Modelling uncertainty of the Rhenium-Osmium cosmic clock

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Abstract

write abstract

Contents

Chapter 2

Theory

2.1 Cosmology

2.1.1 Baryonic matter

The known elementary particles are fermions and bosons, where the fermions are divided into leptons and quarks. By combining quarks into groups of two and three via the strong force mesons and baryons are created**?**. Most known matter in the universe is made up of electrons, protons and neutrons. Since protons and neutrons make up most of the mass of these particles it is common to refer to standard model particles as the baryonic mass component of the universe.

2.1.2 Dark matter

The rotation curves of galaxies depends on the force of attraction (gravity), which depends on the (enclosed) mass within the galaxy. However the kinematics of stars does not reproduce the observable mass, even after taking gas into account. This suggests a presence of particles that do not interact with regular baryonic matter. The phenomenon was dubbed "dark matter" and is believed to only interact with baryonic matter through gravity**?**, *ch.24.3*.

2.1.3 Dark Energy

Hubble calculated the distance, d, to 18 galaxies by means of Cepheid variable stars, and combining his results with the velocity, v from Slipher a linear relation was found, $v = H_0 d$, with some constant H_0, the hubble constant. Galaxies moving away with greater velocities at greater distances, suggests the universe is expanding. This is later supported by additional observations and theories?, *ch.27.2*.

In solutions to the tensor-field equations from general relativity, such an expansion comes natural if one considers a cosmological constant Λ. Such a component introduces an acceleration of the universe and is often called dark energy, or cosmological constant.

In an expanding universe, there are two sets of coordinates. Real coordinates which map the distances in real space between galaxies and comoving coordinates which follow the expansion of the universe.

2.1.4 Λ CDM

The standard model of cosmology is the combination of the above components; baryonic matter, cold dark matter (CDM) and dark energy (Λ). The individual components have been well established from observations, e.g. Wilkinson Microwave Anisotropy Probe ?.

2.1.5 Big bang nucleosynthesis

Stars create heavier elements from lighter elements and produce energy as a result. Given the age of the universe and the stellar populations helium could not have been created in stars in the observed abundances from extra solar stars. Starting with the big bang model of the universe, what elements would have been synthezised to create the nuclear abundances that would later become the first stars? After inflation separates quantum fluctuations into particles, the universe was very dense and very hot. All matter (baryons, leptons, and dark matter) and energy tightly packed, interating and coupled. As the universe expands temperature and density drops accordingly. After the hadrons form, nuclear matter can form. Due to thermal equilibrium between neutrinos, electrons, and baryons the neutron-proton ratio is related by the boltzmann distribution. At the temperatures of weak interaction freeze-out, when this thermal equlibirum is no longer valid, the neutron proton ratio is two-to-five. Since it takes some time for nucleosynthesis to take place and eventually form nuclear particles that are not instantly photodisintegrated. During this time free neutrons decay to protons with a half-life of ten minutes, diminishing the final neutron proton ratio to one-to-seven at the time of nucleosynthesis. This means that there are two neutrons for every fourteen protons when nuclei can form. Some basic math produces one

α-particle for every twelve free protons. The mass fraction of helium is therefore one fourth of the total nuclear mass budget in the universe, while hydrogen makes of three fourths of the total budget. More detailed calculations of nucleosynthesis yield trace amount of ${}^{\mathrm{H}}_{3}1$, ${}^{\mathrm{He}}_{3}2$, ${}^{\mathrm{Li}}_{7}3$, ${}^{\mathrm{Be}}_{7}4$, but the dominant products are ${}^{\mathrm{H}}_{1}1$ with $\simeq 75\%$ of the mass in the universe and ${}^{\mathrm{He}}_{4}2$ with $\simeq 25\%$.
include image of big bang model

2.2 Nuclear physics

2.2.1 Nuclear shell model

The atom is build up of electrons around a nucleus of protons and neutrons. The electric coulomb forces keep the negatively charged electrons around the positively charged protons in the nucleus. The protons and the neutrons are bound together by the strong nuclear force. See figure **??** for illustration.

The quantum mechanical model of the atom is build up by quantum particles (electrons) in the coulomb potential of the nucleus. The energy of the electrons is defined by their radial quantum number, angular momentum quantum number, and intrinsic spin (analogous to rotation about the particles own axis).

The strong force that holds the core together is not as well understood as the electric coulomb force. In order to make a quantum mechanical model of the core it is assumed that all the particles in the nucleus combined make up a central, harmonic potential. The protons and neutrons are then modelled as quantum mechanical particles in the central field. The states of the different particles is given by the principle quantum number n, the orbital angular momentum quantum number l, and the total angular momentum quantum number $j = l \pm \frac{1}{2}$. Similar to the aotmic model**?**, *ch.2.4*. The energy of these state do not stack linearly, but group together in a seemingly clumsy manners. If particularly many energy states are grouped together, and the binding energy of nucleons peaks, the group is called a magic number (see figure **??**).

2.2.2 Mass and binding energy

The total mass of the nucleus is given by the sum it's consituents, the nucleons. Dividing by the mass number (number of nucleons in the core) one gets the average mass per nucleon. This should be pretty elementary, but it turns out that the mass per nucleon dimishes as mass number increases. Each proton and neutron becomes lighter as more protons and neutrons are stacked into the central potential of the nucleus. This energy is analogous to the energy needed to release nucleons from the nucleus potential?. See figure **??** to see how the average binding energy per nucleon evolves with number of nucleons in the nucleus. A classical example is two lighter nuclei colliding to one heavier nucleus. Since the mass per nucleon is lower, but the total number of particles before and after has not changed the total energy has lowered. This excess energy (or mass) is radiated away as thermal photons. This implies that synthesizing heavier elements up to iron (peak binding energy in figure **??**) from lighter elements releases energy. Since protons and neutrons are fermions they follow the Pauli exclusion principle, stating that a maximum of two particles can exist in any given quantum state in a bound system, and they must have opposite spins to do so?*, ch.1.7.3*. E.g. Take a nucleus and continue to stack neutrons onto it, as the neutrons take on higher and higher energy states (from the Pauli exclusion principle) the nucleus eventually reaches a level where any new neutron would no longer be bound. The neutrons would therefore be immediately expelled. If some protons were added, the strong force would be even stronger and more neutrons could be added to the nucleus. The reverse is also true if protons were added continously. This point in the nuclear chart (neutron number - proton number map) is called the neutron drip line and proton drip line respectively?.

2.2.3 Reaction rates

A nuclear reaction in stellar environments is usually depicted as two quantum particles, 1 and 2, interacting to make two new quantum particles, 3 and 4. Written as: $1+2 \rightarrow 3+4$ or $1(2,3)4$ where 2 and 3 are *usually* the lighter particles “impacting onto” or “emitting from” the larger nuclei 1 and 4. If particle 2 is a photon, (absorption of light), the process is a photodisintegration process and the energy released is negative. If particle 3 is a photon, then energy is created from two nuclei colliding and merging to a single nucleus, the energy released is positive. The probability of a given reaction happening is called the nuclear cross-section, and is measured per area. The cross-section is velocity dependant, so the reaction probability in a stellar volume is therefore the integral of cross-section over the velocity distribution. For thermal velocities in an ideal gas the Maxwell distribution? can, and is usually adopted?. The reaction rate then is the probability times the number density of each nuclear specie, as more particles closer together means more possible reactions?. The end result is that nuclear reactions are dependent on the density and thermal velocity (temperature) in stellar environments, and produces energy as long as the fusing particles are lighter than iron.

