona forms. The corona is responsible for extreme-UV and X-ray emissions as well as the acceleration of particles to high energies.

Solar/stellar winds have two sources, 1) a slow wind, ~ 400 km/s, from along the equatorial plane and 2) a fast wind, 500 - 800 km/s, launched through the optically dark corona holes. The largest coronal holes are located above magnetic poles. There is an asymmetry in the N-pole vs. S-pole wind velocities that changes according to the solar cycle. When the sun is at its maximum magnetic activity level (solar-max), the polar wind asymmetry is greatest. While winds are more intense during magnetic activity, the winds occur continuously and decrease, along with their erosive properties, over time as the star ages. A third source of particles from stars is a violent coronal mass ejection (CME).

SEPs form the high-energy tail of the distribution of solar wind particles. The lowest energy cosmic rays, up to a few GeV include the SEPs, while most of the lower energy particles from non-solar sources do not reach the Earth's surface. The stellar wind and SEPs in particular are responsible for planetary atmospheric mass loss, which is particularly important for planets orbiting low-mass M-type stars [21]. This is true, especially during the early active phase of stellar evolution. The lighter gases such as hydrogen and helium are susceptible to escape from rocky planet atmospheres. These gases have escaped and continue to completely escape from the Earth's atmosphere due to

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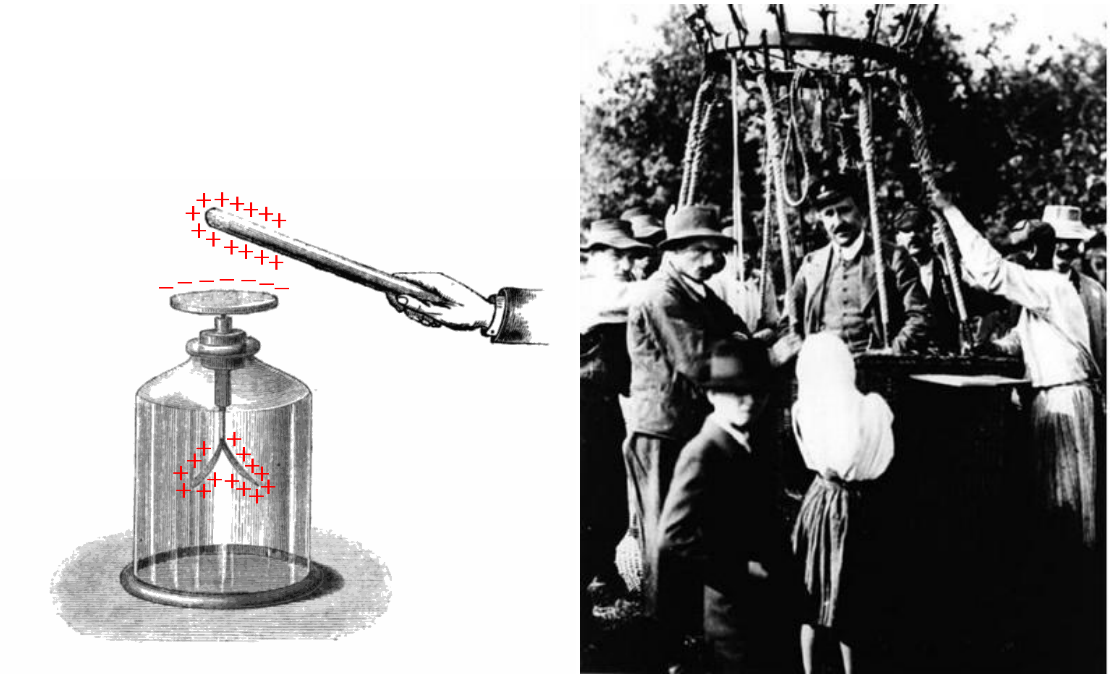

Figure 4: The discovery of cosmic rays. **Left:** A drawing of a gold-leaf electroscope. **Right:** A photograph of Victor Hess and assistants performing a balloon experiment in a successful effort to discover the nature of cosmic rays. While at first, the radiation decreased with altitude, it reversed and increased to 3 times ground levels at high altitude. Credit: Public Domain.

Earth's relatively low surface gravity. Water vapor, on the other hand, generally does not escape from the Earth's atmosphere due to a cold trap below the stratosphere, however, water reaching the stratosphere may be lost by hydrodynamic escape and/or photolysis [22].

The ozone levels at Earth are frequently measured and found to be inversely related to solar activity. For example in 1989, a solar proton event caused a 1-2% drop in the column-averaged ozone levels [23]. Although measurements were not available at the time, a 14% localized depletion of ozone for 4 years is believed to have occurred in 1859 [24], as a result of the Carrington event.

2.3 Cosmic Rays

The 1800s was a period of great discovery in the physics of electricity and magnetism through the experiments of Ampère, Faraday, and others, culminating in the unification of all electric and magnetic phenomena by James Maxwell, in 1855, into the equations of electromagnetism which remain a basis of modern technology. In 1865, Maxwell [25] showed that light is an electromagnetic wave and predicted the existence of radio waves. A measurement device called a gold leaf electroscope, as shown in Figure 4 (left), was commonly used in physics laboratories by the late 1800s. However, the electroscope presented a puzzle. A charge could be placed on an electroscope, but the charge would slowly and spontaneously disappear. It was thought (correctly) that natural radioactivity from the Earth delivered charge to electroscopes causing them to discharge. To test this idea, Theodor Wulf measured the effect of the radiation on an electroscope at the top of the Eiffel Tower and found that it decreased by a little more than 50% compared to

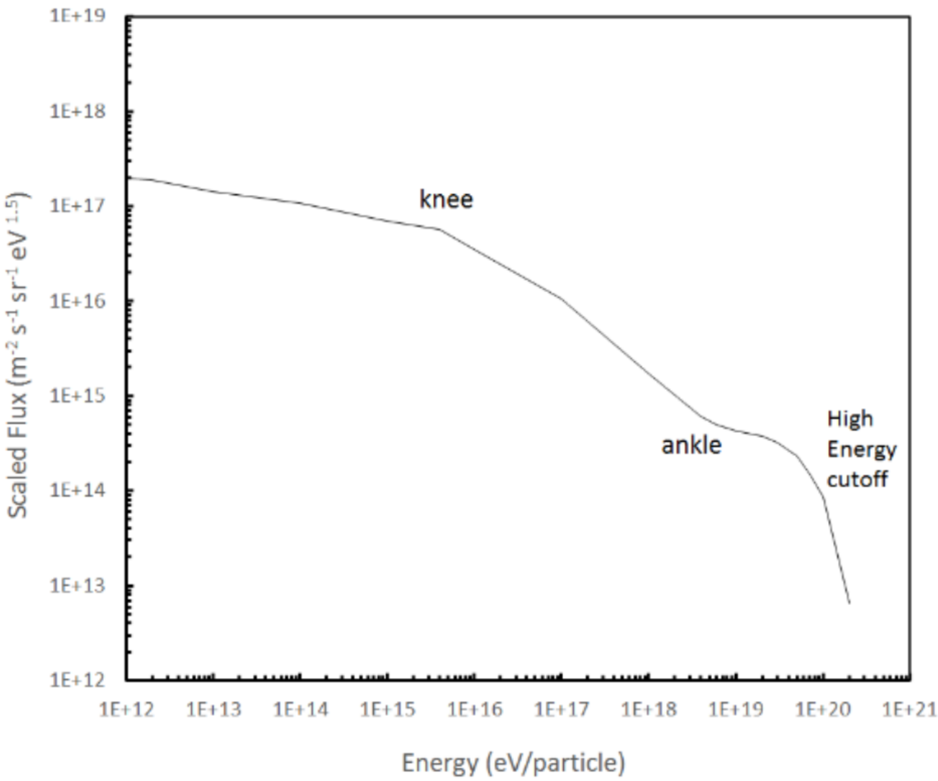

Figure 5: The cosmic-ray (CR) spectrum as detected on Earth is shown. The scaled flux is defined as the number of particles per unit area, per time, per energy, multiplied with energy to the 2.5 power, giving the units on the ordinate. SEPs (Solar Energetic Particles) can contribute significantly, if outside Earth, like on the Moon. SEPs can dominate lower energy cosmic rays on an unprotected exoplanet, especially because of their burst-like character. The spectrum shown here, on Earth, includes no SEPs whatsoever. Instead, Galactic cosmic rays (GCRs) dominate the spectrum at Earth from below 1 GeV to about $10^{17.5}$ eV, for protons to about $10^{19.0}$ eV for heavier nuclei, like iron. This feature is called the ankle. Above that energy, GCRs are taken over by extragalactic CRs, which reach the highest energies observed. The high-energy cutoff is about 10^{20} eV. Credit: Mason and Biermann [33].

ground measurements. However, this was much less than expected given the 300-m distance above the ground. Victor Hess took the experiment much further (literally) by performing high-altitude balloon experiments using electroscopes from 1911 to 1913 [26], see Figure 4 (right). Hess showed the mysterious radiation that would cause electroscopes to lose their charge, while at first decreasing with altitude as the balloon rose above the surface of the Earth, the radiation began increasing as the balloon went higher and higher in the atmosphere. It became clear that this radiation consisted of particles from beyond Earth and thus it was called cosmic radiation or cosmic rays. The source of this mysterious radiation was unclear until 1934 when Walter Baade and Fritz Zwicky suggested that gaseous remnants of supernova explosions are a source of Galactic cosmic rays [27]. However, it was still unclear how particles could be accelerated to such high energies. The cosmic ray spectrum as detected at Earth is shown in Figure 5.

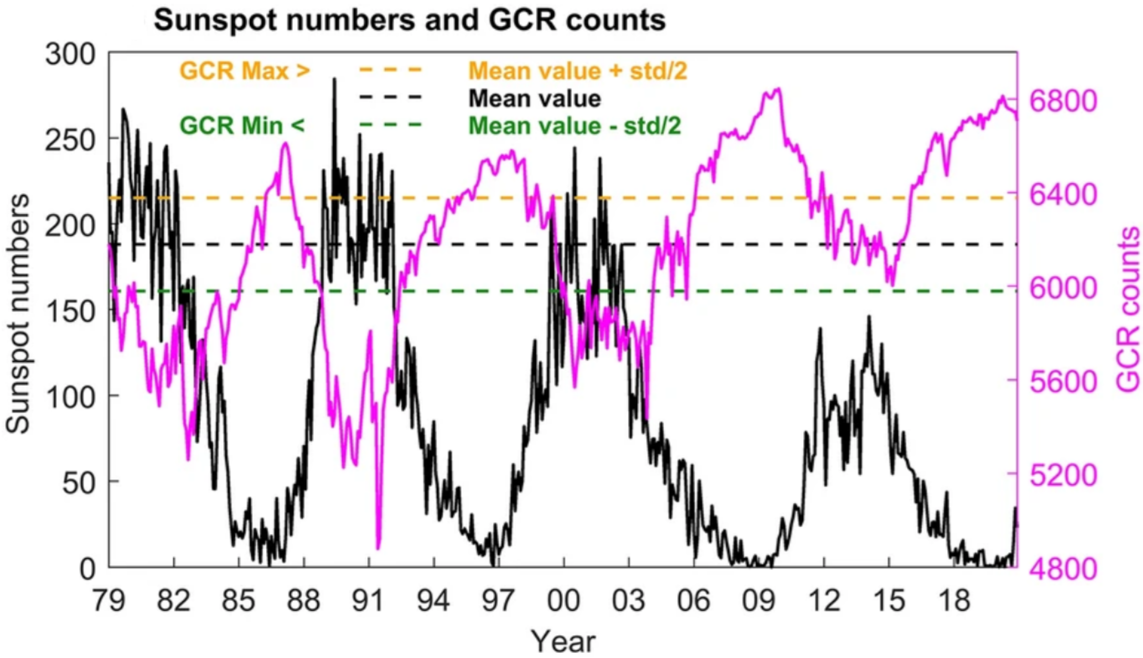

Figure 6: The anti-correlation between cosmic ray flux and solar activity is shown. The sunspot number, a measure of solar activity, is shown in black and the Galactic cosmic ray (GCR) flux, in light purple, are both shown as a function of time for 1979 to 2021. The mean of the GCR level is shown as the black horizontal dashed line, bracketed by yellow and green dashed lines showing statistical deviations from the mean. Credit: Kumar et al. [28].

2.3.1 Detecting Cosmic Rays

Thick layers of ice have existed in Greenland and Antarctica for thousands of years. Some of the oxygen preserved in this ice is struck by a cosmic ray or SEP and turned into beryllium-10 through a process called cosmic ray spallation - defined as a nucleosynthesis process, involving a collision which removes some protons and/or neutrons from a nucleus, so turning it into another nucleus. This is important because ice core measurements of beryllium-10 allow a direct proxy for the history of cosmic ray flux. These measurements show that the cosmic ray flux is inversely related to the magnetic dipole strength of the Earth and in addition, the cosmic ray flux is inversely related to the magnetic activity of the Sun [28], see Figure 6.

The Voyager 1 and 2 spacecrafts, famous for their flybys of the outer planets, continued outward providing the first opportunity to directly measure the flux of interstellar GCRs. As they left the Solar System they moved from the heliosphere, eventually passing through the heliopause - the region surrounding the Solar System where the solar wind pressure balances the interstellar medium, and then out into interstellar space. More specifically, due to the interaction between the solar wind plasma and interstellar plasma, a contact discontinuity forms separating the two distinct plasma populations. The heliopause is an extended region, with some thickness, between the heliosphere and the interstellar medium. The Voyager spacecrafts tracked the GCR flux [29] as they went and sent the data back to Earth. As predicted, they were able to detect where the plasma flow changed from a flow dominated by the solar wind into a flow dominated by the GCR flux. The interstellar proton number flux per kinetic energy is 15 times higher [30] (at low energies) than it is in Earth's orbit.

2.3.2 Galactic Cosmic Rays

Enrico Fermi first proposed, in 1949 [31,32], a mechanism called diffusive shock acceleration that he and others studied in detail, see more references in our review [33], to explain the process of accelerating electrons to the energies needed for the Galactic cosmic rays that are measured on Earth. During a supernova, the dying star ejects its gaseous envelope into space. The ejected material inevitably plows into either the stellar wind of the precursor star, the immediate environment inside of an OB super bubble, or directly with the interstellar medium. This forms a supersonic shock, within which some particles are accelerated to velocities approaching the speed of light. Diffusive shock acceleration is like a tennis match, where a particle is sent repeatedly across the shock, reflected by magnetic irregularities. During each cycle, it either gains momentum or gets lost downstream. The competition between these two: further acceleration and loss downstream gives the spectrum [34]. Upon release, these relativistic particles have an enormous energy as they speed across the galaxy. For an entire particle population the transport is usually diffusive, but it is sometimes convective (in the Galactic wind); diffusive transport is limited by the Alfvén speed.

See Figure 5 showing the cosmic ray spectrum as detected on Earth. From below 1 GeV to about 3 x 10^{18} GeV, referred to as the ankle, the spectrum is dominated by Galactic cosmic rays (GCRs). For locations outside the protective shielding of Earth, for example, the Moon, the low energy end of the cosmic ray spectrum would also contain SEPs. Compared to GCRs however, SEPs are only relatively low energy, see an informative review of GCRs [35].

The spiral arms of galaxies are considered the main location of GCR sources. Supernovae, especially from high-mass stars exploding into the remnants of their winds, while likely the main source [36-39], are certainly not the only sources of Galactic cosmic rays. Other GCR sources include white dwarf novae, low and high-mass X-ray binaries - which are either low- or high-mass normal stars respectively, transferring matter onto a neutron star or a black hole, and microquasars - which are accreting compact stars (either a black hole or fast-rotating neutron star) with jets.

2.3.3 Extra-Galactic Cosmic Rays

The highest-energy cosmic rays originate mainly from sources outside of the Milky Way and thus are called extra-galactic cosmic rays (EGCRs). There are two reasons for this. 1) Only the highest-energy cosmic rays can escape their galaxy of origin and 2) only the highest-energy EGCRs can penetrate the magnetic field of the Milky Way, which blocks all but the highest-energy EGCRs in a manner analogous to the astrosphere surrounding a star and its planetary system. This is because, in an active disk-forming galaxy, a magnetized wind is driven vertically from the disk of the galaxy [40]. The disk wind blocks incoming particles, similar to the solar wind, up to a threshold energy that is significantly higher than in the solar wind.

High-energy cosmic rays, especially ultra-high energy cosmic rays (UHECRs), create an air shower when they hit a particle at the top of the atmosphere. The collision of a UHECR primary particle with an atmospheric nucleus creates an air shower because an enormous amount of kinetic energy is converted into potentially millions of secondary particles as shown schematically in Figure 7. Secondary particles are created in the atmosphere, including muons, neutrinos,

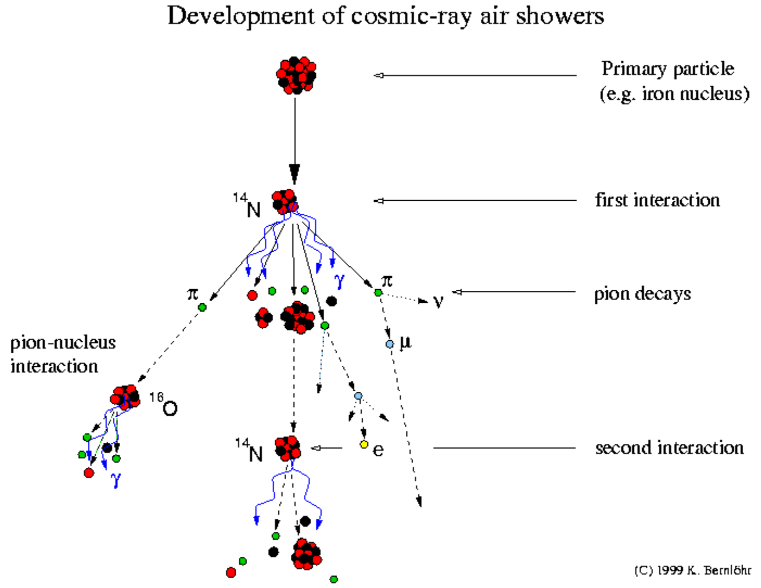

Figure 7: Schematic showing particles and radiation resulting from cosmic ray air showers in Earth's atmosphere. Pions, π, produced in the first interaction either impact another atmospheric nucleus, shown at the left, or decay into a muon μ and a neutrino ν, shown on the right. Credit: K. Bernlöhr.

electrons, positrons, neutrons, and protons. Besides the harmless neutrinos, muons have the greatest penetration capacity.