2.2.4 Weak interactions and β^--decay

Interactions with the weak force cause different decay reactions. The most common weak interactions are listed below

free neutron decay $n \rightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}_e$

β^-**-decay** ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}} \rightarrow {}^{\mathrm{A}}_{\mathrm{Z+1}}\mathrm{Y}_{\mathrm{N-1}} + \mathrm{e}^- + \bar{\nu}_e$

β^+ **decay** ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}} \rightarrow {}^{\mathrm{A}}_{\mathrm{Z-1}}\mathrm{Y}_{\mathrm{N+1}} + \mathrm{e}^+ + \nu$

electron capture ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}} + \mathrm{e}^- \rightarrow {}^{\mathrm{A}}_{\mathrm{Z-1}}\mathrm{Y}_{\mathrm{N+1}} + \nu$

anti-neutrino capture ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}} + \bar{\nu} \rightarrow {}^{\mathrm{A}}_{\mathrm{Z+1}}\mathrm{Y}_{\mathrm{N-1}} + \mathrm{e}^-$

neutrino capture ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}} + \nu \rightarrow {}^{\mathrm{A}}_{\mathrm{Z-1}}\mathrm{Y}_{\mathrm{N+1}} + \mathrm{e}^+$

The β^--decay transitions depend on the initial and final quantum states of the entire nucleus. Transitions which are independant lepton energies are most likely to occur (out of all the weak interactions considered) and are called allowed transitions. The forbidden transitions are weak interactions that are less probable. In stellar environments, with high temperatures the nuclei in question can be excited to higher energies. The increased number of possible states increases the net reaction probability and therefore the overall decay rate. This also means that the chance of observing forbidden transitions is higher. Assuming that a radioactive decay occurs at a random point in time, with a uniform distribution in time, The probability of decay of a single particle is proportionale with time. The probaiblity of decay of two particles will be twice as much, meaning decay probability is proportional to the amount of radioactive particles present. Consider then an amount of particles, N, large enough to turn probability into observable decays, even at infinitesimal timescales. The number of decays, dN, is then given by:

$$\begin{aligned} \mathrm{d}N &\propto N\mathrm{d}t \\ \mathrm{d}N &= C_{\mathrm{decay}} N\mathrm{d}t = -\lambda N\mathrm{d}t \\ \frac{\mathrm{d}N}{\mathrm{d}t} &= -\lambda N \\ N(t) &= N_0 e^{-\lambda(t-t_0)} \end{aligned} \tag{2.1}$$

dt is the infinitesimal timeinterval. C_{decay} is the proportionality constant. Since the decay-process removes number of atoms from the nuclear specie, it will always be negative. λ is the positive proporitonality constant, called the decay constant (because it will not change for a given reaction with constant density and constant temperature).

Solving the differentialequation, eq.2.1 gives the time evolution of numbers of particles, given and initial abundance N_0 at time t_0. The half-life is the time when the abundance is half it's orginial value, $T_{1/2} = \frac{\ln 2}{\lambda}$, while mean lifetime is the average lifetime integrated for all particles $\tau = \lambda^{-1}$.
Some relevant half-lifes free neutrons, $^{\mathrm{C}}_{6}14$, $^{187}_{75}\mathrm{Re}$.

$$\begin{aligned} T_{1/2}(n) &= 10.2 \text{ min} && \text{from ?, } \textit{ch.1.8} \\ T_{1/2}(^{\mathrm{C}}_{6}14) &= 5700 \text{ yr} && \text{from NDS}^1 \\ T_{1/2}(\ ^{187}_{75}\mathrm{Re} \text{ ground state}) &= 4.33 \times 10^{10} \text{ yr} && \text{from NDS}^1 \\ T_{1/2}(\ ^{187}_{75}\mathrm{Re} \text{ first excited state}) &= 4.33 \times 555.3 \text{ ns} && \text{from NDS}^1 \\ T_{1/2}(\ ^{187}_{75}\mathrm{Re} \text{ second excited state}) &= 4.33 \times 114 \text{ ns} && \text{from NDS}^1 \end{aligned}$$

Chart of nuclides is a two dimensional map of all nuclides with amount of protons on the y-axis and neutrons on the x-axis. A small section of the isotopes between $^{1}_{1}\mathrm{H}$ and $^{52}_{26}\mathrm{Fe}$ can be found in figure 2.1.

2.2.5 Nucleosynthesis beyond iron

For elements heavier than iron, collision with other elements will cost energy instead of release energy. In stellar environments, the temperatures and excess energies are very high so some heavier elements can form from energetic light particles colliding with energetic iron particles. However this will be in trace amounts and does not explain the relatively high amount of heavy elements found in the solar system?.

[1] IAEA Nuclear Data Service Livechart

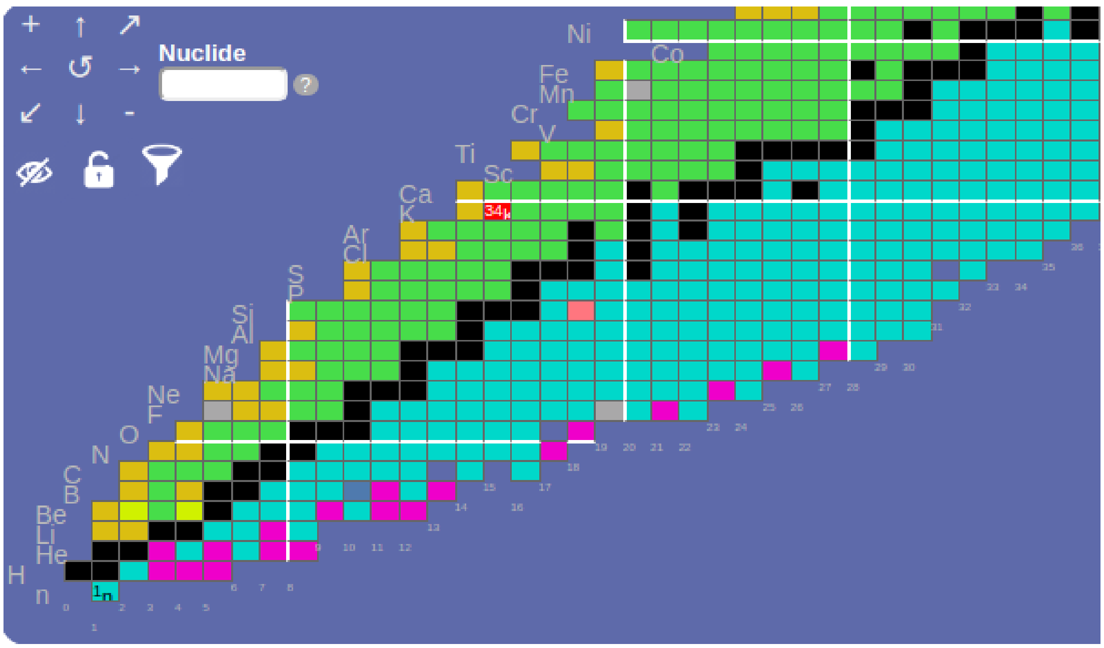


Figure 2.1: Excerpt from low-mass region of the chart of nuclides.
Colors: Black - stable isotopes, cyan - β^{-}-decay unstability, green - β^{+}-decay unstability, orange - proton emission, magenta - neutron emission. Image credit: IAEA Nuclear Data Services Livechart NDS livechart, retrieved 24.05.18.

In order to create heavier elements than iron, seeds close to the iron peak (see figure **??**) are bombarded by lighter particles, like neutrons and protons, in order to increase mass-number one collision at a time. These processes of creating heavier elements are called proton capture process and neutron capture processes. Due to the additional coulomb barrier between protons, neutron capture processes are more probable and likely to occur**?**

Slow neutron capture process

Imagine a stream of neutrons onto some heavy seed nuclei, Two competing reactions take place. The capture of a neutron onto the seed nuclei and the radioactive β^--decay (in a neutron-heavy nucleus the electron emission is more probable then the positron emission).