The UHECRs are not strongly deflected by magnetic fields and their observed directions indicate that they do not typically come from Galactic sources. This is a strong clue that processes of accelerating UHECRs occur in extreme environments such as Active Galactic Nuclei (AGN) and/or starburst galaxies, for example, the nearby starburst galaxy M82. The cosmic ray telescope known as the Telescope Array (TA) detected an excess of UHECRs probably originating from M82 [41,42]. See our discussions [33,37] on black hole mergers in the context of the nearby starburst galaxy M82.

A few definitions of related terms are in order. Active galactic nuclei (AGN) are supermassive black holes (SMBHs) in the centers of galaxies and are often associated with radio galaxies. Quasars, or quasi-stellar objects, are AGN that are not at first obviously associated with galaxies because they appear as (distant) star-like points sources of light. Blazars - named after BL Lac, an unusual quasar, are AGN with relativistic jets that happened to be pointed directly towards us and are also likely sources of UHECRs impacting Earth's atmosphere. Neutrinos are likely also produced by an AGN jet [43, 44]. This is due to the high optical depths for interactions between protons and photons within the jet launching region.

3. Supernovae (SNe)

A supernova (plural: supernovae) is an explosion of a star. There are several ways that this can happen. The mass, and to a lesser extent, the composition, of the progenitor star determines what type of supernova will occur. Much, if not all, of the material making up the progenitor star is ejected into the interstellar medium.

Ancient Chinese astronomers discovered several "guest stars" that they observed to suddenly appear and brighten very quickly, in a few days, and then slowly fade away over several months. Several of these guest stars have been associated with supernova remnants in modern times including SN 185, SN 363, SN 386, SN 393, SN 1006, and SN 1054 (The Crab Nebula). The numbers correspond to the year of the original observation. Western astronomers also noticed new stars which they called novae - the Latin plural form of nova. The Crab SN 1054, was brighter than Venus, visible during daylight for 23 days and at night for 653 days. However, in 1885 an outburst was seen to reach sixth magnitude and was called S Andromedae. It resides in the nucleus of the Andromeda Galaxy (M31). Once the distance to M31 became known, Walter Baade and Fritz Zwicky realized that the 1885 S Andromedae eruption was very different than a normal nova - now known to be an explosion on the surface of a white dwarf, they called it and others like it a super-nova [27]. This designation, now with the hyphen removed, was based on the enormous energy output released by a supernova over a short time. S Andromedae was a type Ia supernova called SN 1885A, Several nearby supernova remnants[1] are shown in Figure 8. Some historical supernovae - those discovered at their maximum brightness, including the remnants of Chinese guest stars, are shown in Figure 9. Some other recent supernovae, but not seen in historical times, are shown in Figure 10 .

3.1 Supernova Classification

The supernovae (SNe) are distinguished by their observational characteristics. Specifically, lines (especially hydrogen) in the spectra of a supernova allow the categorization of these stellar explosions. See Figure 11 showing the types of supernovae and some of their properties relevant to our discussion.

Summary of Supernova Classification:

- Type I supernovae are those without hydrogen in their spectra, while Type II supernovae do have spectral lines from hydrogen.
- Type Ia do not have hydrogen in their spectra, but they do have ionized silicon (615 nm). Types Ib and Ic, do not have hydrogen or silicon. Type Ib supernovae have neutral helium and Type Ic supernova spectra have little or no helium.
- Type II supernovae all have hydrogen, but Type IIb spectra change into Type Ib, having no hydrogen. Type IIn supernovae have narrow hydrogen lines. Those Type II supernovae without narrow hydrogen lines are classified as either Type II-L supernovae that have a linearly declining light curve or Type II-P, which decline and then reach a plateau in brightness.

[1]In Figures 8, 9, 10, and 12: the distance, age (as of 2023), supernova type, and the remaining compact star; either a neutron star (NS), a black hole (BH), or none, for each supernova are given if known. The distance unit light year (ly) is used rather than parsec (pc), used elsewhere in this paper, to aid in comparison to the age. Note: 1 pc = 3.26 ly.

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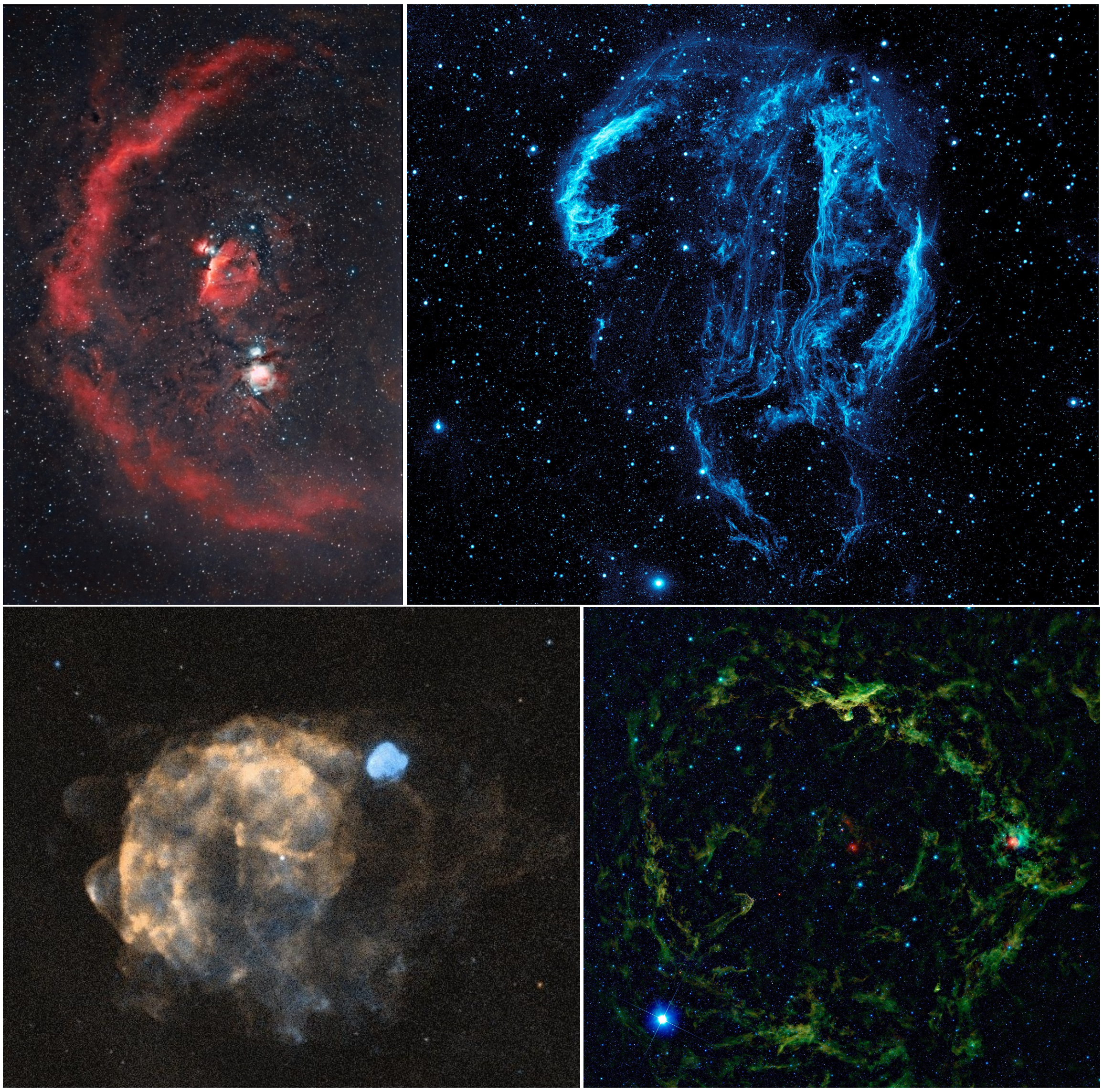


Figure 8: The nearest supernovae remnants: **Top Row:** Bernard's Loop (520-1430 ly, ∼2 million yrs ago). Barnard's Loop partly surrounds the Orion Nebula and the dark Horsehead Nebula and measures 10^{o} on the sky, which is 20 times the angular diameter of the Full Moon: RGB, and Hydrogen-alpha light. Credit Hunter Wilson. On the right is an ultraviolet image of the Cygnus Loop (5000-1,470 ly, 8000 years ago). Credit NASA: GALAX. **Bottom:** The Vela Supernova Remnant (715-915 ly, ∼11,500 yrs ago, type II, NS-Vela Pulsar) is shown in this X-ray image along with the smaller, closer, and more recent Vela Jr. supernova remnant (700 ly, Sept 13, 1271, NS). Vela Jr. is seen in front of the top right part of the Vela remnant. Credit ROSAT. On the bottom right an infrared image of the Lambda-Orionis Ring supernova remnant (1,100 ly, ∼1 million yrs ago) with the bright supergiant star Betelgeuse appearing blue in this infrared image. Credit: NASA.

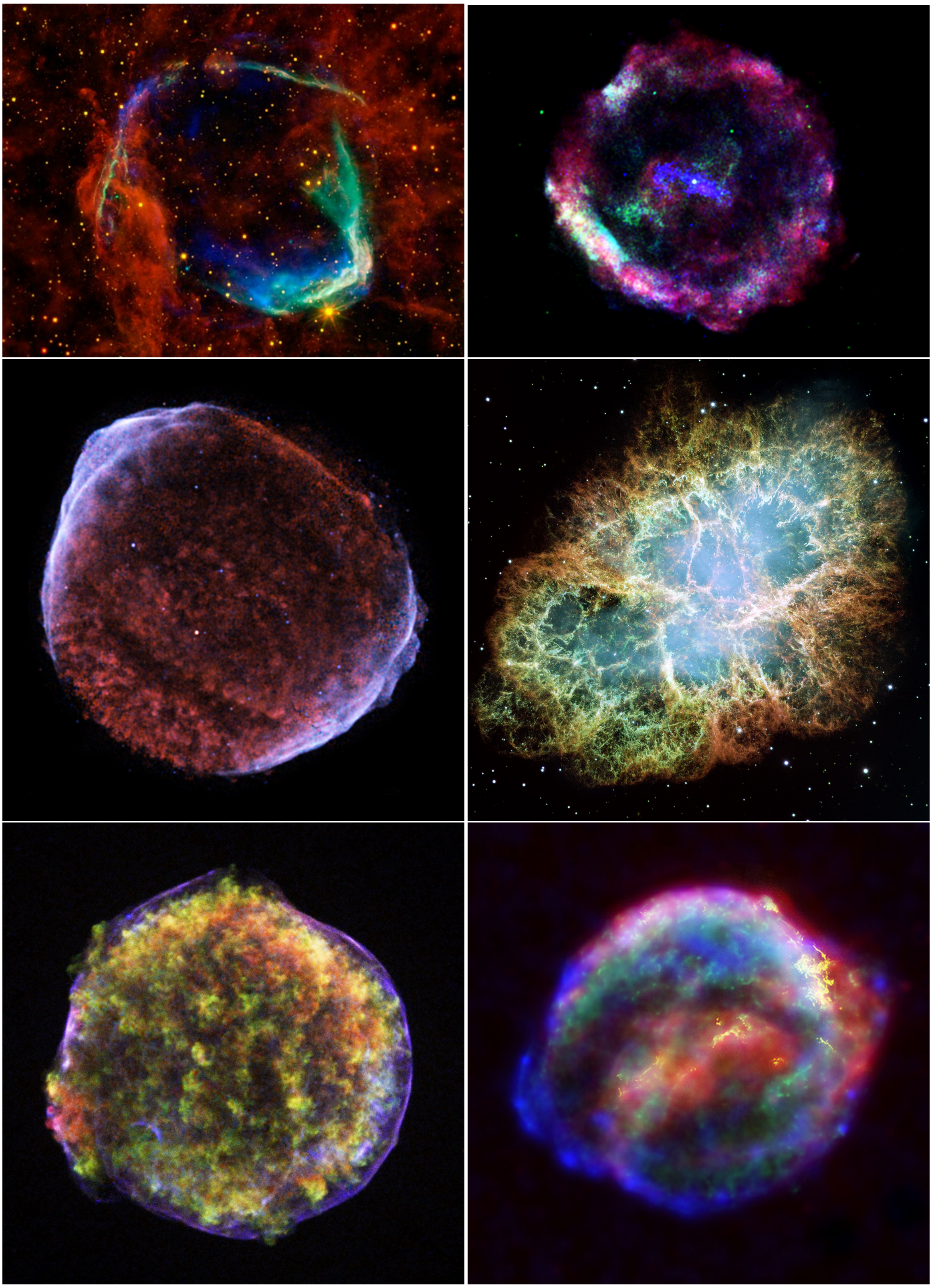


Figure 9: Historically identified Milky Way supernovae remnants. **Top Row:** SN 185 (~9100 ly, 1838 yrs ago, Ia, none) and SN 386 (~20,000 ly, 1637 yrs ago, II), **Middle Row:** SN 1006 (~7200 ly, 1017 yrs ago, Ia, none) and SN 1054 (Crab Nebula ~6300 ly, 969 yrs ago, II, NS-Crab Pulsar), **Bottom Row:** SN 1572 (Tycho's Supernova, ~7500 ly, 451 yrs ago, Ia, none) and SN 1604 (Kepler's Supernova, ~16,000 ly, 419 yrs ago, Ia, none). Credit: NASA/Chandra.

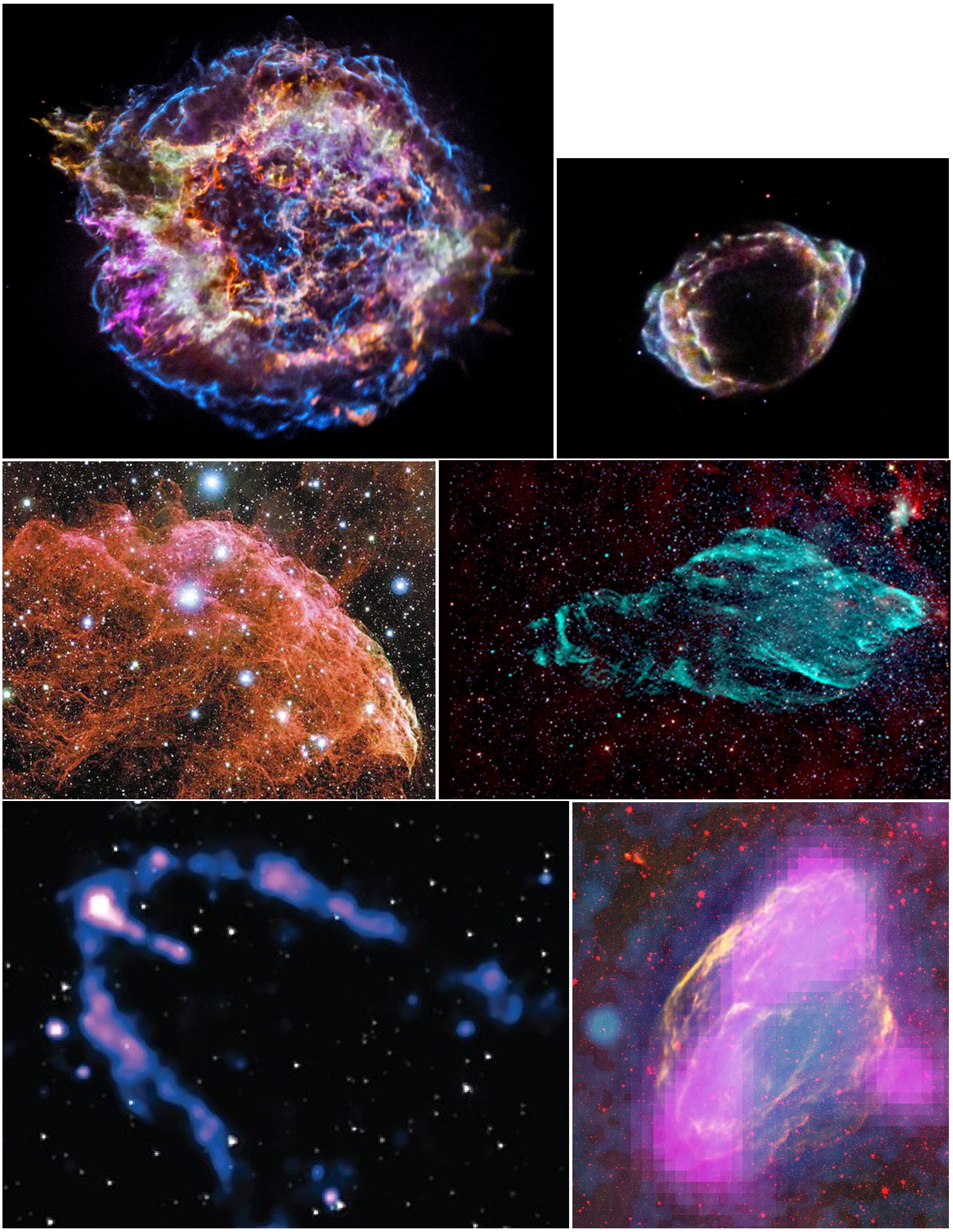


Figure 10: Recent SNe, not historically discovered: **Top Row:** Cas A (11,000 ly, ~300 years ago, IIb, NS) is the brightest extra-solar radio source above 1 GHz, and G1.9+0.3 (near the Galactic center 25,000 ly, occurred ~1868, Ia, none). **Middle Row:** IC443 or the Jellyfish Nebula (3000 ly, ~ 30,000 yrs ago, II, NS), and W50 or the Manatee Nebula (18,000 ly, ~20,000 years ago, II, BH or NS). W50 contains the microquasar SS 433. **Bottom Row:** Geminga (800 ly, 300,000 yrs ago, II, NS-Geminga Pulsar), and W44 (10,400 ly, 16,000 to 20,000 yrs ago). Credit: NASA Chandra (X-ray) Observatory in X-ray, infrared, and optical composite images.

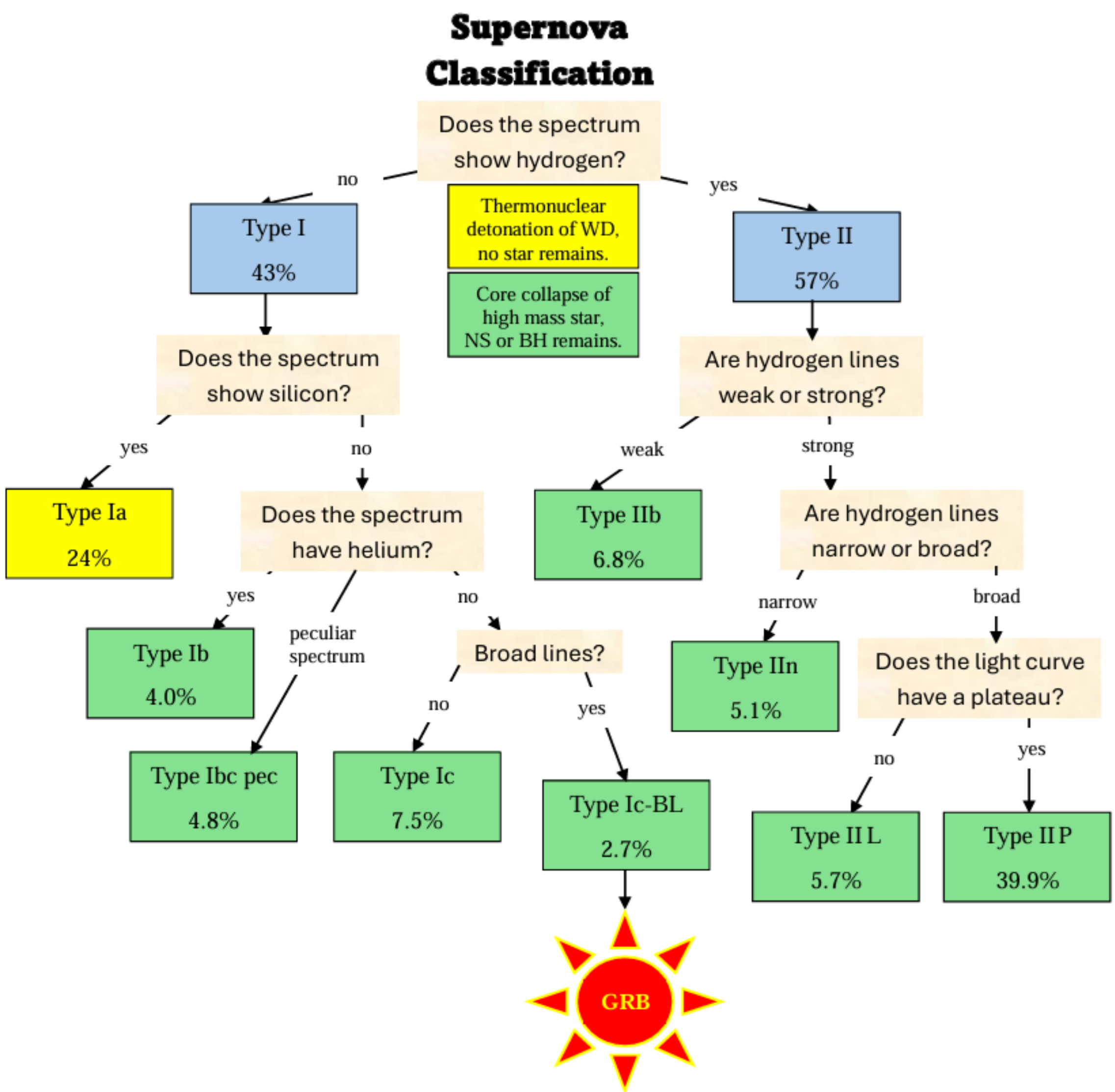


Figure 11: SN Classification scheme based on spectral lines of hydrogen, silicon, and helium. They are also classified according to their luminosity and their light curve characteristics. The brightest SNe are also called superluminous SNe (SLSN).

3.2 Supernova Mechanisms

Type Ia supernovae are caused by either of two possible mechanisms 1) the thermal nuclear runaway explosion of an accreting white dwarf in a binary system, called the single degenerate channel, or 2) the merger of two white dwarfs, called the double generate channel. In either case, no star remains after a Type Ia supernova.

Type Ib, c and all Type II supernovae involve the core collapse at the end of the life of a single star. The difference is for those without and with hydrogen in their spectra respectively. Type Ib supernovae have had their outer hydrogen layer lost, and Type Ic supernova have also lost their helium, likely due to winds during the giant or supergiant phases of stellar evolution.

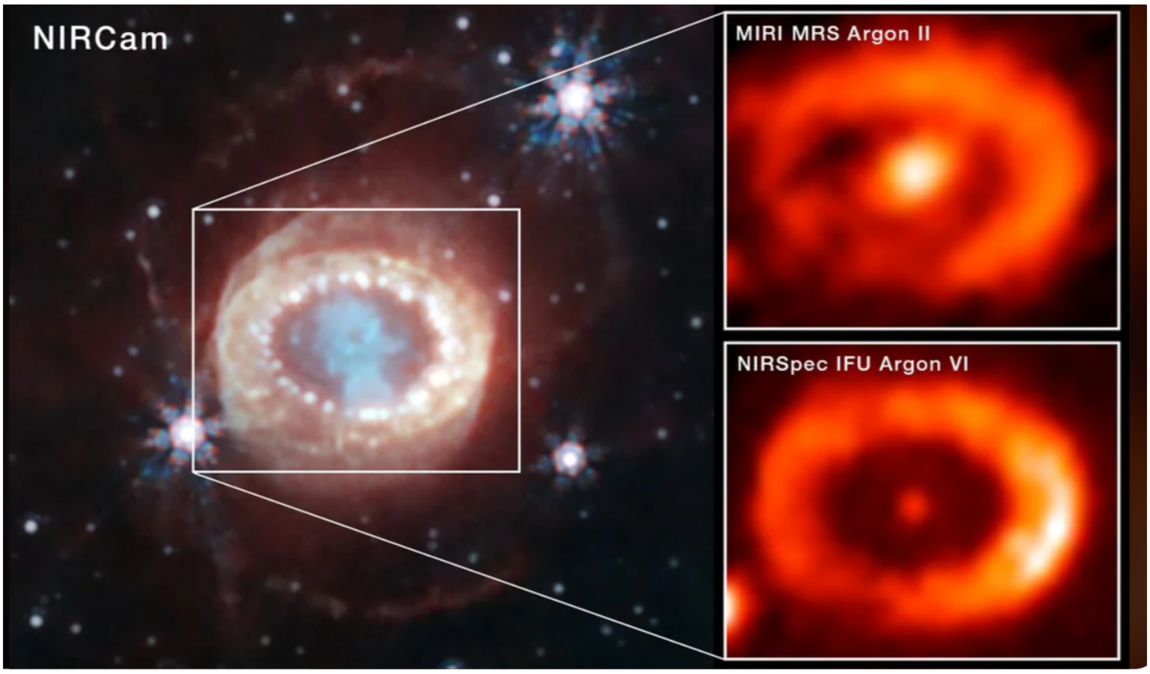


Figure 12: JWST images of the supernova SN 1987A (in the LMC at a distance of 168,000 ly, occurred 24 February 1987, 36 years ago, II-P, NS) allowing the detection of the neutron star formed as a result of the explosion. Credits: The images shown are using the Near-infrared Camera (NIRCam) and the Mid-Infrared camera (MIRCam) of JWST. Credit NASA, ESA, CSA, STScI, C. Fransson (Stockholm University), M. Matsuura (Cardiff University), M. J. Barlow (University College London), P. J. Kavanagh (Maynooth University), J. Larsson (KTH Royal Institute of Technology)

Figure 13: JWST images of OB super-bubbles (NGC 406) observed in the nearby Local Group galaxy, M33, about 20 Mpc away. These are likely sites for cosmic thunderstorms [83]. Credit NASA:JWST

Single stars with masses above 8 - 10 $M_\odot$ commonly explode as core-collapse supernovae where the exact cut-off depends on rotation and metallicity, [45-47]. Stars with a zero-age main sequence (ZAMS) mass between about 10 and 25 $M_\odot$ make neutron stars. Very massive stars, above about 25 $M_\odot$, produce stellar mass black holes and much more massive stars can just blow up without a remnant.

Neutrinos were detected from SN 1987A [48,49], which occurred in the Large Magellanic Cloud (LMC). The neutrinos may have been pulsed with a period of 8.9 ms, suggesting that SN 1987A produced a neutron star [50], which has recently been confirmed in images showing a neutron star from the James Webb Space Telescope (JWST), see Figure 12 [51]. A possible SN mechanism is called the magneto-rotational explosion [52]. The Crab Nebula, with an X-ray image shown in Figure 9 and an optical image shown in Figure 14 [53] contains a neutron star that is a pulsar spinning 33 times each second. Note in particular, the jet shown in the inset image of Figure 14 [54].

Very high-mass stars, the O and B types, explode into the wind of their progenitor star. As the shock goes through the wind it continues into an OB super-bubble, see the JWST image of OB-superbubbles in the nearby galaxy M33, shown in Figure 13. Some supernovae, like the SLSN, are several powers of 10 times more luminous than the supernova remnants in the Milky Way, which might be connected to their wind properties, since the explosion runs into their own previously ejected winds. Several are seen in the nearby galaxy M82. In our 2018 review on the astrophysical and cosmological constraints on life [33], we predicted that supernovae that explode into their winds, like the SLSN, have more adverse effects on habitability than had been previously thought, since those studies involved only Milky Way SNe. Such lethal distances have now been revised with details given in the next section.

These high-mass SNe may be divided further into those that make Red Super-Giant (RSG) stars and Blue Super-Giant (BSG) stars. Both form a black hole, and both show a shock speed of about 10% of the speed of light with a prior wind mass loss rate of about 10^{-5} $M_\odot$ yr^{-1}. But the prior wind of a RSG star is dense and slow, and that of a BSG star is tenuous and fast.

The Fermi gamma-ray telescope brought about the confirmation of cosmic ray acceleration in supernova remnants; specifically by detecting gamma rays resulting from pion-decay. These gamma rays were first seen in the supernova remnants IC 433 and W44 [55]. A cut-off in the gamma-ray spectrum was detected resulting from the decay of neutral pions. Cosmic rays are first accelerated to high energies by magnetic fields, they then interact with the interstellar medium surrounding these supernovae. Detection is possible because neutral pions decay quickly into gamma rays while the charged pions become electrons, positrons, and neutrinos. Fermi gamma-ray telescope observations combined with a theoretical understanding of particle acceleration due to shocks within supernova remnants provide a strong general understanding of the origin of Galactic cosmic rays (GCRs). Over the course of galactic evolution, the flux of ultra-high-energy particles originating from starburst and normal galaxies may dominate over AGN in the flux observed at Earth [56].

3.3 Supernova Rates in the Milky Way

The supernova rate for high-mass progenitors in our Galaxy is well established from gamma-ray line spectroscopy. Gamma rays are emitted during the decay of the radioactive isotope aluminium-26. The isotope, ^{26}Al, is formed in the SN and decays into magnesium [57,58]. The resulting

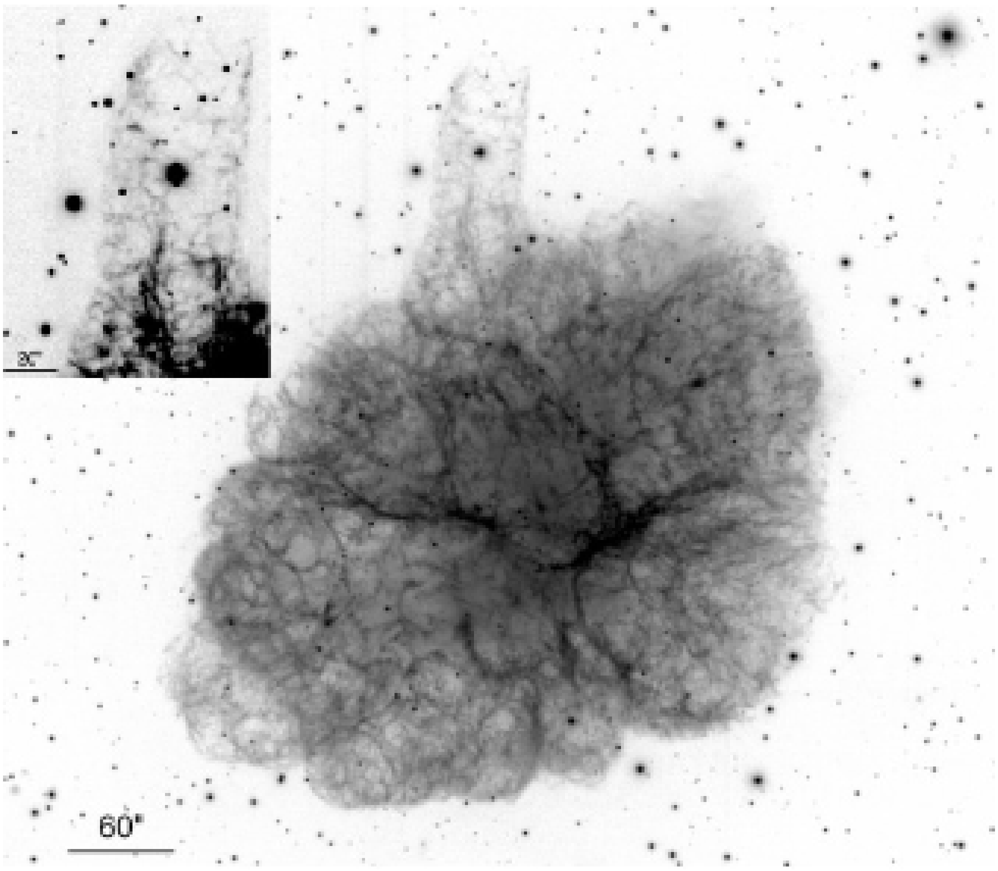


Figure 14: Supernova remnants accelerate Galactic cosmic rays. The 970-year-old Crab Nebula supernova remnant is located at a distance of 2 kpc. The neutron star created as a result of this type II explosion is known as the Crab Pulsar. This Subaru telescope image shows remarkable details of its jet in this O III image that has been scaled logarithmically to show jet details. Inset: More detailed view of the jet. Similar jets are seen in Cas A (Figure 10: top). Credit: Mason and Biermann [33], Original credit: Rudie et al. [53].

present-day SN-rate for all stars with a ZAMS mass above about 10 $M_{\odot}$ is one every 75 years, all above 25 $M_{\odot}$ every 400 years, and all above 33 $M_{\odot}$ every 600 years. To emphasize again, those stars with ZAMS mass between 10 and 25 $M_{\odot}$ make neutron stars, and all with ZAMS mass above about 25 $M_{\odot}$ make black holes. The most common massive star (core-collapse) SNe makes a neutron star, presumably at high rotation. Chieffi and Limongi [59-61] describe a rotational model for SNe. The most massive black hole is expected to be about 38 $M_{\odot}$; and two generation mergers may happen, allowing the most massive stellar mass BH to be about 150 $M_{\odot}$, as observed in GW detections.