If the neutron capture is much slower then the radioactive decay, any new isotope must be stable or will decay to a stable isobar with the same mass number. This is called the slow neutron capture process, or s-process for short. It will create heavy nuclei along the valley of stability[1]. For such a process to occur in stellar environments there must be access to a high density of neutrons and heavy seed nuclei from the iron peak. The heavy seed nuclei can just as easily have been produced by another massive star and ejected into the interstellar medium. Free neutrons on the other hand have a short lifespan and must have been created in the local environments. Some processes in the hydrostatic helium burning processes produce excess amounts of neutrons, as do the subsequent α-capture processes in carbon burning. In addition to high neutron density requirements, the temperature must be high enough for thermal reactions to occur, but can not be so hot that most of the heavy seed nuclei are photodisintegrated before a significant amount of heavy nuclei can be synthesized. This means that the optimal site for most of s-process nucleosynthesis is the late time helium-burning phase of stars with relatively low mass. These are asymptotic giant branch stars with mass below roughly three solar masses?. Numerical nuclear reaction networks in stars of this kind have lead to synthesis distributions that correspond with s-only abundances in the solar system. The exact site can include many stellar mass range and mixing episodes between different layers of the stellar interior, which can cause some new sites.
Abundances by Suess and Urey, (s+r)-processes suggested by BBFH, review by iliadis- and basdevant-books

[1] line of stable nuclei in the chart of nuclides, see black colored squares in figure 2.1

Classic stellar model paper, Arnould?
sncp-images hereby named the s-process

Rapid neutron capture process

Modelling the s-process contributions and scaling them to fit the solar observed number abundances results in a differential pattern with clear structure. There are uncertainties in the s-process contribution, and solar observed abundances as well, but some nuclei cannot be produced by regular slow neutron capture process. A rapid neutron capture process is required, and such a process adds to many nuclei already "filled partially" by the s-process to account for the observed solar abundances**?**. This pattern is from a separate process called rapid neutron capture process, where the neutron capture rate is much higher than the β^{-}-decay rate. In such a process the heavy seed nuclei (assumed to be iron peak nuclei from a old supernova), will capture many neutrons until the nucleus is saturated with neutrons. At that point neutrons are emitted away as soon as they are captured. A distribution of neutron-heavy isotopes for a given seed specie is then left over time, kept in equilibrium by the constant bombardment of high energy neutrons. The distribution will have a maximum given by the equilibrium conditions where most heavy isotopes will reside. The nuclei in greatest abundance will β^{-}-decay (to an isobar with greater atomic number) in greatest abundance. In the heavier elements the process begins anew, with neutrons captured onto the nucleus and eventually escaping until an equilibrium distribution is reached. This process is faster than the β^{-}-decay process (by definition) and will reach equilibrium before a significant fraction of nuclei decay to isobars with higher atomic number. When the high energy neutrons are no longer available in the same quantities, the r-process will stop and leave distributions of neutron-heavy isotopes that eventually will decay to stable isotopes far heavier than iron**?**. This sort of process require a much higher number density of neutrons than the s-process described above, and the scales of $10^{21} cm^{-3}$. The astrophysical site, and details, of this process, are greatly debated. reference to debate of r-process sites The output yields of the process are observed in our sun as well as old stars, but these stars could not have created those elements themselves so the process must be relatively quick in order to eject elements into the interstellar medium to be absorbed by our sun and other older stars. hereby named the r-process

Proton capture process

The same capture process can happen to the proton heavy side of nuclei, with dense regions of high energy protons. This is less likely to occur due to the added repulsive coulomb force and will therefore have smaller rates, but is necessary to explain the natural occurance of some isotopes in the nuclear chart?.

Distributions of neutron capture processes

include image of isotope equilibrium distributions here
include r-process pattern here
include plot about s-process r-process in nuclear chart
see path: `/other_data/arnould_plots/etc`

In this project, the r-process is of most interest, since the abundance of $^{187}_{75}\mathrm{Re}$ is solely determined by r-process events and the s-process sites are less debated.

discuss possible sites

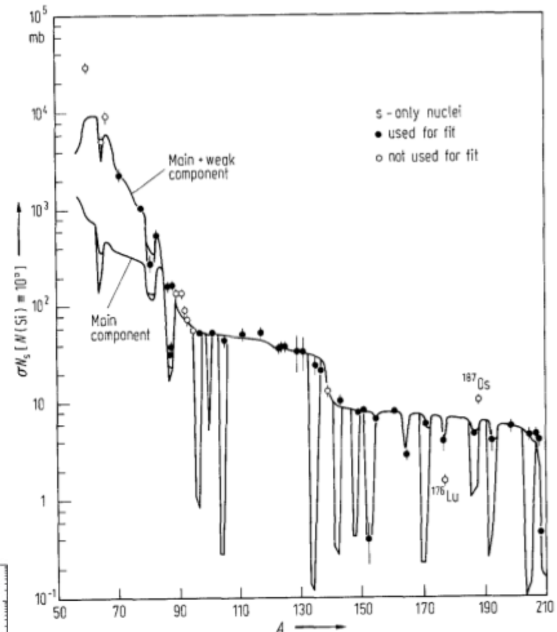
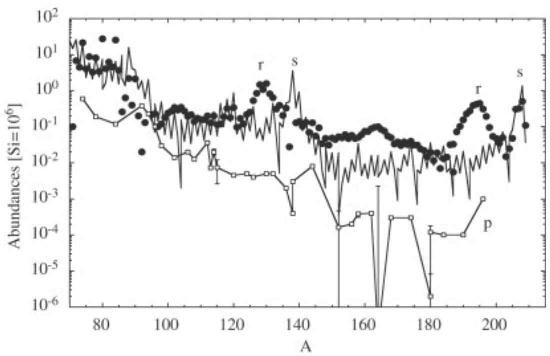


Fig. 4. Computer fit of σN (neutron cross section times abundance) versus mass number. Full symbols are s-only nuclei and are used for the fit. Open symbols are s-only nuclei which were not used for the fit. The ^{187}Os abundance has grown by decay of ^{187}Re, and ^{176}Lu has decayed since s-process synthesis, a long time before solar system formation. S-process contributions to nuclei produced by more than one nucleosynthetic processes can be interpolated. The negative spikes indicate the presence of branching points. Three different neutron exposures are required, at low, intermediate and high (^{208}Pb) masses (see text).



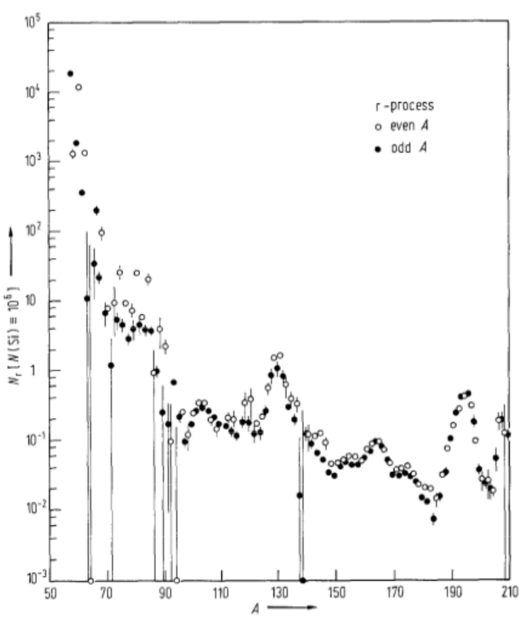


Fig. 5. Subtraction of s-process nuclei from total abundances leads to r-process abundances. Full circles denote odd mass numbers and open circles even mass numbers.

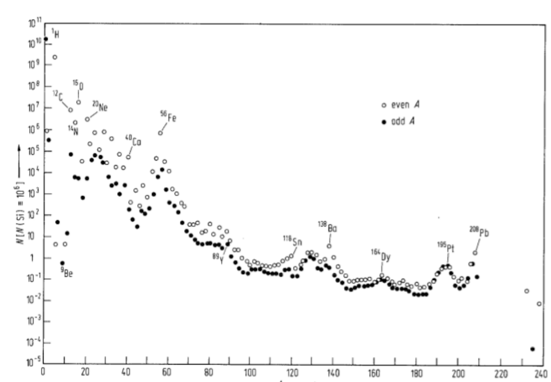


Fig. 7. Solar-system abundances by mass number.