SNe that blow up into their progenitor winds, often SNe IIn, are formed from high-mass stars, at least $25 M_{\odot}$. They have almost an order of magnitude higher total cosmic ray energy budget than standard SNe, i.e. those SNe that explode into the ISM and make neutron stars. Wolf-Rayet (WR) stars [62] are likely observed examples of future super-luminous supernovae (SLSNe). These SLSNe eject a cosmic ray population at an energy rate of about 10^{43} erg/s for about $10^{4.5}$ years; yielding enormous total energy of 10^{55} ergs [63]. Notice that the total energy here is many orders

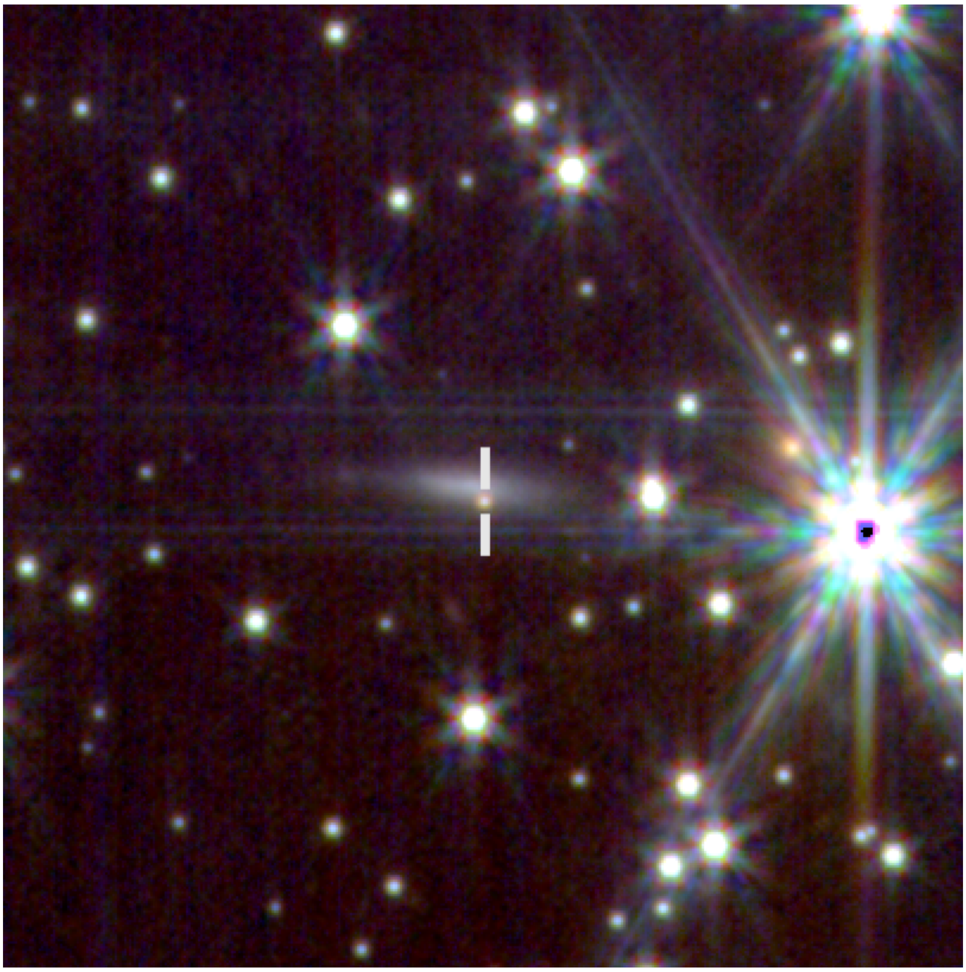
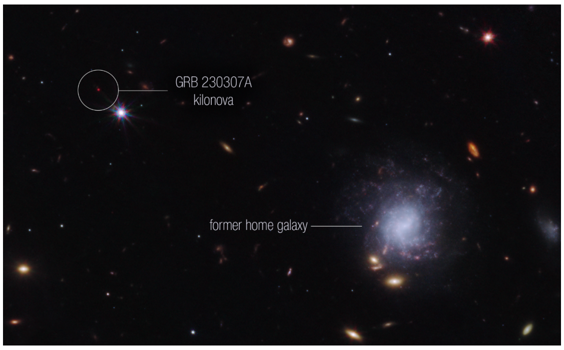


Figure 15: JWST Observation of the Gamma-ray burst GRB 221009A in the infrared using NIRCam. The elongated smudge in the center is the GRB host galaxy, while the bright source on the right is a nearby star. Credit NASA: JWST

of magnitude higher than the nominal SN energy of 10^{51} ergs, as this includes the total rotational energy available from the spin-down of a black hole. As mentioned, this process in our Galaxy makes a black hole every 400 years. So the total energy available is 10^{55} ergs every 400 years, which is $10^{10.1}$ s, for a power of $10^{44.9}$ erg/s, far higher than normally assumed for cosmic rays. Much of that energy is blown off into the halo/wind and never enters the standard cosmic ray population in a thick disk. That kind of blowout has been observed [64]. For this estimate, the low mass limit of massive star evolution that produces a black hole was used, with a ZAMS mass of 25 $M_{\odot}$, and a black hole mass estimate of 10 $M_{\odot}$. It is quite plausible that such an outburst finally funnels into the halo/wind, becoming a blow-out network of tunnels like those discussed by Cox and Smith [65]. These cosmic ray particles become an intergalactic cosmic ray population.

It is important to note that most massive stars are in a binary, triplet, or quadruplet system [66], implying that the black hole can be flung out into the halo/wind before it ejects all the energy.



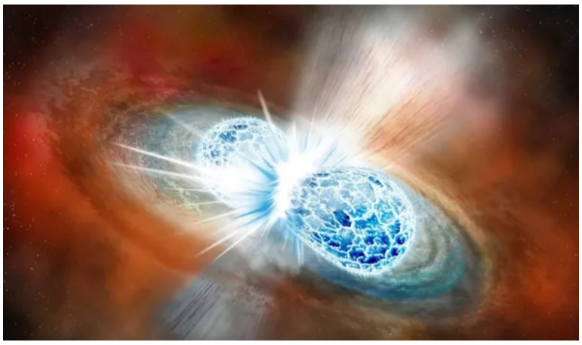


Figure 16: Left: JWST image of the kilonova associated with GRB 230307A and the galaxy from which the neutron star binary escaped ~100 Myr ago. **Right:** An artistic impression of the merger of two neutron stars producing a kilonova and GRB. Credit: NASA, ESA, CSA, STScI, A. Levan (Radboud University and University of Warwick).

4. Gamma-Ray Bursts (GRBs) and Kilonovae

Sometimes when there is a supernova there's also a gamma-ray burst (GRB). Discovered serendipitously by the Vela satellite on July 2, 1967, GRBs are rare stellar explosions that generate an enormous quantity of high-energy radiation and are the most energetic short-term events in the universe. Intense beams of high-energy electromagnetic radiation (gamma rays) are emitted in opposite directions into two narrow ~10^{o} angular diameter cones.

In 2014, Biermann at al. [67] suggested that one to a few GRBs occurring about 1 Myr ago within about 3 kpc of the Galactic center can account for the excess of cosmic rays detected by the Aquino Giant Air Shower Array (AGASA) [68]. However, this excess was not confirmed by IceTop - the surface array component of the IceCube neutrino telescope [69]. In this scenario, the highest energy particles accelerated from a GRB are mostly neutrons. This is because protons remain trapped in the magnetic field and thus lose energy adiabatically during their escape. The relativistic neutrons travel through the Galactic disc and decay after some time into a proton, an electron, and an anti-neutrino, see the inset image of neutron decay in Figure 2. The proton is subsequently caught and trapped by the magnetic field of the Galactic disc and with a small probability of 1/20, the proton will interact with the interstellar medium to again become a neutron which may travel to us undeflected.

The Gamma-ray burst GRB 221009A, named because it was the first GRB detected on October 9, 2022, likely indicated the birth of a black hole. Fermi's Large Area Telescope (Fermi-LAT) recorded gamma-ray photons for more than 10 hours from the burst [70]. Photons with energies of over 100 MeV were detected. GRB 221009A is considered to be a once-in-10,000-year event as it was relatively close. See Figure 15 for a James Webb Space Telescope (JWST) image of the GRB and its host galaxy. Just five months later, GRB 230307A became the second brightest GRB yet detected [70]. It was long-duration GRBs associated with compact object merger and a kilonova, see Figure 17. Kilonovae also emit gravitational waves. For example, the kilonova AT2017gfo is associated with the gravitational wave neutron star merger, GW170817 [71].

4.1 GRB Mechanisms

The GRB jet is an ultra-relativistic bipolar outflow. The jet decelerates as it slams into and sweeps up material from the surrounding environment. A small amount of matter is accelerated by shocks to non-thermal energies. The shocked material subsequently radiates away part of its energy from X-rays to gamma rays.

GRBs come in two distinct types:

- A short GRB is created by the merger of a compact binary star, consisting of two neutron stars or a black hole and a neutron star. This happens after a relatively long period of the emission of gravitational radiation (gravitational waves) which removes angular momentum from the binary, causing the separation of the stars to decrease. This slow in-spiral happens until the stars are so close that they get torn apart by gravitational tidal forces.
- A long GRB is a single-star event triggered by a high-mass star's collapse and a black hole's formation. These GRBs are likely related to the Type Ic-BL supernovae, see Figure 11.

The compact star merger explosion, called a kilonova (Figure 16), leaves behind a single black hole. High mass stars in multiple, especially quadruple systems, can have a binary black hole merger followed by a second generation black hole merger, leading to a black hole exceeding 100 $M_{\odot}$. In such a merger, already observed, if one or both of the two black hole spins is/are high, then there are powerful jet(s), that carve out a destructive cone as seen in M82 [33,37, and references therein].

5. Other Galactic Cosmic Ray (GCR) sources: Novae and Microquasars

Novae are cataclysmic binary star systems in which matter is transferred from a normal main-sequence star onto a white dwarf [73]. The transferred material is mostly hydrogen, accumulating in a layer until a critical mass is reached, causing a thermonuclear explosion on the surface of the white dwarf. The nova rapidly brightens in a few days to $\sim 10^5$ $L_{\odot}$. Most, if not all of the accumulated matter is ejected into space. Novae accelerate particles, electrons or protons, to high energies. In addition to at least three classical novae, and one symbiotic nova detected by the Fermi-LAT Observatory, gamma rays were detected by the MAGIC telescopes from RS Ophiuchi [74], which is one of the 10 known recurrent novae in the Milky Way, during its 2021 outburst. Protons are accelerated to hundreds of GeV in the nova shock. In the case of a recurrent nova (one that erupts every hundred years or less), like RS Oph, accelerated protons will create a 10 pc wide bubble of enhanced cosmic ray density [74].

Microquasars are sources of Galactic cosmic rays, as they are scaled-down versions of active galactic nuclei (AGN). Microquasars are most properly defined as radio-jet X-ray binaries, see the review [75]. In a microquasar, matter from a normal star companion in a binary system transfers matter onto a stellar mass black hole and mildly relativistic, collimated, particle jets are ejected. The first microquasar to be recognized as such is GRS 1915+105, discovered by Felix Mirabel and Luis Rodriguiz when the ejected material was detected at radio wavelengths moving at what appeared to

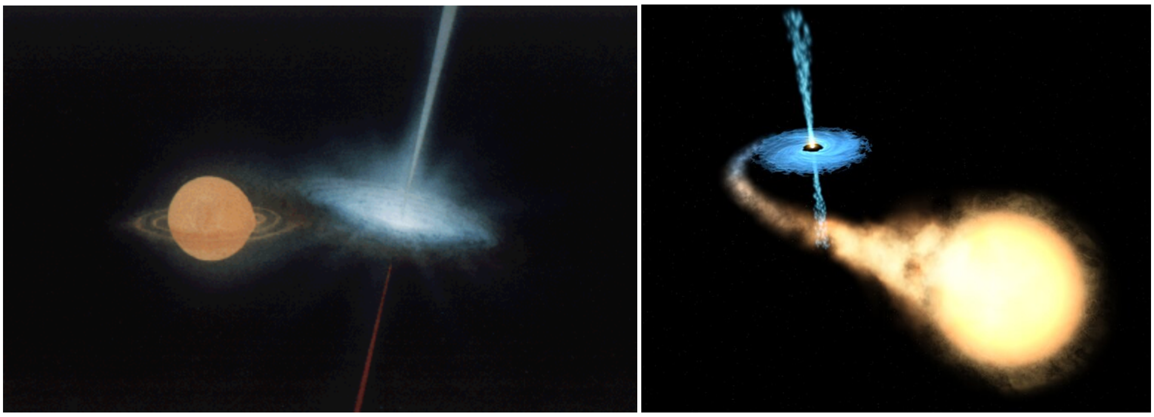


Figure 17: Artist's impressions of the microquasars SS 433 and GRO J1655-40. Microquasars are X-ray binary stars with radio-emitting jets. Note that SS433 is the optical source that can be seen in the middle of the supernova remnant W40 (The Manatee Nebula) shown in Figure 10. Credit: NASA; ESA, NASA and Felix Mirabel.

be superluminal velocities [76]. This discovery linked the essential physics of an accreting black hole in the Milky Way with quasars, which are accreting supermassive black holes at the centers of some galaxies, with black holes millions to billions of times more mass than a microquasar. The best-known microquasar in the Galaxy, SS 433 [77], is characterized by precessing jets of material moving at 17% of the speed of light, 0.17c; see the artist's impression of SS 433 in the left panel of Figure 17.

GRO J1655-40 was the third microquasar to be discovered in the Milky Way [78]. The artist's impression in Figure 17 (right) shows that the companion star in microquasars survives the supernova and the formation of the black hole and now transfers material to feed the black hole. The companion, or donor star, fills its Roche lobe and transfers matter to an accretion disk, which is very luminous in the X-ray and optical part of the spectrum. The disk radiates much of the energy of the transferred matter and most of the matter is accreted into the black hole, while a tiny amount of material is accelerated by strong magnetic fields very close to the black hole which launches jets. Cygnus X-1, the first discovered black hole in the galaxy and microquasar was found to emit short-duration bursts of very high energy emission [79], which are essentially indistinguishable from gamma-ray bursts, using the Compton Gamma-Ray Observatory's Burst and Transit Source Experiment (CGRO-BATSE) from 2 keV to 2 MeV and later confirmed at much higher energies of 100 GeV using the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) [80]. See van Paradijs [81] for a discussion of super-Eddington accretion and Mirabel et al. [82] for a discussion on the ionization due to stellar mass black holes.

6. Cosmic Ray Protection

There are several layers of protection from ionizing radiation for life on the surface of Earth-like planets. Consider an extra-galactic UHECR traveling through intergalactic space that enters the Milky Way galaxy. It first encounters the Galactic disk wind and then the astropause surrounding the planetary system. If it makes it this far, then it must pass through the planetary magnetosphere,

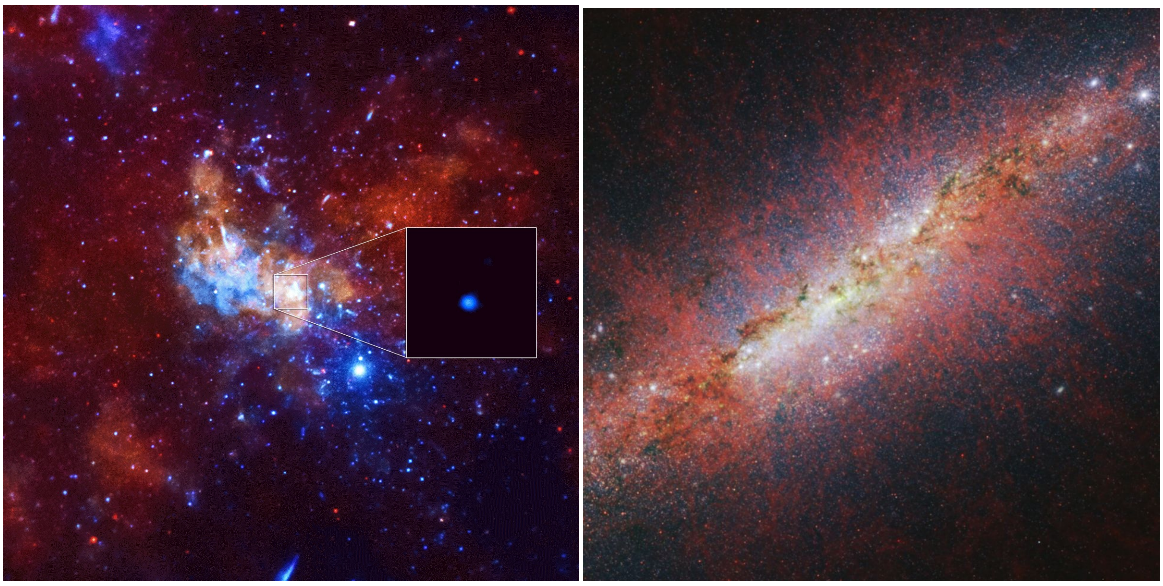


Figure 18: Left: X-ray image of the galactic wind from the Milky Way central region. The inset image shows a flare from the vicinity of the Galactic center black hole, Sagittarius A*. **Right:** Galactic winds from the starburst galaxy M82 are shown in this JWST image. Credit: NASA/JWST

the ozone layer, and the atmosphere, before impacting life. These layers of protection are discussed in that order in this section.

6.1 Galactic Disk Wind, Galactosphere, and Galactopause

The disk of the Milky Way currently forms SNe at a rate that sustains a global magnetic disk-wind [40]. The existence of this disk-wind emanating outward from the Galactic plane provides efficient protection for life against extra-Galactic cosmic rays. The wind is most intense near the center of the Milky Way, see the X-ray image of the Galactic center region in the left panel of Figure 18 and dramatically more intense in star forming galaxies like M82 shown in the right panel of Figure 18. To some extent, these Galactic cosmic rays are contained within the disk of the Galaxy. The steady supply of expanding supernova remnants in the disk of the Milky Way generates a relatively high cosmic ray density within the disk, as it takes about 10 million years for the cosmic ray particles on average to escape the confinement of the Galaxy's magnetic field. By analogy with the stellar wind and its boundary layer outside, known as the astrosphere and astropause, we may call the Galactic magnetic field and the Galactic magnetic wind with its boundary layer the Galactosphere and Galactopause. Note that the Galactosphere is not necessarily spherical. As long as there are enough expanding supernova remnants to replenish the Galactic cosmic ray medium, planets within the disk will be bathed in cosmic rays. The containment time is energy-dependent. High-energy cosmic rays are contained for shorter times than those with lower energies. The highest-energy cosmic rays are rare as they penetrate the Galactopause and remain in the galaxy for a relatively short time, but they cause the most damage to life. The impact with the atmosphere of a single high energy cosmic ray called the primary cosmic ray, produces an air shower, see Figure 7, resulting in huge numbers of secondary cosmic ray particles.

The associated Galactic disk magnetic field has a protective aspect analogous to the Earth's magnetic field. Just as the Earth's magnetic field deflects SEPs and GCRs, many extra-galactic cosmic rays (EGCRs) are deflected by the magnetic field of the disk of the Milky Way and other galaxies. The Galactic disk wind thus reduces the impact of EGCRs on planetary surface life. The Galactic magnetic field prevents many low-energy EGCRs from penetrating the Galactopause and entering the Galactosphere. However, the highest energy particles do penetrate the Galactopause and thus enter the Galactic disk. These UHECRs can also penetrate the heliosphere surrounding the Solar System and the magnetosphere of the Earth. Upon impacting the atmosphere, these high-energy particles create air showers. As a result, many secondary particles potentially impact life on the surface of planets.