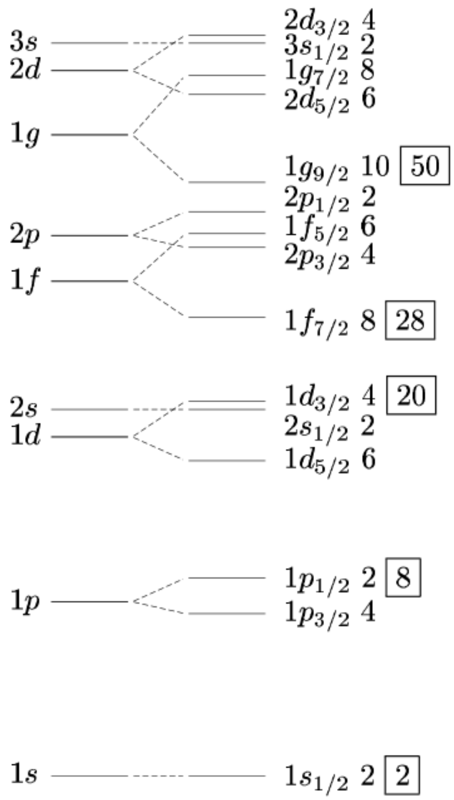


Figure 2.2: Energy states of the nuclear orbitals/shells. This shows how the energy-states group together to form clusters of energy-states separeted by so-called magic numbers.
The energy states are grouped together by their principle quantum number n, with their orbital splitting l shown in the left column. As can be seen, each orbital term greater then zero (s=0, p=1, ...) are split into two sub-levels determined by their spin-orbit terms in the second column from the left. The third column represent the number of nucleons possible per level, and the far right column indicate magic numbers?ch.2.4.
Image credit: Bakken at English Wikipedia [CC BY-SA 3.0], from Wikimedia Commons

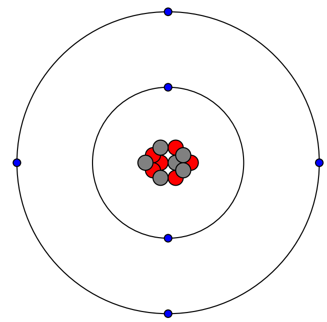


Figure 2.3: Figurative representation of a $^{12}_{6}$C -atom with six protons, neutrons, and electrons. The protons (red) and neutrons (gray) occupy the nucleus in the center, while the electrons (blue) orbit around them. According to quantum physics the electrons do not rotate around the nucleus in spherical orbits, but occupy orbitals/energy states around the nucleus as probability distributions. Real and relative sizes do not apply.

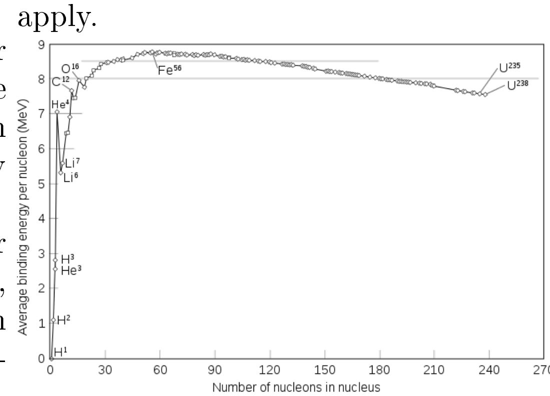


Figure 2.4: The binding energy per nucleon in the nucleus for isotopes up to $^{238}_{92}$U . The peak at $^{56}_{26}$Fe means that the nucleons are most tightly bound, and have the least amount of potential energy.
Image Credit: Wikipedia Commons

2.3 Stellar evolution

This section is summarized from ?, *ch.12,13,15*

Regions of space with higher density then their surroundings are called giant molecular clouds and can extend as wide as insert reference and are the birth place of stars.

Some regions of these giant molecular clouds will have even larger overdensities and gravity dictates that these overdense regions will eventually fall in on themselves.

A star is a sphere of gas with high enough density, and subsequentally high enough temperature, to maintain stable fusion processes in the core.

How large such a subregion must be to collapse is given by the Jeans criterion. The virial theorem states that for a gas in equilibrium the relation between kinetic energy from thermal motion, E_k, and potential energy from gravitational collapse, E_p, is given by: $2E_k + E_p = 0$. This means that when a cloud of gas collapses, this equilibrium no longer holds and the gravitational potential energy is greater then the thermodynamical kinetic energy. This unequilibrium is called the Jeans criterion. For a spherically symmetric gas, with no rotation, magnetic fields, turbulence or pressure from outside forces the mass of the subregion must exceed the Jeans mass: $M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$ or the region must cover a smaller volume then covered by the Jeans radius: $R_J = \left(\frac{15kT}{4\pi G\mu m_H \rho_0}\right)^{1/2}$ where k and T is the thermal energy, G is the newtonian gravitational constant, μ and m_H is the average moleular weight, and ρ_0 is the initial density of the subregion.

Including an external gas pressure, P_0, gives the Bonnor-Ebert mass criterion: $M_{BE} = \frac{c_{BE}\frac{kT}{\mu m_H}}{P_0^{1/2}G^{3/2}}$ where $c_{BE} = 1.18$ is a dimensionless constant, and all other variables are given in the text.

Assuming that any pressure-gradient inside the gas is too small to affect the dynamics and that all the gravitational potential energy released is effectively radiated away, making the gas isothermal, all parts of the gas will collapse to a single point at the same time[2]. This kind of collapse is called homologous collapse and the free-fall time when all gas reaches the "singular point" is given by: $t_{ff} = \left(\frac{3\pi}{32G\rho_0}\right)^{1/2}$ where all variables are given previously in this section. When temperatures increase, some of the heavier elements will ionize and the

[2] Naturally the gas can't collapse to a singularity, but it will collapse to a radius very small compared to the original radius.