This type of Galactic magnetic protection for life is unavailable for planets orbiting stars in the Galactic halo. Importantly, not all disk galaxies have such winds. M31, the Andromeda Galaxy, for instance is not known to have such a wind. There is a condition for disk galaxies to have such a wind [40] in the form of a star formation rate per disk area; this implies a certain energy input rate to establish a persistent wind. Being in a disk Galaxy with magnetized disk wind is therefore not so common and is most helpful to life on planets in high-density clusters of galaxies with many accreting black holes, especially black holes with jets, and many supernova remnants as was common especially in the early universe [33]. The recently identified "cosmic thunderstorms" [83], also see [84], associated with OB-superbubbles, see Figure 13, are a likely threat to the biospheres of the few planets that they impact.

6.2 The Protective Astropause

The solar wind produces a bubble around the Solar System called the heliosphere, see Figure 19. The size and shape of the heliosphere are time variable and it extends out to a distance of about 120 AU from the Sun. This is where the solar wind and interstellar medium pressures balance. The solar wind decreases below the supersonic threshold and the particle density increases at the heliopause, which is a sort of surface for the heliosphere. The two Voyager spacecrafts have provided measurements of the conditions around the heliopause, with trajectories shown in Figure 19. Generalizing to other stars, we will more commonly refer to the astrosphere and the astropause.

The astropause protects a biosphere from GCRs, which is analogous to, but different in detail from the protection a planetary atmosphere provides [85]. When GCRs collide with the astropause, and if they have an initial energy that is less than about 300 MeV, then they are blocked by the astropause. Higher energy cosmic rays may lose some energy, slowing down, as they cross the astropause and move into the planetary system. This happens because magnetic fields within the termination shock, see Figure 19, interact with these lower-energy GCR particles causing them to slow down. Evidence that the astropause is an effective barrier against low energy cosmic rays comes from the observation that the strength of the solar wind is variable and those variations show an anti-correlation of solar activity with GCR flux, recall Figure 6, showing that the protection mechanism provided by the astropause operates as theoretically expected from the pressure balance between the solar wind and the local interstellar medium. A tiny fraction of those cosmic rays making it past the astropause interact with the planetary magnetosphere and/or impact the surface of the Earth.

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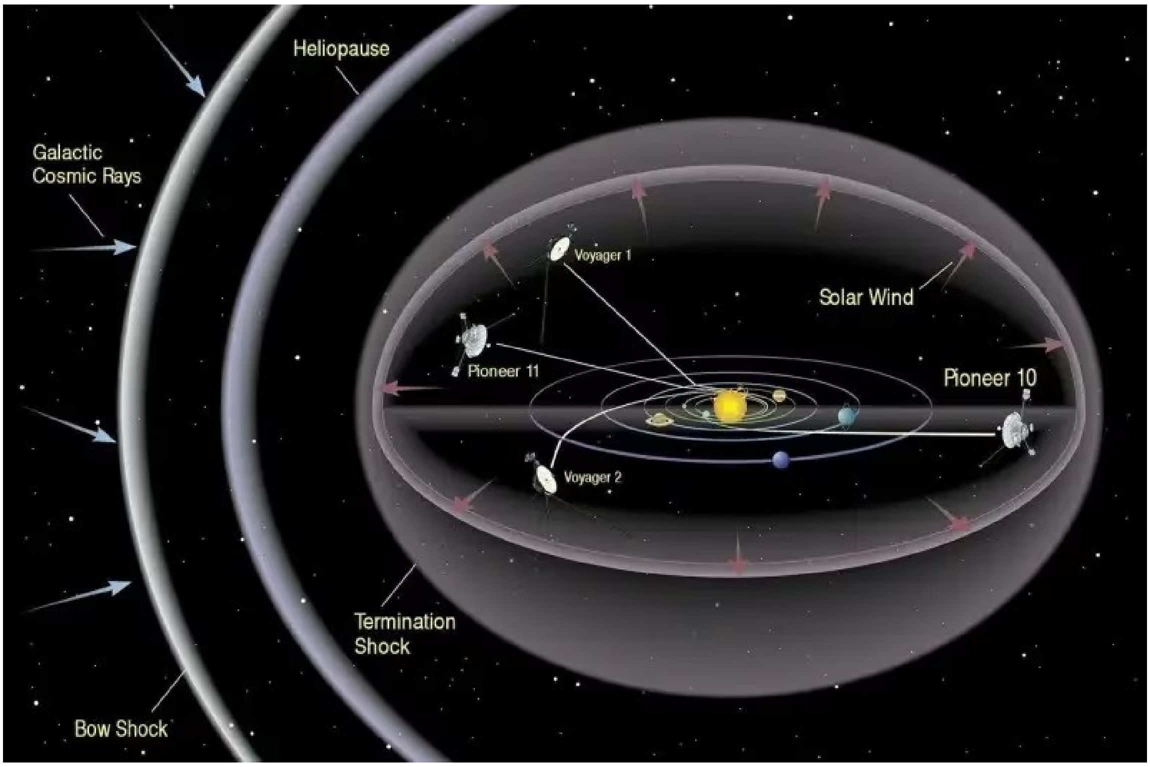

Figure 19: An artist's impression of the heliosphere and the Pioneer 10 and 11, and Voyager 1 and 2 spacecraft trajectories. The bow shock as shown indicates that the Solar System is moving to the left in this illustration. Credit NASA.

In 1959, Edward Ney [86] noted that the variation in cosmic rays, due to the solar cycle, had major effects on the Earth's stratosphere and troposphere. Ney might have been the first to suggest that cosmic rays could produce significant climatological effects. It is important to point out that the Earth's magnetosphere also protects the atmosphere from low-energy SEPs and GCRs, but Earth's equatorial regions are far more protected than the polar regions since the Earth's magnetic and spin axes are reasonably well-aligned.

The cosmic ray intensity on Earth, see Figure 5, was found to vary inversely with the solar cycle. When the magnetic activity of the Sun increased due to its normal 22-year magnetic activity cycle, the cosmic ray level at energies below about 10 GeV, which originates from sources in the Milky Way, decreased. Likewise, when magnetic activity such as sunspots, flares, coronal mass ejections, and so on is at a minimum, the low-energy cosmic ray intensity rises. So, ironically, the active Sun decreases the exposure of life on Earth to cosmic rays.

Henrick Svensmark and Eigil Friis-Christense [87] took the GCR-climate connection further and developed the idea that Galactic cosmic rays modulate climate through cloud formation. The idea is that cosmic rays produce ions in the atmosphere and experiments show that ions may act as seeds for the nucleation process in cloud formation. The effect on climate follows because clouds are highly reflective, with an albedo of 0.9, compared to the much darker land and ocean surfaces. For reference, the albedo of the Earth is 0.39, where 0 is totally absorbing and 1 is totally reflecting. A sustained increase in albedo results in atmosphere and surface cooling. If this cooling results in

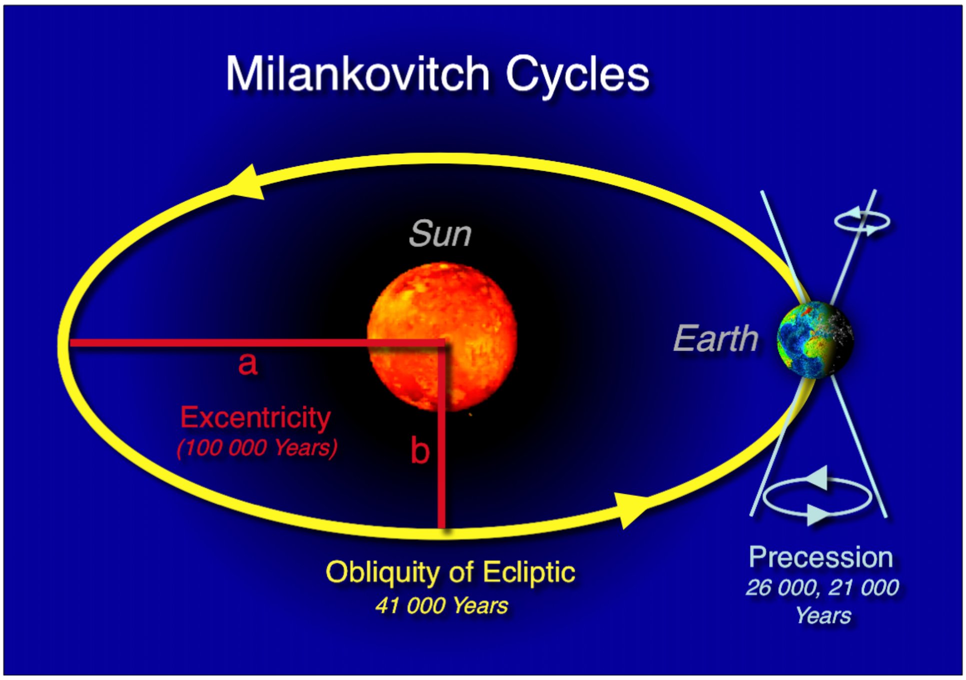

Figure 20: An illustration of the three orbital, Milankovitch [89], cycles. These orbital variations independently drive changes in the amount of light from the Sun that reaches Earth. For example, the period of precession varies between about 21,000 and 26,000 years, with 25,772 years being the current rate. Credit: Creative Commons free use.

a significant increase in the land and sea ice coverage, then the albedo is further increased and a runaway freezing might occur. Tropical ice sheets or even a snowball Earth era might follow.

Nir Shaviv [88] suggested that this might be caused by an unusually intense period of cosmic ray exposure, further suggesting that these periods might occur during crossings of the Solar System through the spiral arms. The spiral arms of the Milky Way and other star-forming galaxies are characterized by star-forming regions and giant molecular clouds. Both of these are potential causes for mass extinctions. Since most supernovae occur soon after the formation of the progenitor star, they do not travel far from their birthplace. So a system has a fair chance of exposure to a supernova remnant at close distance while traveling through a region of high star formation. Shaviv also found a strong correlation between cosmic ray intensity, recorded in meteorite samples, and the times of ice ages. Nuclear reactions within the meteoroid allow for the dating of the exposure.

There is strong evidence for another driver of glaciation cycles in the recent past, based on the Earth's orbital variations. There are three cycles, collectively called the Milankovitch Cycles [89], based on variations in the Earth's eccentricity, inclination, and its semi-major axis - one-half of the long axis of the ellipse, see Figure 20. Specifically, each of these orbital elements oscillates with a different period and each has some effect on the distance between the Earth and the Sun and thus on climate. In 1976, Hays et al. [90] using sediment cores from the deep ocean found that Milankovitch cycles correspond to major climate change, especially ice ages over the past 450,000 yrs. Ice cores in Greenland and Antarctica also provide strong evidence of orbital-induced climate cycles. Mars has been shown to undergo more extreme cases of each of the three Milankovitch

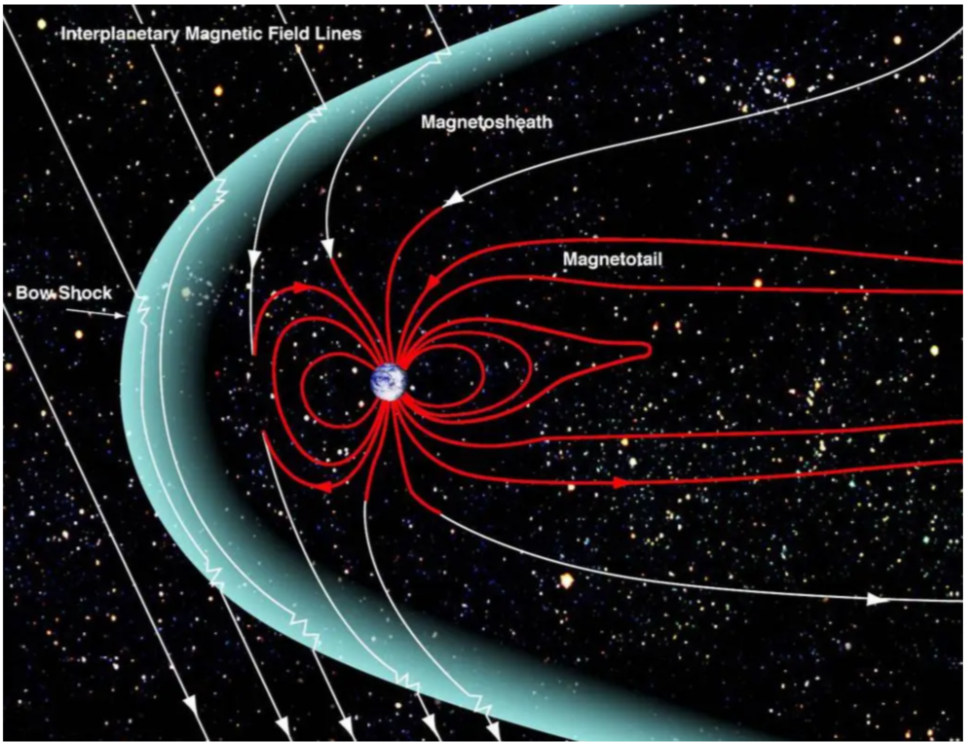

Figure 21: An artist's impression of the Earth's magnetosphere. The Earth's magnetosphere interacts with the solar wind, creating a bow shock. The bow shock is a conical feature with its symmetry axis in the plane of the figure, with the Earth's motion directed to the left. Credit: NASA.

cycles. If large enough, orbital variations have the potential to periodically remove a planet from the circumstellar habitable zone only to return it hundreds of thousands of years later. The narrow CHZ for complex life, see our habitable zones review [91], suggests that only those planets with a low eccentricity and relatively small amplitude orbital cycles, like Earth, are likely to be inhabited by complex life.

6.3 Planetary Magnetosphere Protection

The magnetic field of a planet can also be an important source of protection for life on the surface. The first discovery of the space age is that of the Earth's radiation belts by instruments built by James van Allen and flown on the very first US spacecraft, Explorer 1, in 1958 [92]. This was the discovery of the Earth's magnetosphere which deflects and traps charged particles. See the schematic of the magnetosphere in Figure 21. This protection originates because of the magnetic dynamo within the Earth's liquid core, driven by the Earth's rotation. The magnetic field deflects charged particles changing their direction such that many either miss Earth or impact the planet's surface within small regions near the magnetic poles. This can be seen by following the interplanetary magnetic field lines shown in Figure 21. Note that magnetic fields do not affect neutral particles such as neutrons and neutrinos and that the highest energy GCRs and EGCRs are not stopped by the magnetosphere.

In the Solar System, the magnetic protection of planets plays an important role, as the Earth deflects or traps SEPs, while Mars currently does not have a significant global magnetic field. Despite Mars being further from the Sun, the effect of SEPs impacting the atmosphere on Mars is greater than that of the Earth because of the shielding provided by the Earth's magnetosphere. In addition, Mars is only about 10% as massive as the Earth. So it is much more susceptible to atmospheric mass loss, and therefore today Mars has a very thin carbon dioxide atmosphere, that continues to be lost as detected using the MAVEN spacecraft [93] sent to Mars to measure this loss. A rocky planet with a molten outer core and a relatively fast rotation are all necessary to maintain a planetary magnetic dynamo. While Mars has a spin period of 24.5 hours it is just longer than Earth (23hr 56m), Venus likely has all of the above except for its very slow spin period of 249 days. Venus has a very thick carbon dioxide atmosphere and no significant global magnetic field because of its slow rotation.

6.4 Ozone Protection

Ultraviolet radiation can become a major source of ionizing radiation for surface life if the ozone is destroyed since it is the ozone that protects surface life from exposure to solar UV. The ozone could be destroyed as the result of an unusually energetic solar flare or elevated Galactic cosmic rays. Even an extra-galactic source of cosmic rays, those accelerated in the jet of a supermassive black hole at the center of a nearby active galaxy, Cen A for example, could potentially result in ozone destruction [33]. The ozone layer on Earth acts as a kind of guardrail of protection from ionizing radiation. Cosmic rays and UV light disassociate ozone particles eliminating the ionizing radiation, until the point in which all of the ozone is destroyed and the protection is removed.

The stratosphere is in a constant cycle with oxygen molecules and their interaction with ultraviolet (UV) rays. The ozone layer is created when UV light reacts with oxygen molecules (O_2) to create ozone (O_3) and atomic oxygen (O).

Step 1: Ultraviolet light from the Sun destroys an oxygen molecule (O_2), creating two oxygen radicals (O^*):

$$h\nu + O_2 \rightarrow 2\,O^*.$$

Step 2: Molecular oxygen then reacts with each of the oxygen radicals producing ozone (O_3):

$$O_2 + O^* \rightarrow O_3.$$

Step 3: Ozone then reacts with another oxygen radical forming molecular oxygen:

$$O_3 + O^* \rightarrow 2\,O_2.$$

Step 4: Ozone can also be destroyed by a UV photon, creating molecular oxygen:

$$\mathrm{h}\nu + O_3 \rightarrow O_2 + O^*.$$

This process is called the Chapman cycle, where O_3 is constantly being created and destroyed in these reactions. The thickness of the ozone layer varies greatly over time because it is a constantly adjusting equilibrium between the intensity of solar UV and the O_2 that is being introduced into the atmosphere by organisms undergoing photosynthesis. So with more molecular oxygen provided by plants and other photosynthesizing life, the ozone layer has the capability of replenishing itself, step 2, after being destroyed by UV radiation. Cosmic rays also similarly deplete atmospheric ozone.

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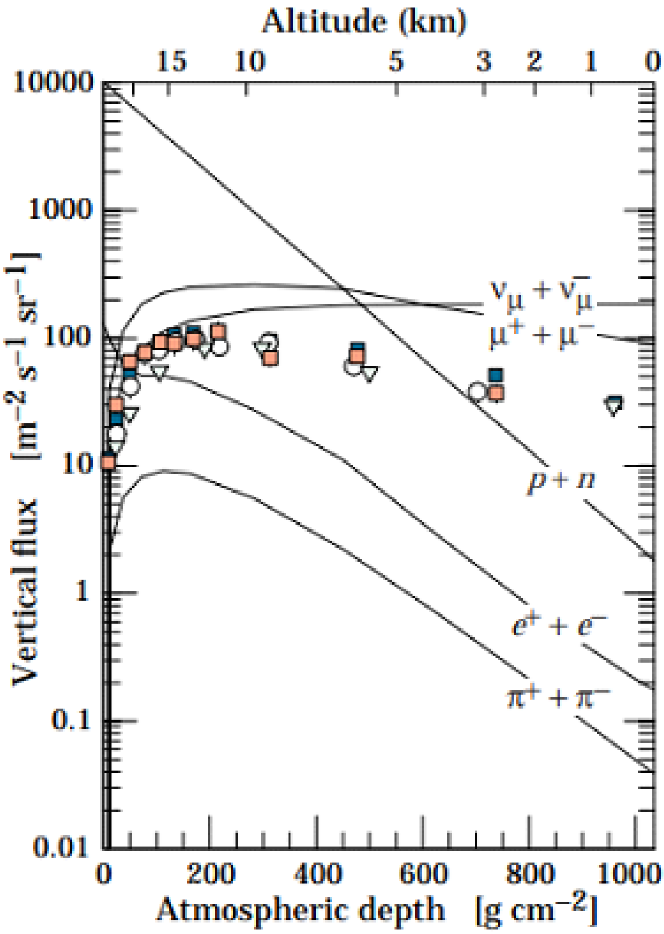

Figure 22: Cosmic ray (CR) penetration vertically through the Earth's atmosphere, from Gaisser and Stanev [99]. Muons, μ^+ and μ^-, are detected at high fluxes all the way to the ground, which is at the right edge of the plot. They are especially harmful to large land and shallow marine animals because on Earth, most muons reach the ground and most of the other ionizing particles do not. Atmospheres that are thinner than Earth are subjected to these other ionizing species in addition to muon exposure. The most energetic primary particles are the Ultra High-Energy Cosmic Rays (UHECRs) which can produce 10^8 or even more secondary particles.

Theoretical effects of SEPs and GCRs on the atmospheres of Earth-like planets residing in the habitable zone of active M dwarf stars have been studied by Grießmeier et al. [94,95] and Grenfell at al. [96]. For the cases studied, the worst effect is for high SEP flux, eliminating all of the planetary ozone. In most cases, some of the ozone is eliminated while some remains. M-type main sequence stars are known for having substantial and long-lived magnetic activity, subjecting habitable zone planets to UV and SEP flux from flares. In 2010, Segura et al. [97] modeled the atmospheric effects of a large flare like that detected in the M-type main sequence star AD Leonis. Two effects were modeled with the largest effect on ozone destruction being nitrous oxide (NO) production by SEPs, which would destroy 90% of the ozone at about 2 years after the flare with a slow recovery of about 50 years. The UV emission from such a flare should have minimal impact on the amount of atmospheric ozone.

6.5 Atmospheric Protection

Of the two things that we have to protect surface life from GCR-induced radiation dose, the thickness of the atmosphere and the strength of the magnetic field, the thickness of the atmosphere is more important [98]. A thicker atmosphere provides a longer path length for both the primary and secondary cosmic rays. A thick atmosphere especially lowers the flux of secondary particles at the surface. In Figure 22, the penetration depth in the atmosphere for various secondary particles is shown [99].

Ultimately it is the atmosphere that provides the most protection for life to the influx of cosmic ray particles. In a large air shower, many muons make it to the ground and into shallow waters. If the secondary particles are energetic enough and their flux is sufficiently high, muons can have an impact even on subsurface life [100]. If the radiation dose is too high, the chances of life as we know it on an Earth-like exoplanet are diminishingly low.

7. Stellar Explosions and Complex Life

A very nearby supernova might have an irreversible effect on any existing surface life and the future habitability of an Earth-like planet. The worst-case scenario is if the pressure of the remnant encounters the astrosphere and overcomes the solar wind ram pressure producing an astrosphere collapse. An astrosphere collapse could also occur when a planetary system passes through a giant molecular cloud [85].

7.1 Exposure to a Nearby Supernova

A summary of the main effects of a nearby SNe on the biosphere is as follows in decreasing order of severity. Much of this also applies to nearby exposure to a compact binary star merger explosion, called a kilonova, see Figure 16.

1) If the planet experiences an astrosphere collapse, then habitability may be compromised. Without astrosphere protection, the pressure of the expanding supernova remnant and the compressed interstellar medium might significantly erode the atmosphere of an otherwise habitable planet.

2) The initial bright phase of the supernova is quite bright at many wavelengths, but it does not last long. Consider that the Crab Nebula was visible during the day for 23 days. The burst of electromagnetic radiation continued to arrive at the planet over a few months to a year. In the case of about 7% of core-collapse SNe that explode into their own winds - the SNe IIn type, the X-ray and UV luminosity is much greater and lasts much longer than other supernova types.

3) The burst of cosmic ray particles is larger and lasts longer than the electromagnetic effect. Life would be without ozone protection for hundreds to thousands of years as a result of a nearby supernova explosion.

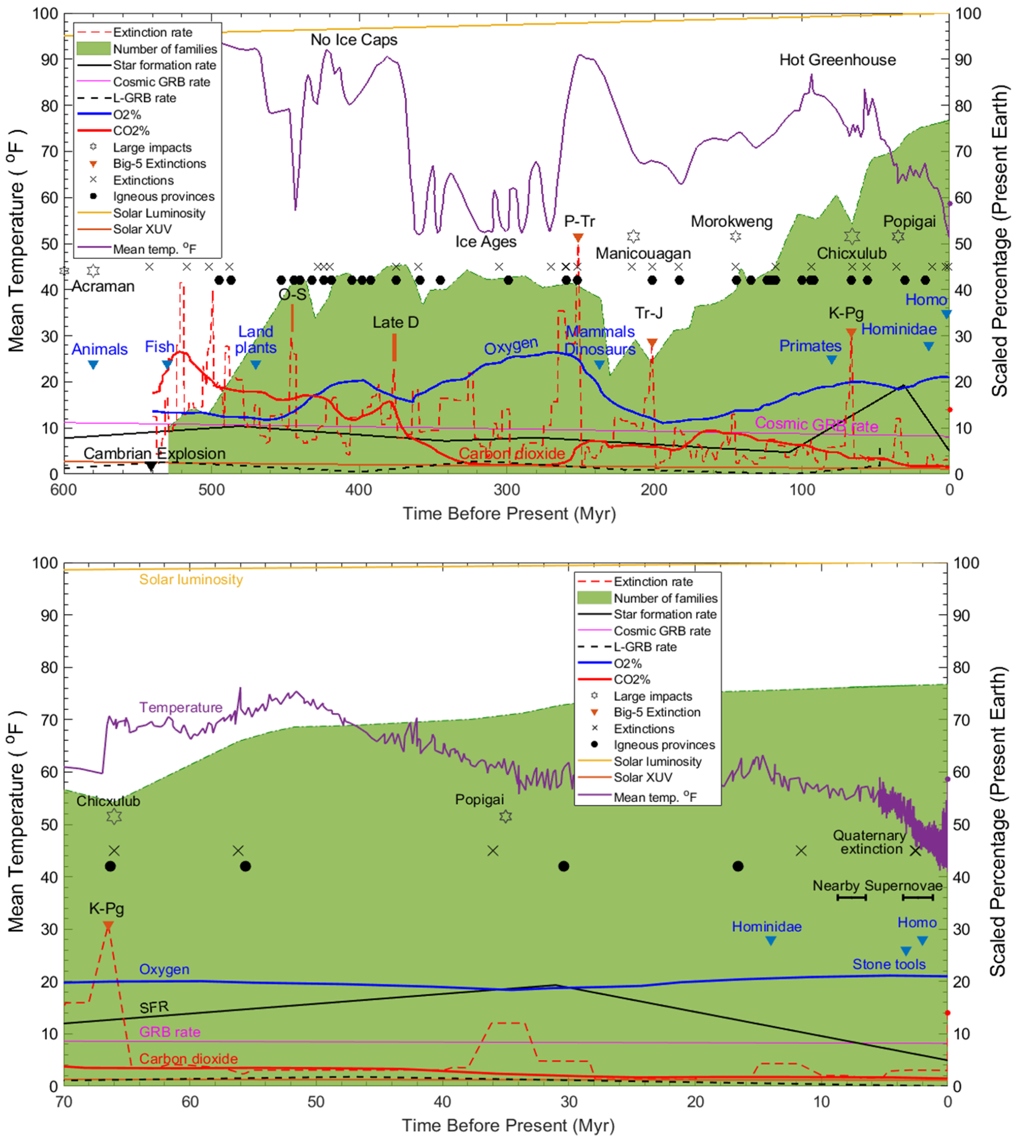

Figure 23: Timeline of Earth habitability. **Top:** The mean surface temperature of Earth (purple line) from δ^{18}O measurements given in °F = 9/5 °C + 32. for plotting convenience, along with impact craters, major extinction, large igneous (volcanic) provinces, and times of appearance for key points in human ancestry. There is considerable linkage and feedback between life, temperature, and mass extinction. In particular, ice ages (~300 Myr ago) occurred while CO_2 was at a minimum. Major mass extinctions occur in response to drastic temperature changes. **Bottom:** See text for a discussion of the End-Pliocene/Quaternary megafaunal extinction, 2.588 Myr ago, marked by X, just before the rise of genus homo and just after the first known use of stone tools. solar luminosity and XUV are by now widely divergent. The temperature curve (purple) shows unresolved Milankovitch cycles (due to Earth's orbital variations) during the most recent several million years. Human feedback is evident in the temperature and extinction rate (dots) on the right vertical axis showing sudden present-day anthropogenic effects.

4) Even in the case of SNe occurring just beyond the lethal distance, radioactive material ends up at the bottom of the ocean and can be dated.

7.2 Evidence for Nearby SNe

In Figure 23 a comprehensive timeline of events associated with the habitability of the Earth is shown. There is strong evidence that at least one core-collapse SNe occurred between 2 and 3 Myr ago, at a distance of 50 to 100 pc, and a possible second supernova a few million years earlier. This comes from the discovery of tiny amounts of radioactive ^{60}Fe and other radioactive elements in thinly sliced layers of ocean seamount sediments [101-106]. Radioactive iron continues to slowly rain down on Earth from cosmic rays, which have been found in Antarctic ice. Particles trapped in the Galaxy's magnetic field from SNe across the Milky Way, that exploded in the last 10 Myr were also found in samples from the surface of the Moon [107] and in near-Earth space [108].

A period of global cooling and mass extinction known as the end-Pliocene is also dated at 2.6 Myr ago. The Pliocene (5.333 - 2.58 Myr ago) means roughly - the beginning of the modern era. See the timeline in Figure 23, including the End-Pliocene/Quaternary megafaunal extinction. Although this is not considered one of the Big-Five major mass extinctions; one out of three large marine animal species, including many seabird species and turtles, went extinct. These extinctions possibly also included the Megalodon - the largest shark known with the notable characteristic of having young in shallow waters; compared to the great white sharks which raise young in deep waters. Perhaps not coincidentally, great white sharks managed to survive the End-Pliocene mass extinction.

The connection between the nearby SNe events and the extinction of marine animals is circumstantial. However, the presence of global cooling and the extinction of marine animals in shallow waters is consistent with a lethal supernova explanation. From this empirical evidence, a working assumption is that one or a few nearby SNe, within 10 - 100 pc, are a potential cause of known mass extinctions on Earth and likely also Earth-like planets, with the severity dependent on the distance and type of supernova event.

Both nearby SNe and more distant ones affect the habitability of Earth-like planets. Because of the Galactic magnetic field, cosmic rays generally do not travel directly from a supernova to the planet. After being accelerated in the supernova remnant which lasts for up to tens of thousands of years, the cosmic rays spread throughout the Galaxy following the magnetic field lines of force. Since cosmic rays are charged particles they freely move along magnetic field lines, but are blocked from moving perpendicular to the magnetic field, so they move diffusively, very slowly, see the review article on diffusive shock acceleration [109]. The consequence is that GCRs maintain their high energies and velocities while being trapped in the galactic magnetic field for about 10 Myr for GeV protons; for higher energy (E) particles, that containment time goes down as $E^{-1/3}$, due to the Kolmogorov spectrum of interstellar turbulence. Thus the galactic magnetic field less easily traps the highest energy cosmic rays. This is a double-edged sword for habitability.

Much research has been done on the effects of a nearby supernova. However, less attention has been paid to the impact of many distant supernovae that result in the overall cosmic ray background. The effects of a nearby supernova are short-term. The impact of many distant supernovae occurring as the result of starburst conditions in the disk of the Galaxy would be a long-term detriment to complex life on the surface and in shallow waters. The likely suppression of complex life forms

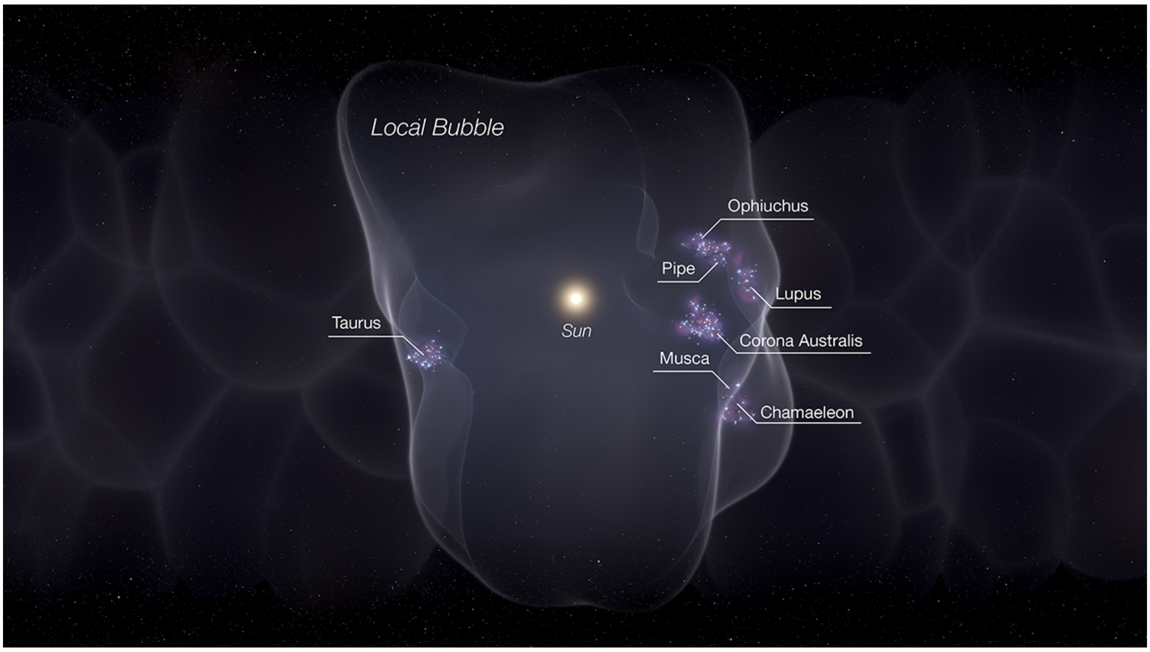

Figure 24: Artist's illustration of the Local Bubble. Star formation is occurring on the bubble's surface. Beginning about 14 Myr ago one, or likely more than one, supernova created and began to inflate a 10 pc wide bubble. The expanding shock is responsible for the recent formation of all stars within 300 pc of the Solar System. The Pipe Nebula (Barnard 59, 65, 66, 67, and 78) is a dark nebula in the Ophiuchus constellation. Credit: CfA, Leah Hustak (STScI).

would last for as long as the starburst lasts, 100 million years or more, like the most recent encounters between the Milky Way and the Sagittarius Galaxy, 1 and 2 billion years ago.

7.2.1 The Local Bubble

The sun is roughly in the center of the Local Bubble - a structure about 300 parsecs in diameter having about 10% of the density of the surrounding interstellar medium, see the illustration in Figure 24. The Local Bubble was formed about 14 Myr ago, resulting from the birth of a star cluster followed by about 15 SNe explosions. Using Hipparcos, a satellite used to measure stellar parallaxes, Breitschwerdt and collaborators [110] identified the Scorpius-Centaurus OB Association as the most likely source for the formation of the Local Bubble. They found that the ^{60}Fe arises from two supernovae, 90 - 100 pc, from Earth. The closest one occurred 2.3 Myr ago and the second closest exploded 1.5 Myr ago each with a mass of about $9M_{\odot}$. After its formation, the Local Bubble expanded. The pressure triggered four periods of star formation that occurred at the surface of the Local Bubble's expanding shell [111]: About 10 Myr ago the Upper Scorpius Association and the older population in Ophiuchus formed, 6 Myr ago the Corona Australis Association and the older stellar population of Taurus formed, 2 Myr ago stars in the Lupus and Chamaeleon constellations formed, as well as the younger stellar populations of Taurus and Ophiuchus, and during the present day dense star-forming molecular gas clouds are seen on the surface of the Local Bubble, see Figure 24. All current nearby star formation (within 200 pc) is occurring on the edges of the Local Bubble as a direct result of the pressure of the expansion, sweeping up and compressing about 2 million solar masses (2 x 10^6 $M_\odot$) of the surrounding interstellar medium. Zucker and collaborators [111] also found that the Sun, which is currently roughly near the center, as shown in Figure 24, entered the rapidly expanding Local Bubble about 5 Myr years ago and was about 300 pc away when the first supernovae exploded about 14 Myr ago caused the bubble to inflate.