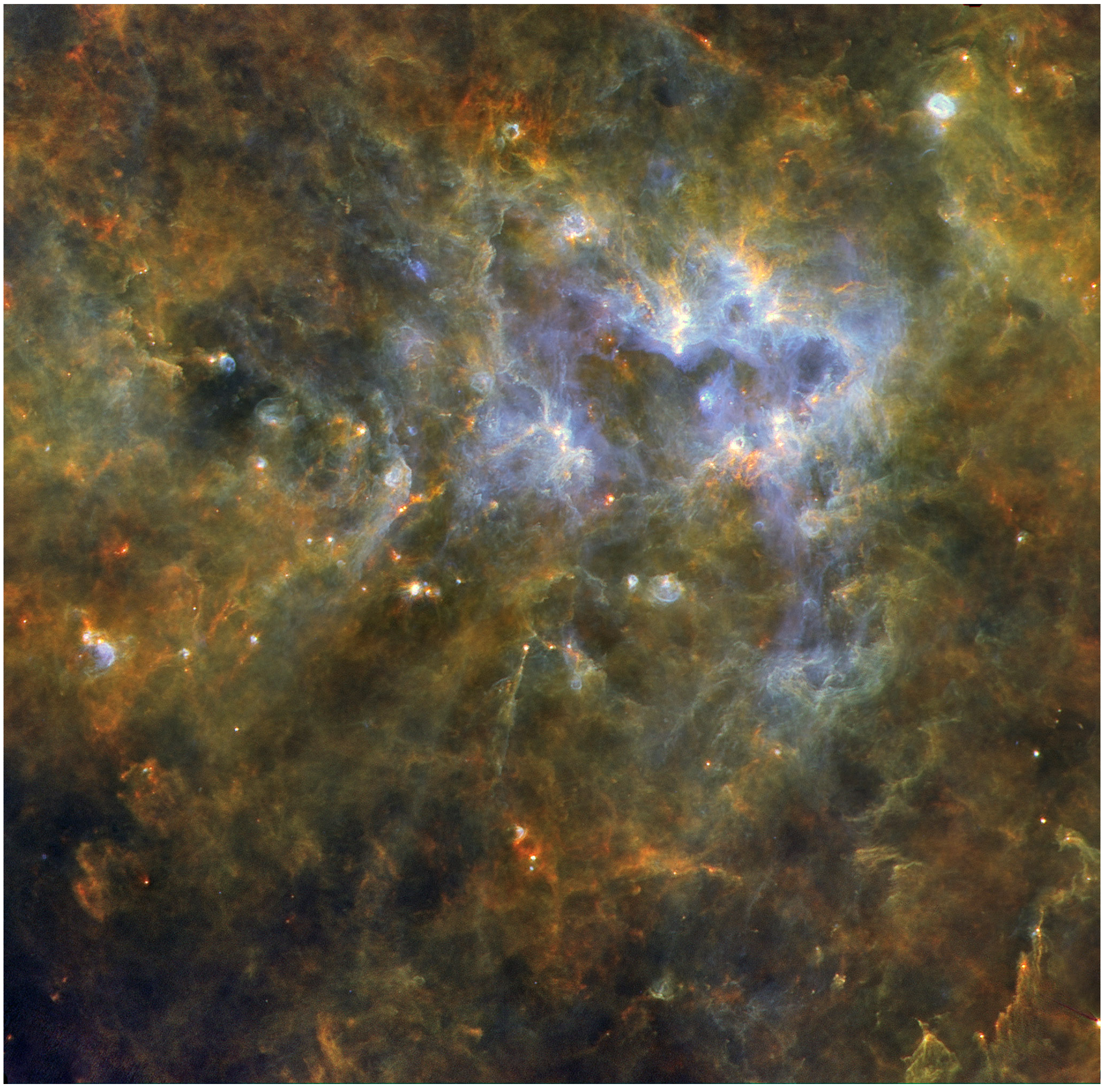


Figure 2.5: "Hidden secrets of a massive star-formation region" by the Herschel telescope and ESA. A giant molecular cloud producing stars when local overdensities in the gas collapses.
Image credit: ESA/Herschel/PACS, SPIRE/Hi-GAL Project. Acknowledgement: UNIMAP / L. Piazzo, La Sapienza – Università di Roma; E. Schisano / G. Li Causi, IAPS/INAF, Italy

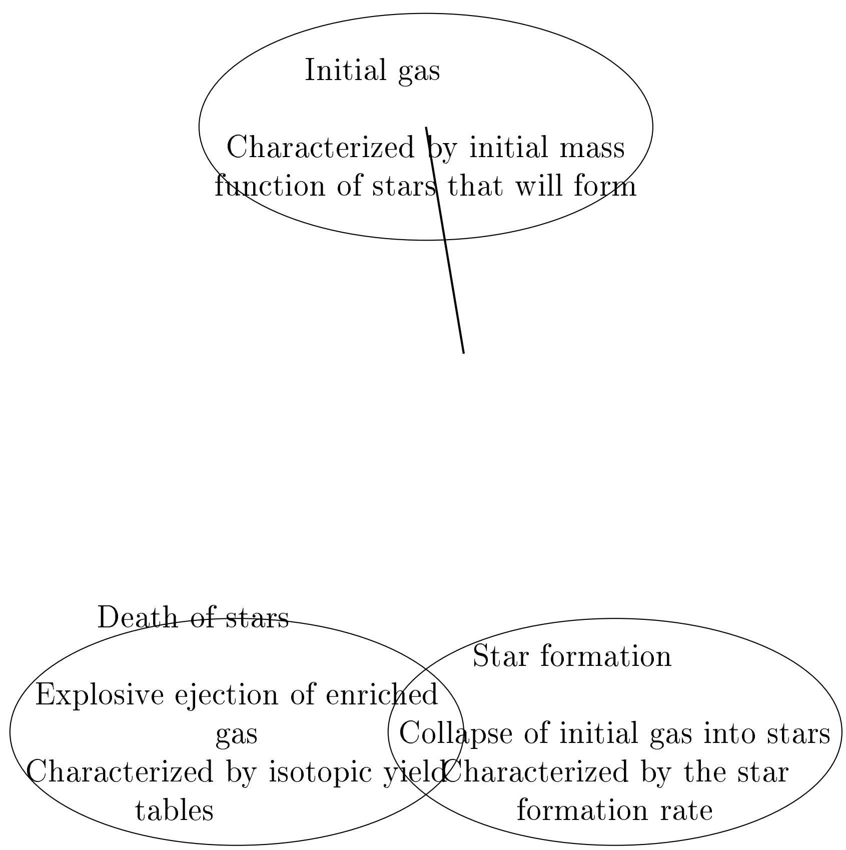

Initial gas
Characterized by initial mass function of stars that will form
Death of stars
Explosive ejection of enriched gas
Characterized by isotopic yield tables
Star formation
Collapse of initial gas into stars
Characterized by the star formation rate

Figure 2.6

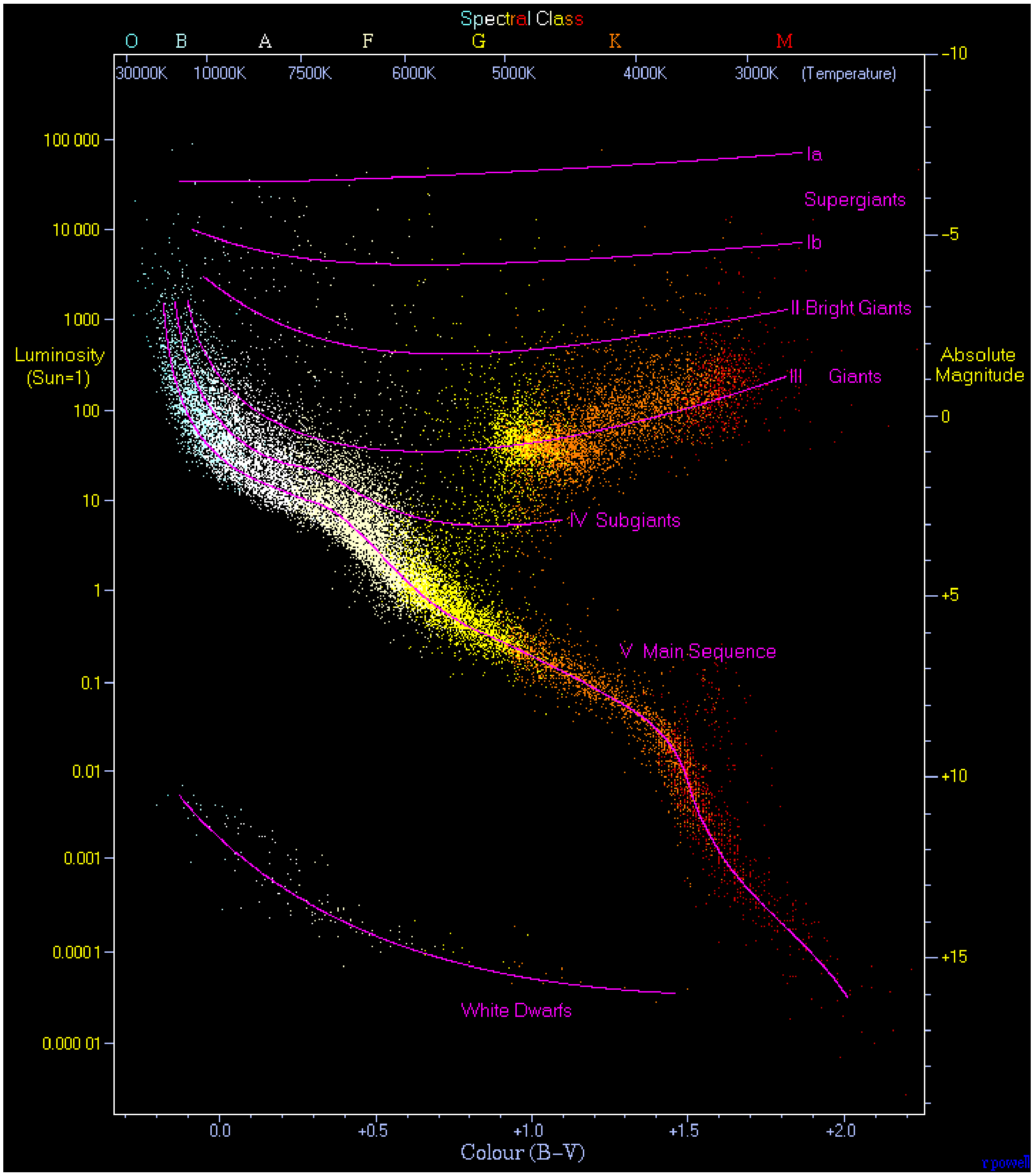


Figure 2.7: "The most famous diagram in astronomy is the Hertzsprung-Russell diagram. This diagram is a plot of luminosity (absolute magnitude) against the colour of the stars ranging from the high-temperature blue-white stars on the left side of the diagram to the low temperature red stars on the right side.
This diagram below is a plot of 22000 stars from the Hipparcos Catalogue together with 1000 low-luminosity stars (red and white dwarfs) from the Gliese Catalogue of Nearby Stars. The ordinary hydrogen-burning dwarf stars like the Sun are found in a band running from top-left to bottom-right called the Main Sequence. Giant stars form their own clump on the upper-right side of the diagram. Above them lie the much rarer bright giants and supergiants. At the lower-left is the band of white dwarfs - these are the dead cores of old stars which have no internal energy source and over billions of years slowly cool down towards the bottom-right of the diagram." Image/description credit: Richard Powell [CC BY-SA 2.5]

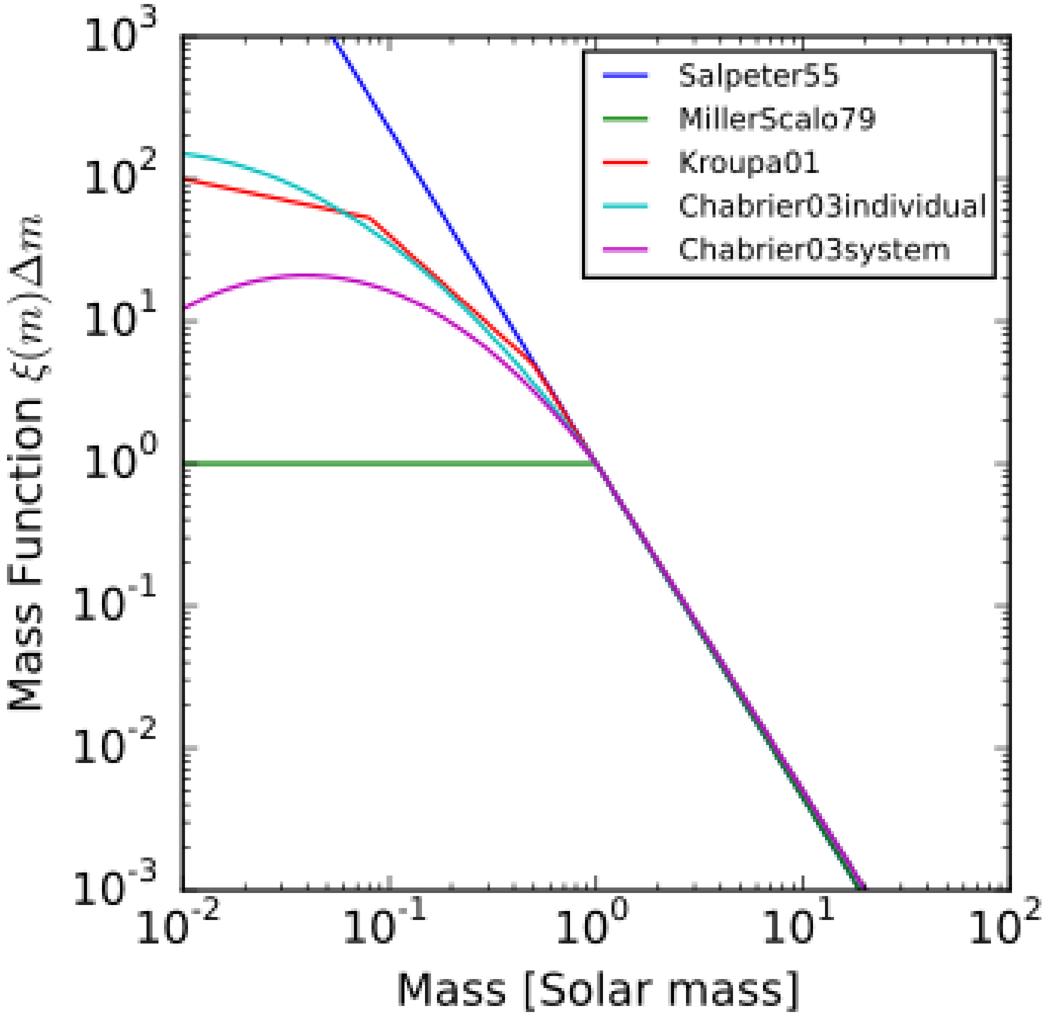


Figure 2.8: A simplified visualization of some of the common initial mass functions in the literature. ?, *and references therein*, ?, ?, ?, ?.
image-credit: By JohannesBuchner [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)], from Wikimedia Commons

free electrons bonds with hydrogen. The H^- ions increase the opacity drastically trapping the heat from gravitational potential energy more efficiently. When this happens the collapse will be adiabatic instead of isothermal, and temperatures will increase. When the gas becomes dominantly adiabatic, but still has no stable fusion process in the core the cloud of gas is called a protostar. Small fusion processes and increased opcity increases the effective surface temperature and luminosity of the gas cloud.

Any inhomogeneities in density, and pressure gradient can cause fracturing of the collapsing gas, as can the presence rotation, turbulence, and magnetic fields. Meaning the subregion is divided into smaller regions where the density might not be big enough or several protostars can be created. This might also lead to binary systems or systems with several stars. The entire giant molecular cloud can also be considered a collapsing gas, but fracturing causes several stars to be born as separate entities inside.

When the density and temperature in the core becomes sufficiently high, the protostar will synthesize hydrogen into helium through the pp-chain, or if the star is massive enough the CNO-cycle. This period of the stars life is the longest and is called the main sequence. In the Hertzsprung Russel diagram this extended curve is well documented, and higher mass stars will find themselves higher in the diagram (more mass means more pressure which means more efficient fusion processes). Throughout the stars life in the main sequence the luminosity and effective temperature will increase steadily as the overall mean molecular weight cahnges in the entire star. The location in the Hertzsprung Russel diagram (i.e. the luminosity and effective surface temperature of the star) when the star first starts to burn steadily (when the star is born so to speak) is called the zero-age main sequence.

The time it takes for a cloud of gas to collapse and reach the zero-age main sequence is inversely proportional to it's mass, while the duration a star spends on the main sequence is roughly proportional to the inverse cube of the mass (from AST1100) . In short massive stars are quickly born and die more quickly, while smaller stars take alot more time. This makes the smaller stars more susceptible to effects from nearby massive stars that ionize or explode while the smaller stars are still forming. Dispite this, observations show that the mass distribution function of stars massively favor low mass stars.

(include plot of initial mass distributions here?)