7.2.2 Mass Extinctions

The geological record shows the production of banded iron formations, indicating oxidation of the oceans 2.4 Gyr ago called the Great Oxygenation Event (GOE), which resulted in the extinction of all species unable to survive in the post-GOE oxygen atmosphere and shallow seas, see the oxygen data in Figure 23. The concept of major mass extinction - defined by the loss of at least 75% of species, is only valid in a practical way on Earth going back to just before the Cambrian explosion. This is when we can find significant information in the fossil record. Since the Cambrian Explosion (538.8 Gyr ago), five events called the Big-Five mass extinctions occurred along with about six more minor mass extinctions, based on the fossil record mainly of marine life [112] giving an average mass extinction rate of 1 every 50 Myr ago from all causes. It is important to point out that natural selection drives speciation, - the creation of new species by divergent evolution, (note the Integrated Synthesis of Evolution in Figure 1) and the destruction of species by background extinctions. The background extinction rate depends on the lifetime of the species as about 10% of species go extinct after 1 Myr, 30% go extinct after 10 Myr, and 65% of species go extinct after 100 Myr [112].

The most recent of the Big-Five mass extinctions, 66 Myr ago was likely triggered by an asteroid or comet impact [113] creating the Chicxulub crater on the coast of the Yucatan Peninsula. However, extreme volcanism, occurring at about the same time in the Deccan Traps, 65 Myr ago, may have been a contributing cause. See Bailer-Jones [114] for a thorough review of mass extinctions and especially for a proper analysis of claimed extinction periodicities, finding that non-periodic impacts and terrestrial causes: extreme volcanism, and sea level changes among others, should explain most mass extinctions [115]. Let us consider now the other four of the Big-Five mass extinctions. Extreme underwater volcanism from the Central Atlantic Magmatic Province (CAMP) caused a global increase in temperature and a dramatic change in ocean chemical composition and thus is a likely cause of the Triassic-Jurassic extinction: 210 Myr ago [116]. Extreme volcanism combined with the ignition of fossil fuel deposits is a likely cause of the Permian-Triassic Extinction: 250 Myr ago [117,118]. Volcano eruptions elevated atmospheric CO_2 and hydrogen sulfide (H_2S) levels causing acid rain and ocean acidification, among other changes in both ocean and land surface chemistry. Supernova-induced climate change might be the cause of the complex Devonian Extinction: 365 Myr ago, [119,120], which extended over about 10 Myr. However, during the same period rapid growth and diversification of land plants produced global cooling as CO_2 was dramatically withdrawn from the atmosphere. A GRB has been proposed to have caused the Ordovician-Silurian Extinction: 444 Myr ago [121], affecting mostly small marine organisms. However, plate tectonics might be the culprit as the tectonic uplift of mountains created lots of weathering, resulting in the sequestration of atmospheric CO_2. A drop in temperature followed along with changes in ocean chemistry. The resulting cyclic glacial and interglacial periods created large changes in the sea level, moving shorelines and habitats dramatically.

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7.3 Prior work on biological effects of SNe exposure

The possible relation between mass extinction and supernova explosions dates back to at least the 1950s when Schindewolf considered the possible effects of radioactive elements from SNe. Soon after, Victor Krassovskij and Iosif Šklovskij [122] considered the effects of cosmic rays, from SNe on the Earth's atmosphere and biosphere and were followed by many others, a few of which we discuss here.

In 1968, Katelyn Terry and Wallace Tucker [123] argued that exposure to cosmic rays from SNe could have caused the extinction of many animals without the simultaneous extinction of plants, due to the higher radiation tolerance of plants. Malvin Ruderman [124] suggested, in 1974, that the main effect of a nearby supernova on the biosphere would be the depletion of the ozone (O_3) layer by the production of nitrous oxide (NO). This idea was followed up by John Ellis and David Schramm [125] who performed an analysis of O_3 destruction and replenishment and found a supernova at a distance of 10 pc would cause a 95% ozone reduction that would last for hundreds of years. A supernova at a distance of about 10 parsecs would produce a cosmic ray fluence of 7.4 x 10^6 erg cm^{-2}yr^{-1}, substantially above the normal cosmic ray flux experienced by Earth today of 9 x 10^4 erg cm^{-2}yr^{-1}. Today's fluence produces a radiation dose at Earth's surface of 0.03 R/yr and produces 10^7 NO molecules cm^{-2}yr.$^{-1}$ They argue this dramatic increase in NO production would destroy the ozone layer and the radiation dose would diminish only after 300 years. Mass extinction occurs after the disruption of the food chain, which results from long-term exposure to UV radiation without ozone protection. The widespread death of photosynthetic organisms would lengthen the recovery time since most of the O_3 production, needed to replenish the destroyed ozone layer, would be absent.

Ellis and Schramm [125] also suggested that the nearby (160 pc) Geminga supernova remnant, shown in the bottom left panel of Figure 10, which exploded about 300,000 years ago and is currently a gamma ray source, as well as a millisecond pulsar PSR J0437-4715 (150 pc), which is also young, are examples that having a supernova explode nearby is common. They concluded that SNe should be considered as one among several causes of mass extinctions of life on Earth. They estimated that a nearby supernova explosion might remove the ozone protection, thereby exposing the surface to solar UV. Plankton and reef destruction and ultimately widespread extinction on both land and in shallow marine environments would ensue. They also point out the apparent fragility of Earth's ozone protection given the increase in the size of the Antarctic ozone hole caused by humans. Using these cases they estimate a modern nearby supernova rate, within 10 parsecs, of about one every 500 Myr. We can check this estimate using the SN rates obtained from gamma-ray spectroscopy: As discussed earlier the SN rate in the Galaxy is about 1 every 50 years, including SN Ia. So in the solar neighborhood the SN rate is roughly 1 every 100 years per $10^{8.5}$ pc^2, so 1 per 100 x 10^6 years per $10^{2.5}$ pc^2, so these estimates agree.

Paul Crutzen and Christoph Bruhl [126] used atmosphere model calculations to derive an O_3 depletion of 20% and 60%, for the equatorial and high latitude regions of the Earth respectively. Neil Gehrels and collaborators [127] used the high-energy observations of SN 1987A to evaluate the ionizing flux and employed a two-dimensional local transport model to further investigate O_3 depletion due to a nearby supernova. They concluded that O_3 depletion from the combined effects of gamma rays and cosmic rays from a supernova explosion closer than 8 pc, would be quite

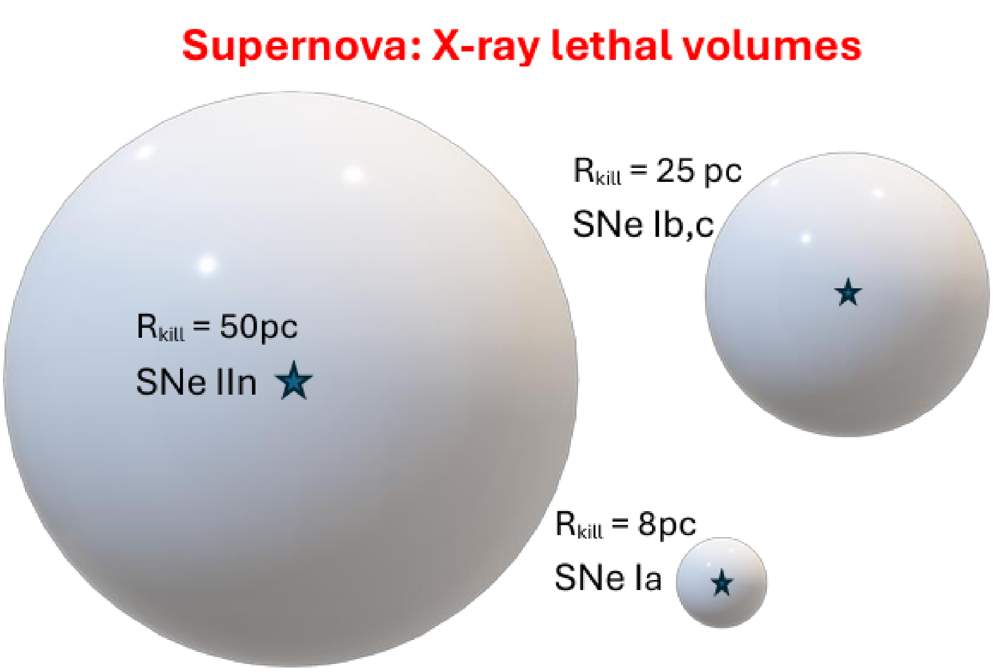

Figure 25: SNe lethal volumes from X-ray depletion of atmospheric ozone are shown depending on type of SNe [129]. The cosmic-ray lethal volumes are all about 20 pc [130], but lethality occurs much later, peaking thousands of years after the explosion.

destructive. A supernova with a total gamma-ray energy of about 1.8 x 10^{47} erg was assumed.

N. Shaviv and collaborators [128] argued that Earth passes through a spiral arm once every 100 million years or so with each passing taking about 10 million years and that these passages might result in mass extinctions due to exposure to SNe. Linking the mass extinction record with specific supernova remnants, like those shown in Figures 8, 9, and 10, is problematic, pointing out, that the remnants of explosions occurring near Earth at the time of the major mass extinctions would be far from us by now.

As described earlier, very massive stars eject a substantial amount of their mass as wind as they near the end. The supernova then explodes into the escaped material. The resulting shocks that occur when the SN ejecta impacts the wind make these, often the SNe IIn type explosions, much brighter in X-rays than a typical SN. Brutton et al. [129] estimated the X-ray luminosity of SNe of different types. The resulting X-ray lethal volumes are shown in Figure 25. The latest estimates for the cosmic-ray lethal distance have been revised upward by Thomas and Yelland to 20 pc [130]. Cosmic ray exposure within this volume would last roughly 10,000 years. The threat to life posed by a kilonova is similar to a common core-collapse supernova with a lethal distance estimated to be 11 pc [131].

7.4 Prior work on biological effects of GRB exposure

The dangers of GRBs to life on an Earth-like planet have been modeled by Adrian Mellot and Brian Thomas and collaborators in a series of studies [132-134]. Gamma rays from GRBs are too brief to do extensive damage unless they are quite close, or if they are beamed in the direction of the planet because the radiation integrated over time is what drives their impact. Direct cosmic ray flux from a gamma-ray burst, is probably isotropic and would be sterilizing only if the GRB is very close, within about 20 pc, as they are likely associated with the SNe IIc-BL type of supernova, as noted in the classification scheme of Figure 11.

The effects of a close and beamed GRB, range from the extreme case, the delivery of enough energy to cause hydrodynamic atmospheric removal, to the more benign and more frequent case of the removal of ozone, exposing the planet's surface to the UV radiation of the planets host star. Planets, even in nearby galaxies, can have ozone depletion due to a GRB if the planet is caught in the beam. In most cases, direct exposure to a GRB would result in a widespread mass extinction over a large surface area, but not planetary sterilization. Life could recover sufficiently well depending on the specific lineages that undergo extinction.

In 2007, Douglas Galante and Jorge Ernesto Horvath examined the biological impacts of direct GRBs and found that there may be significant ozone depletion at distances of up to 100 kpc [135]. It was suggested that stellar UVB radiation reaching the ground would result from being in the beam of a GRB. In 2014, Tsvi Piran and Raul Jimenez used stellar luminosity functions and the observed GRB rates to estimate that the probability of a lethal GRB, defined as causing a mass extinction, on a planet within 4 kpc of the Galactic center is 95% [136]. They further conclude that the probability of mass extinction by GRB decreases to 50% beyond 10 kpc. Earth, at a Galactocentric distance of 8 kpc is likely to have been exposed to one sterilizing GRB event.

Piran and Jimenez [136] also argued that the long GRBs are the most dangerous type and that short GRBs have fairly negligible effects on habitability, again because it is the total integrated ionizing radiation that counts, so since long gamma-ray bursts last longer than short gamma-ray bursts, they have a greater impact on the habitability of nearby planets. Long GRBs have a strong metallicity dependence, so they are likely to have occurred mostly during the early history of the Milky Way. Nowadays, GRBs are most likely to occur in the outskirts of the Milky Way, beyond about 15 kpc.

8. Ionizing Radiation Effects on Cells

For single-cell organisms, the effect is straightforward, ionizing radiation can either kill the cell, cause a mutation in the cell's DNA, or have no effect. On the other hand, the situation for multicellular organisms, i.e. complex life, is more varied. The effect of radiation exposure on health depends on the patient absorbed dose, by the type of radiation, and especially on the affected organ or type of tissue.

In 1999, Charles Cockell [137] studied the effect of UV-B radiation on life. See also the review by Lewis Dartnel on ionizing radiation and life [138]. Recall that, in addition to high-energy electromagnetic radiation, UV, X-rays, and gamma rays, ionizing radiation also consists of particles: protons, electrons, neutrons, the nuclei of helium atoms, and even the nuclei of more massive atoms, see Section 2. A small subset of circumbinary habitable zone planets may benefit from the tidal braking of one or both stars in a close binary, as binary synchronization reduces stellar magnetic activity, the so-called Binary Habitability Mechanism [139-141].

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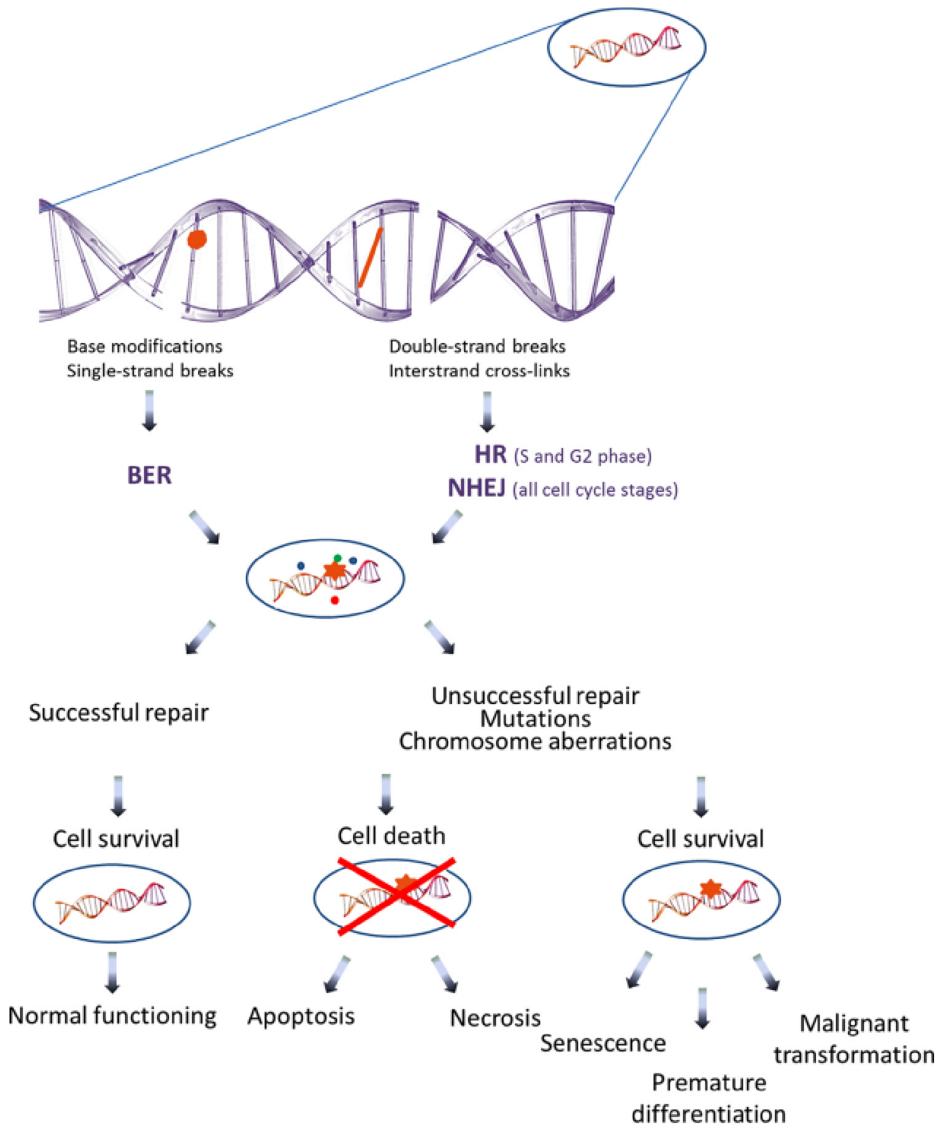

Figure 26: DNA damage and repair is shown schematically. BER stands for base error repair, HR stands for homologous reconstruction and NHEJ stands for non-homologous end-joining. See text for more details. Credit: Creative Commons free use.

When ionizing radiation impacts a cell, the particle energy is absorbed by the cellular molecules. This energy removes electrons from the molecules, which is the meaning of ionization, or it may break molecular bonds entirely. These molecules called radicals are chemically reactive and may either be charged or neutral. Other cell molecules react with these radicals which may result in cell damage. Sometimes proteins may be damaged and DNA may be broken and errors can be written over the existing DNA code. Many, but not all of these breaks are repaired, see Figure 26.

DNA repair is the final layer of protection, as noted in Section 6, for life against ionizing radiation. The evolutionary invention of DNA repair was one of the most beneficial milestones on the road to complex life on Earth. Modern cells can repair radiation damage efficiently in many cases, especially when small errors are introduced. In other cases, several things are possible, if a defect goes unrepaired or if the repair is faulty then altered DNA results. Suppose these mutations occur in the sexual reproduction cells of either the male or female and allow the organism to maintain life and replicate. In that case, the mutation enters the species population. If the cell can repair the radiation damage, life then continues as normal. If the cell is unable to repair the damage it dies by apoptosis, which is programmed cell death. Under high radiation doses, the cell dies directly from the damage itself, which is called necrosis, see Figure 26. Surviving cells may result in premature aging (senescence), premature differentiation, or malignant (cancerous) tumors.