During the main sequence, where hydrogen is burned into helium in the core, higher mass stars will have a much higher central temperature and density. This means that the hydrogen burning core will be dominated by the CNO-cycle, and the star will have a convective layer that develops in the envelope and stretches deep into the star. Stars with lower mass on the other hand will have cores dominated by the pp-chain because their central temperature is lower. The energy transport will also be mostly radiative from the core out to the envelope. Really low mass stars on the other hand will develop convective layer from the center outwards. As the stars age, more hydrogen will burn into helium and the mean molecular weight will increase, steadily increasing the temperature, radius and luminosity of the stars on the main-sequence.

When the core of a low-mass star is depleted of hydrogen and filled with helium the pp-chain will stop in the core, but it will continue in a shell around the core due to high temperatures. The hydrogen burning shell around the core will provide more energy and cause the envelope to expand, this causes the luminosity to increase, but surface temperature to decrease. higher mass stars will contract, and the convective layer disappears steadily as the core runs out of hydrogen fuel. The contraction heats the core and hydrogen shell burning will power the star.

As more helium is accreted onto the inert, isothermal helium core, which will collapse when it reaches the chandrasekhar limit. The collapse of the core causes heating, which infaltes the envelope. Inflating the envelope causes the surface temperature to decrease, this is called the sub giant branch. The inflated envelope stabilizes and becomes convective from the large temperature gradient. The ffective energy transport causes the luminosity to increase into the red giant tip. This leads to the first dredge-up where material from outside the core can be mixed into the upper envelope. The collapsed core can now start fusing helium into carbon and oxygen through the triple alpha process. The core will then expand, cooling the hydrogen shell and decrease the overall luminosity of the star. Stars with lower masses will develop a electron degenerate core which will cause the core helium flash once the helium is "ignited" nearly simountaneously.

The envelope will contract following the expansion of the helium burning core, causing the effective surface temperature to rise. When stable radius, helium burning core and hydrogen burning shell is reached the star will have settled onto the horizontal branch. This is the main sequence equivalent of helium burning stars. As the helium is exhausted in the core, the core will start to contract, expanding the envelope, and the effective surface temperature will decrease toward the redder side of the horizontal branch.

When the heliumn has been expended in the core, leaving a inert core of carbon and oxygen with a helium burning shell around it. The helium burning shell will dominate over the hydrogen burning shell lying on top of it, the increased temperature will cause the hydrogen burning shell to expand and essentially stop energy production. When the helium burning shell exhausts all it's fuel the envelope will expand and become convective, the ensuing mix of material from bottom envelope (helium burning shell) to top envelope is called the second dredge-up. The convective energy transport is more effective, making the luminosity of the star increase. In the hertzsprung-russel diagram, this moves the star up into the asymptotic giant branch. At this point, the hydrogen burning shell will dominate the energy production of the star once again. The "ash" from the hydrogen burning shell (the top shell) will "rain" down onto the inert helium burning shell (bottom shell). When the temperature is high enough and the bottom shell has enough material, the bottom shell of helium will ignite. Do to the isothermal layer of the helium shell, triple alpha burning will commence in the entire shell simountaneously, in an explosive fashion. This explosion, called the helium shell flash, is less explosive the the helium core flash, but might eject more material because it is closer to the surface. When the helium has been exhausted once again, the shell compresses and the entire process repeats. The repetition of helium flashes is called the third dredge-up, mixing material from the hydrogen and helium shells into the upper envelope.

During the asymptotic giant branch stars loose alot of their material by ejection into the interstellar medium. This ejection can be from helium flashes, pulsations of the envelope, high luminosity, low surface gravity, high radiation pressure. The combination of effects is not surely determined, but simulations and observations show that the mass-loss must be great during this stage.

After the helium-flashes have subsided, the envelope has been ejected, the shell-burning have stopped, the star remains as a hot inert core of carbon and oxygen (with some hydrogen and helium surrounding it). This remnant is called a white dwarf. This white dwarf will continue to glow until it has radiated away all it's thermal energy.

Evolution of massive stars: Stars with mass $M \gtrsim 8M_{\odot}$ evolve a bit differently. They have no helium flashes. Their high mass means that the central density, pressure, and temperature will be higher. The hydrogen burning core will fill up with helium, and when sufficient mass has been reached the helium will start to fuse into carbon and oxygen through the triple alpha process and hydrogen will burn in a shell around it. The carbon in the core will then continue to fuse with more helium into oxygen and neon, with some sodium and magnesium produced. The oxygen in the core will eventually start to fuse into silicon, and the silicon will eventually start to fuse into sulfur, argon and iron. In this high temperature and high density environment, this process will not be straight forward, many different carbon isotopes will fuse with other particles into many different heavier isotopes. The details above outlines the general trend. Assuming that there is an equilibrium of nuclear reactions the stars interior will resemble an onion like shell structure with the heaviest elements deepest in the star.

Fusion processes cannot produce excess energy for elements heavier then iron. Although trace amounts of heavier elements can be created from the excess thermal energy. In the centre of the core, the free electrons can merge with the free protons to create neutrons and release neutrinos add nuclear reactions The sudden loss of electrons causes the electron degeneracy to drop suddenly and the centre of the core will collapse supersonically until the density is roughly 3 times the nucleon density. At this point the centre of the core, consisting of mostly neutrons will experience a repulsive effect of the strong nuclear force. This is equivalent to a pauli exclusion principle of neutrons. The repulsive force causes the core to stiffen and rebound. The shock from the rebounding core meets the falling core on top, causing a shockwave that travels outward from the inner core.

Simulations suggest that the shockwave released will be absorbed by the surrounding layers. The stalled shockwave leaves a shell of high density. This shell is dense enough to absorb a significant amount of the neutrinoes released during collapse. If a small amount of the neutrino energy is transferred to the stalled shockwave it will restart and eject the surrounding layers into the interstellar medium. The travelling shockwave can be observed as a type Ib, Ic, or II supernova, also called a core collapse supernova. The remnant of such an event will be a neutron star or (if the mass is great enough to overcome the repulsive force of the strong nuclear force) a black hole.

2.3.1 Type 1a supernova

"When a white dwarf (WD) composed of carbon and oxygen accreting mass from a companion star in a binary system approaches the Chandrasekhar mass [$M_{Ch} \simeq$ 1.38 solar masses ($M_{\odot}$)], high temperature causes the ignition of explosive nuclear burning reactions that process stellar material and produce energy. The star explodes leaving no remnant, producing a Type Ia supernova (SNIa) (K. Nomoto, F.-K. Thielemann, K. Yokoi, ApJ 286, 644 (1984))."**?**

In the thermonuclear explosion iron peak elements(mostly Ni and Fe isotopes and below) are synthesized and ejected into the interstellar medium. During accretion, helium and hydrogen burmning layers develop and helium flashes occur. These flashes can cause major mixing of hydrogen into the carbon-layers which again can cause neutron producing reactions in greater numbers. Neutron capture processes can occur on the surface of type 1a supernovae if the produced neutron densities are high enough?. The isotope distributions also seemed to fill in some missing yields from type II supernovae.

Typical type 1a supernovae are heated from the deacy of ${}^{\mathrm{Ni}}_{28}56$ and will eject $\simeq 1.4M_{\odot}$ of material at a ejecta velocity of $\simeq 10Mms^{-1} \simeq 0.03c$ (cite tanaka 16)

2.3.2 Neutron star mergers

The idea of mergers of compact objects(either neutron stars or black holes) by emission of gravitational waves have been around for a long time. The general concept is build on two compact objects orbiting eachother, interacting with the spatial curvature and creating ripples. These ripples maifest as waves in the fabric of space-time and carry gravitational energy away from two compact objects. The two objects move closer as a result of the lost energy, and increases the orbital velocity accordingly. These gravitational waves distort space itself and can be detected by large laser interferometers that detect spatial disturbances smaller then the width of a nucleus (add reference to ligo paper) .