Deterministic radiation damage occurs when radiation the dose exceeds a certain threshold resulting in the widespread killing of cells, followed by compromise of organ function. Above this threshold, the severity of radiation damage increases roughly linearly with the dose. Below the threshold dose, no deterministic damage occurs. Deterministic radiation effects may occur well after the exposure, however, they occur faster with exposure to higher doses.

Stochastic radiation damage is when changes occur in the genetic material, namely the DNA, of cells. The severity of stochastic damage is not affected by the dose. In other words, stochastic damage is a threshold effect; so that it either happens or it does not happen, but beyond the threshold there is no relation between dose and damage. However, the probability of damage directly depends on the dose. So, both low-dose and high-dose ionizing radiation will potentially result in stochastic damage. Cancer is an example of stochastic radiation damage which can occur long after the exposure and may be heritable, meaning passed to the next generation. Once inherited, the mutated gene has several possibilities, the organism may not be able to reproduce, or it can reproduce but at a lower fitness, meaning with a lower probability of reproducing. On the other hand, its fitness may also be improved! Fitness here is defined in the Darwinian sense that success is defined as the number of copies, capable of replicating themselves, of the organism, in particular the DNA of the organism, that exist in the next generation.

8.1 What are Mutations?

Stochastic radiation damage, if not repaired, involves changes in the genetic sequence of an organism called mutations. The biological effect of a mutation might affect the organism, and/or some or all of the organism's offspring. Here we are specifically concerned with the mutations causing a change in the nucleic acids that make up DNA. For the mutation to be inherited, it must have affected a reproductive cell. The effects of mutations can be harmful, neutral, or beneficial. Most are neutral often because the cell is capable of some DNA repair, see Figure 26. Most of the rest are harmful, but a small minority are beneficial. A measure of an organism's ability to survive and reproduce is called the fitness of the organism. The offspring must also be able to reproduce. Genetic mutations drive evolution because mutations provide diversity from which natural selection operates such that the fittest have the best chance of replicating their DNA. See the simple example of a mutation effect on a population shown in Figure 27. Experimental results (left panel) show that mutations in non-reproductive cells can lead to premature death, where fitness equals 0. In some cases, the lineage ends without affecting the reproductive cells. The more severe the mutation, that is the more base pairs that are affected by a mutation, the more likely it is that the mutation will be detrimental. In the left panel of Figure 27, it is seen that many of the mutations cause no change

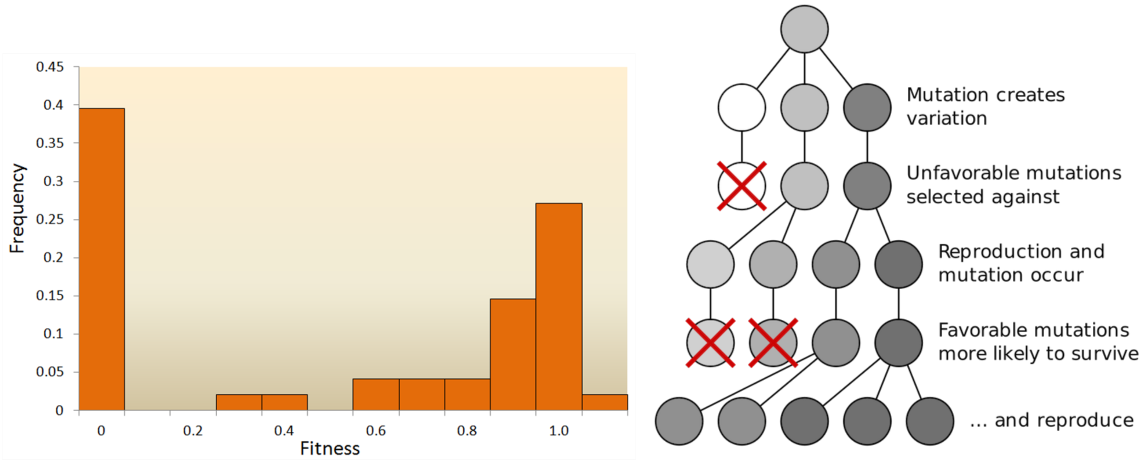

Figure 27: Left: Experimental results of fitness changes after mutation [142]. A fitness factor of 0 means that the organism dies. A fitness factor of 1 means that the fitness is unchanged. Values between 0 and 1 represent decreased fitness and values above 1 imply increased fitness. Mutations benefit a few lucky organisms with $f > 1$, at the cost of the death of many with $f = 0$. Credit: Sanjuán et al. [142]. **Right:** A simplified evolution illustration is shown. The parent organism has neutral fitness (gray). A mutation creates 3 variations in the next generation, one reduced fitness (white), one unchanged (gray), and one improved fitness (dark-gray). The neutral and improved fitness organisms reproduce and more mutations and variations occur. Ultimately, the favorable mutations remain in the gene pool, while those with decreased fitness do not. Credit: Creative Commons free use.

in fitness, giving a value of 1, while only a very few receive an improved fitness, a value greater than one. In addition, the vast majority of mutations whether neutral, detrimental, or beneficial, have very small effects at the current level of Earth's background radiation dosage. The right panel of Figure 27 shows a simplification of how beneficial mutations, while rare, propagate through a population after generations of natural selection.

Even low doses of natural radioactivity in bedrock influence the mutation rate. At these low doses, one possibility is that DNA damage may occur through the accumulation of oxidation damage. All life on Earth is exposed to natural radioactivity. Animals are exposed to radioactivity through the food they eat. Natural radioactivity exposure is rarely, if ever, harmful to individual organisms, however, it can be a major source of mutations. Particles can come from radioactivity in rocks which inevitably gets into our food and drinking water. In this way, our own body provides a background of ionizing radiation. In at least one study [143], mutations were directly linked to increased exposure to radioactive bedrock. Mitochondrial DNA damage was found to be significantly more severe (60% increase) than nuclear DNA damage (30% increase) in the genome of a species of waterlouse, after a factor of three increase in exposure to radioactive bedrock. The model organism was chosen because it is found in subterranean environments, therefore excluding UV light as the cause for mutations.

Mutations are certainly a double-edged sword for life on Earth. The fact that cells are efficient at repairing many effects of ionizing radiation suggests that repair mechanisms have evolved to deal with the deleterious effects. However, two factors determine the total number of both hazardous and beneficial mutations. The number of mutated organisms in the next generation depends on the mutation rate and the population size. If a species has a large population size, then it may benefit, by increasing the diversity of the genome, from an increase in the mutation rate. A more diverse population can adapt to environmental changes more readily than a less diverse population. However, this is at great cost to the population size, reduced by the large number of organisms killed or made sterile by the mutations or simply have less fit offspring. If the population is large enough, the benefits of a few organisms with better fitness outweigh the population lost, allowing for population growth over time.

8.2 The Impact of Mutations on Population Evolution

Mutations provide the diversity for populations upon which Darwin's natural selection drives evolution. Radioactivity and cosmic rays can impact the molecular evolution of a species by determining the rate at which different types of mutations appear and accumulate. There are two ways that this can happen in DNA. One is the breaking of the sugar-phosphate backbone of DNA. This can be either a single-strand or a double-strand break, see Figure 26. The other mechanism is indirect as the damage occurs when a water molecule within the cell itself is converted to an oxygen radical, O^*, by ionizing radiation, the reactive oxygen then damages the DNA, which is also shown schematically in Figure 26.

The double-stranded breaks are by far the most dangerous despite there being two repair mechanisms, homologous recombination, and non-homologous in the end-joining of double-strand DNA breaks. Interestingly, in our context, non-homologous end-joining unlike homologous recombination, does not use a template to reconstruct the missing strand of genetic information. Because it only restores the continuity of the DNA molecule, but not its information, this reconstruction suffers from frequent errors such as deletions, unrepaired point mutations, and chromosomal anomalies, all of which have been shown to occur following high radiation doses. The double-strand breaks resulting after a strong radiation dose are found to have been non-homologously rejoined. Repair systems are sensitive and respond non-linearly to radiation dosage. At low dosages, they appear to be inactivated. Moderate dosage activates efficient DNA repair. At high ionizing radiation dosage, the repair mechanisms become inefficient, thus endangering the continuity of the DNA molecule over time, especially during prolonged radiation exposure lasting many generations.

A given population will consist of organisms with a range of fitness. The meaning of fitness itself can change over time because fitness is a measure of how well-suited the organism is to the environment, including short-term fluctuations in the environment. As the environment changes, what it means to be fit also changes. This property is essential to life as we know it because the most important long-term survival property for a population is for it to be able to adapt to environmental change.

The mutation rate for a population affects both the population size and the average fitness of the population. For this discussion, consider changes in the mutation rate which occur on a time scale shorter than a species or population can adapt. An increase in the mutation rate likely leads to a decrease in population size, due to mortality, and in its growth rate. In regards to fitness, two things are possible, an increase in the mutation rate can lead to it decrease in the average fitness of the population due to harmful but not fatal mutations. Again harmful mutations have the potential to change into beneficial mutations if the environment changes move in their favor, but that is not the usual case. And an increase in the mutation rate increases the genetic diversity of the surviving population, essentially by definition. However, diversity also depends on the population size. Despite all of this, a small number of organisms, with higher fitness, will propagate their DNA because their offspring may inherit beneficial traits. The mutation rate itself, in these situations, is a source of stress or in other words, an environmental factor that a population must adapt to in order to survive. For example, an organism can reproduce at a higher rate or slow its growth in response to environmental stress. Again, it all depends on the timescale of environmental change compared with the ability of a given population to adapt. However, it is also reasonable to assume that there exists a threshold dose, for which the damage done by ionizing radiation will not allow the development of complex life in the first place.

8.3 Chiral selection of molecules

Finally, we address a longstanding problem in biology of the dominance of left-handed amino acids to the near exclusion of their right-handed molecular forms [144, 145], this is called organic molecular homochirality. The geometric effect called chirality is illustrated in Figure 28. The fact that many organic molecules do not have a plane of symmetry in their structure, making them chiral, means that pairs of molecules with identical components may have two forms as shown in the figure. There is only one way to form an achiral molecule, like water H_2O, carbon-dioxide CO_2 or methane CH_4, because these are symmetric molecules. Any four component molecule, say with atoms at the corners of a tetrahedron (see Figure 28) will be chiral if all four atoms are different. While they appear identical, as mirror images, they perform different chemistry. An unsolved mystery is why are the amino acids used by life nearly all left-handed, rather than all right handed or some mixture. The appearance of an excess of left-handed amino acids in the Murchison Meteorite [146] has provided fuel for the hypothesis of an astrophysical origin of homochirality.

Exposure to a strong neutrino source produced within a strong magnetic field is a proposed solution [147] and points to a possible essential link between particle astrophysics and organic matter. The molecules essential for life have their origins in interstellar dust. Electron neutrinos are right-handed (spin $1/2$) particles, while electron antineutrinos are left-handed. One established example is the difference in the ^{14}N interaction cross-section to spin directions. Chiral selection of molecules involves the nitrogen interaction cross-section's dependence on the neutrino and on ^{14}N nuclei spin orientations. This produces a chiral preference, introduced by the magnetic field of the neutron star in one model, by preferentially destroying the ^{14}N molecules with right-handed chirality. The freshly formed dust in the SN ejecta itself, or winds from the progenitor star, are likely locations for this process to occur. Dust particles are formed very fast in ejecta around a SN explosion. These dust particles are aligned with respect to the magnetic field, since some atoms have a magnetic moment. In a SN explosion very powerful emission of neutrinos occurs, and can interact with such nuclei, as described. For SN 1987A, the neutrino burst was detected for about 20 seconds [48, 49]. The SN became optically visible about 4 hours after the neutrino event. The formation of a neutron star implies a red giant progenitor which ejected cool material before the explosion, making dust very quickly [148]. The dust formation, that is needed for this process, occurred days after the SN 1987A explosion and the neutrino outburst [149]. So, either dust would need to be there in the stellar wind before the SN explosion, or perhaps more plausibly, the neutrino

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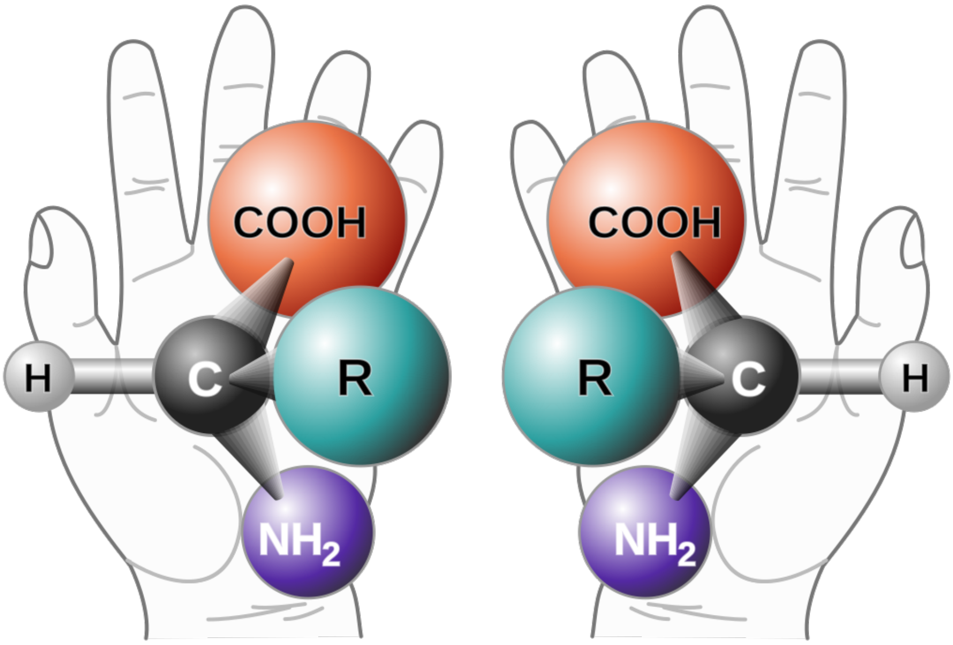

Figure 28: The chirality of molecules is based on a geometric property applicable to all objects in 3-dimensional space. An achiral (non-chiral) object or molecule has at least one plane of symmetry. For example, Water H_2O (like all 3 component molecules) is an achiral molecule because a mirror image of the molecule appears exactly the same as a 180^o rotation around its axis of symmetry. It appears the same from the front as it does from behind. The image shows two molecules made of the same components, but they are different molecules, and hence chiral. This is because (just like the hands) one cannot rotate one molecule to be the same as the other. To put it another way, a right hand cannot fit into a left-handed glove, likewise handedness of molecules affects their chemistry. The assignment of left versus right handedness to molecules, just like for hands is arbitrary. However, for some reason, life on Earth involves mostly left-handed amino acids. Credit: Public Domain.

emission does not stop completely after 20 seconds but slowly decays from a reduced high level, while the budding neutron star is settling down.

Once produced, the chirality imbalance is thought to become amplified in the populations of any amino acid by successive evolution of the molecules [145]. The detection of neutrino emission from the inner Galactic plane using the Ice Cube detector [150], located at the South Pole, and the potential PeVatron supernova remnant G106.3+2.7 seen in very-high-energy gamma rays by the Tibet AS Collaboration [151] are consistent with the related gamma-ray emission from these Milky Way young thin-disk neutrino sources including SNe. This argument on chirality [152], if true, has the consequences that all life in the universe built on these atoms, will have the same chirality.

9. Summary

We began by outlining the early development of high-energy particle physics and the discovery of high-energy electromagnetic radiation. High energy cosmic-ray particles reach almost 10^9 times the energy of the electromagnetic radiation. Cosmic ray particles range for the low energy solar particles to the ultra-high energy cosmic ray particles (UHECRs), On Earth, life is exposed both directly and indirectly to ionizing radiation. The highest energy photons, namely the ultraviolet (UV), X-rays, and γ-rays (gamma rays) are capable of ionizing molecules, especially water, but even DNA. The ability of cells to repair DNA after radiation damage is critical to their survival. Likewise, cosmic ray particles: protons, neutrons, electrons and so on, often ionize atoms, especially when air-showers multiply their effect by creating a cascade of multitudes of secondary particles. Many of these secondary particles reach the surface and shallow waters on Earth affecting life there. On Earth today, the main source of ionizing radiation is natural radioactivity. This is because today, life on Earth is protected by a thick atmosphere, an Ozone layer, a strong global magnetic field, the heliopause - the astropause of the Sun, and the Galactopause (analogous to the astropause, but surrounding the disk of the Milky Way).

Other sources of ionizing radiation, including high-energy electromagnetic radiation from the Sun, solar particle radiation - such as energetic solar particles (SEPs), cosmic rays accelerated by Galactic sources (GCRs) and even some extra-galactic sources (EGCRs), including UHECRs, were more intense and therefore more important in Earth's past. This was especially traumatic when there was a nearby catastrophic event, such as a nearby active galactic nucleus (AGN), a supernova, gamma-ray burst (GRB), or a kilonova - the observed explosion from a merger of compact stars like when two neutron stars in a binary merge or when a black hole mergers with a neutron star. We also discussed a possible connection between the observed chirality of organic molecules and the formation of neutron stars.

We refrained from discussing the effect of an AGN on life, because the relatively low-mass and low activity of the Milky Way's supermassive black hole suggests that it has not accreted significantly in its recent past and thus has had relatively little impact on habitability within the galactic disk. However, these issues arise in (the many) galaxies with a more massive central black hole than the Milky Way. We suggest that nearby supernovae (SNe) and Gamma-rays bursts, if beamed in the direction of an inhabited planet, among others like kilonova, are possible causes of mass-extinctions seen in the fossil record. Certainly, these events, which affect many more exoplanets during times of high star formation rate, associated with galaxy mergers, must be considered as threats in the study of the emergence of complex life in the Milky Way. A key to the success of complex life is its ability to recover from catastrophe, and even benefit from mass extinction (as long as critical lineages survive), which after the environment recovers, opens niches for the survivors.

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