Emission from a binary neutron star merger, or a kilonova, is heated from the decay of r-process elements add reference to nuclear physics section . The ejecta mass and velocity are debated, but estimates are around $v = 30 - 60Mms^{-1} = 0.1 - 0.2c \quad m \simeq 0.01M_{\odot}$ add reference to Tanaka 2016 review article .

During a merger between two neutron star mergers, the two stars move closer to eachother over time from gravitational radiation. When they are close enough to eachother they will disrupt eachothers surface, and surround the merging bodies in a cloud of neutron heavy material that is ejected into the interstellar medium. The force that pulls apart the neutron stars surface is only eachothers gravitational pull and centripetal force. As the main bodies merge, a shock drives ejecting of material that will bombard the surrounding cloud. As the cloud ejects from the colliding stars, the density of neutronmatter will drop until extremely neutron heavy nuclei will form, like droplets from steam. These nuclei are unstable and will β^{-}-decay to more stable isobars. These heavy nuclei will act as seeds for the neutronrich shockwave emitting from the collision. The stream of very dense, high-velocity neutrons onto seed of heavy nuclei is the perfect recipe for r-process nucleosynthesis. this is also from tanaka-article, do I cite again or move the citation

2.4 The $^{187}_{75}$Re - $^{187}_{76}$Os chronometer

This section summarized from ?

In the lanthanides there is a chain of heavy elements with atomic number 74 through 77. These are wolfram, rhenium, osmium, and iridium and a subsection of the chart of nuclides is refereence to figure .

include chart of nuclide section

From the chart on can see the usual path for slow neutron capture along the valley of stability. This is the main contribution to $^{187}_{76}$Os . In a standard s-process analysis, $^{185}_{74}$W and $^{186}_{75}$Re are unstable, and will decay before they can capture neutrons. The s-process path will never synthesize $^{187}_{75}$Re . However if the neutron capture rate is comparable to the β^{-}-decay rates of those nuclides a branching point can occur. A branching point is a point where the synthesizing path of the s-process split due to competing nuclear reactions. In this case a significant fraction of the s-process path can go through $^{186}_{75}$Re to $^{187}_{75}$Re or through $^{185}_{74}$W to $^{186}_{74}$W (which is stable) and onwards to $^{187}_{75}$Re . Apart from these effects $^{187}_{75}$Re is shielded from s-process contribution.

The rapid neutron capture maintains very high neutron numbers until the neutron source "shuts off", at that point the isotopes β^{-}-decay to the valley of stability. Given the long $\tau_{1/2}$ of $^{187}_{75}$Re it can be considered stable, so the $^{187}_{76}$Os isotope is shielded from r-process contribution because almost all β^{-}-decay on the 187-isobar will stop at $^{187}_{75}$Re .

Since $^{187}_{75}$Re is radioactive with a halflife of add here some $^{187}_{75}$Re in the interstellar or stellar medium will decay to $^{187}_{76}$Os . This amount is called the cosmoradiogenic $^{187}_{76}$Os . The fraction between cosmoradiogenic $^{187}_{76}$Os and current $^{187}_{75}$Re is given by the exponential decay-function (assuming ofcourse that the nuclear decay rate is constant for all time, including stellar environments), meaning the time of nucleosynthesis can be calculated from the observed fraction of daughter-parent nuclei.

Clayton attempts to calculate the fraction of cosmoradiogenic osmium and the age of nucleosynthesis from these principles?. A brief summary follows:

The abundance of $^{186}_{76}$Os is due to s-process only, and the abundance of $^{187}_{76}$Os is due to s-process (from $^{186}_{76}$Os) and cosmo radiogenic enrichment from $^{187}_{75}$Re beta-decay. The s-process contribution from $^{186}_{76}$Os is given by the $^{186}_{76}$Os abundance and the ratio between the cross-section of the isotopes. It is shown from nebular Samarium that the two s-only isotopes have nearly identical cross-section times abundance. Extrapolating this to other s-process isotopes, the result is: (denoting abundance of isotope by their chemical name instead of N for simplicity)

$$\bar{\sigma}_{^{186}_{76}\mathrm{Os}}\,^{186}_{76}\mathrm{Os} = \bar{\sigma}_{^{187}_{76}\mathrm{Os}}\,^{186}_{76}\mathrm{Os}_S \quad \rightarrow \quad ^{186}_{76}\mathrm{Os}_S = \frac{\bar{\sigma}_{^{186}_{76}\mathrm{Os}}}{\bar{\sigma}_{^{187}_{76}\mathrm{Os}}}\,^{186}_{76}\mathrm{Os} \tag{2.2}$$

$\bar{\sigma}$ are the neutron-capture cross-sections averaged over the appropriate thermal velocity distributions. The cosmoradiogenic component of $^{187}_{76}\mathrm{Os}$ is therefor the remaining part.

$$^{187}_{76}\mathrm{Os}_c = {}^{187}_{76}\mathrm{Os} - {}^{187}_{76}\mathrm{Os}_s = {}^{187}_{76}\mathrm{Os} - \frac{\bar{\sigma}_{^{186}_{76}\mathrm{Os}}}{\bar{\sigma}_{^{187}_{76}\mathrm{Os}}}\,^{186}_{76}\mathrm{Os} \tag{2.3}$$

Rewriting equation to relative units.

$$\frac{^{187}_{76}\mathrm{Os}_c}{^{187}_{75}\mathrm{Re}} = \frac{^{187}_{76}\mathrm{Os} - \frac{\bar{\sigma}_{^{186}_{76}\mathrm{Os}}}{\bar{\sigma}_{^{187}_{76}\mathrm{Os}}}\,^{186}_{76}\mathrm{Os}}{^{187}_{75}\mathrm{Re}} = \frac{\left(\frac{^{187}_{76}\mathrm{Os}}{Os}\right) - \frac{\bar{\sigma}_{^{186}_{76}\mathrm{Os}}}{\bar{\sigma}_{^{187}_{76}\mathrm{Os}}}\left(\frac{^{186}_{76}\mathrm{Os}}{Os}\right)}{\left(\frac{^{187}_{75}\mathrm{Re}}{Re}\right)}\left(\frac{Os}{Re}\right) \tag{2.4}$$

Origin of time, t=0, is set to Solar systemformation. Assuming that r-process events are supernovae and they began occuring at time T before Solar systemformation(t=0), and the frequency of events decreases exponentially as $f_0 e^{\Lambda t}$, where f_0 is the initial supernovae freqency. According to this model, and Clayton, the amount of cosmoradiogenic $^{187}_{76}\mathrm{Os}$ is given by

$$\frac{^{187}_{76}\mathrm{Os}_c}{^{187}_{75}\mathrm{Re}} = \left[\frac{\Lambda - \lambda}{\Lambda} e^{\lambda T} \frac{1 - e^{-\Lambda T}}{1 - e^{-(\Lambda - \lambda)T}}\right] - 1 \tag{2.5}$$

And the two special cases.
Sudden synthesis ($\Lambda \rightarrow \infty$)

$$\frac{^{187}_{76}\mathrm{Os}_c}{^{187}_{75}\mathrm{Re}} = e^{\lambda t} - 1 \tag{2.6}$$

Uniform synthesis ($\Lambda \rightarrow 0$)

$$\frac{^{187}_{76}\mathrm{Os}_c}{^{187}_{75}\mathrm{Re}} = \frac{\lambda T}{1 - e^{-\lambda t}} - 1 \tag{2.7}$$

end of direct summary

In short, by modelling r-process nucleosynthesis and s-process nucleosynthesis, the fraction of $^{187}_{75}\mathrm{Re}$ - $^{187}_{76}\mathrm{Os}$ in the Solar systemcan predict the time of nucleosynthesis from non-cosmological methods.

What do I mean about the age of nucleosynthesis?

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