Cosmochronology and Radioactivity in Nuclear Astrophysics

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Outline

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Introduction

Cosmochronology is a set of different techniques to determine the age of stars, galaxies and the universe itself. Two reliable methods to determine the age of the universe are going to be studied:

- Measurements of radioactive Thorium and Uranium in stars similar to our Sun.
- The age of the older white dwarfs

Cosmochronometers

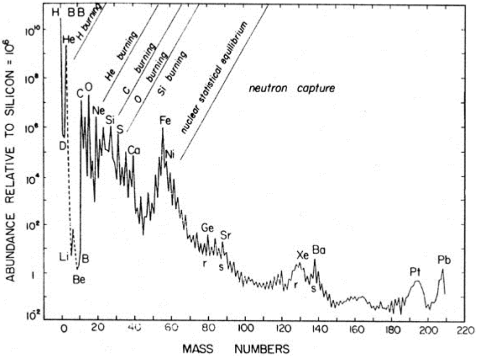
Elemental isotopic abundances deduced from meteorites, the Earth, the Moon, cosmic rays, the Sun and other stellar surfaces.

Long-lived radionuclides: ^{232}Th/^{238}U, ^{235}U/^{238}U and ^{187}Re/^{187}Os. They were produced through the same r-process (rapid neutron capture) and set a lower limit on the age of the universe.

Short-lived radionuclides: ^{129}I/^{127}I, ^{26}Al/^{27}Al and ^{107}Pd/^{110}Pd. They paint a picture on the last nucleosynthetic events that includes a supernovae association with the embryonic solar system.

Abundances

Abundances indicate the quantity of one element compared to others. They are usually written as mass-fraction abundances.



Isotope	Isotopic Abundance
^{232}Th	100 %
^{238}U	99.2742 %
^{235}U	0.7204 %

Pagel, Bernard E. J. Nucleosynthesis and Chemical Evolution of Galaxies. Cambridge University Press, 2009.

Nucleocosmochronology

It uses abundances of radioactive species to establish the age of the elements and its formation time. Some restrictions on the galaxy's duration of the nucleosynthesis process and its age must be taken into account from:

1. The known abundance ratio in the early solar system. This is obtained from the analysis of the meteorites that were condensed when the solar system was form.
2. The known production ratio of a long-lived radioactive species to a stable element or other long-lived isotope. It depends on the physical conditions and nuclear physics involved in the r-processes.
3. The evolution of the chemical abundances with time over Galactic history.

Model-independent age determination

Based on Meyer and Schramm's work, the linear equations that describe the abundance of a radioactive nucleus "i" in the ISM are

$$\frac{dN_i(t)}{dt} = -\lambda_i N_i(t) - \omega(t) N_i(t) + P_i \Psi(t) \tag{1}$$

λ_i is the decaying rate of the i-nucleus.
ω is the rate at which metals leave the ISM for reasons other than radioactive decay.
$\Psi(t)$ is the star formation rate or the rate at which mass becomes into stars at time t.
P_i is the number of i-nuclei produced per unit mass going into stars.

Meyer, B. S. and Schramm, D.N. Astrophys. J. 311, 406, 1986.

The abundance of a radioactive nucleus i after the solidification process at (T + Δ) is:

$$N_i(T+\Delta) = P_i e^{-\lambda_i \Delta - \lambda_i T - \nu(T)} \int_0^T \Psi(t) e^{\lambda_i t + \nu(t)} dt \quad (2)$$

Where

$$\nu(t) = \int_0^t \omega(\xi) d\xi \quad (3)$$

Eq. (2) depends on the effective nucleosynthesis rate Ψe^{ν}.

Meyer, B. S. and Schramm, D.N. Astrophys. J. 311, 406, 1986.

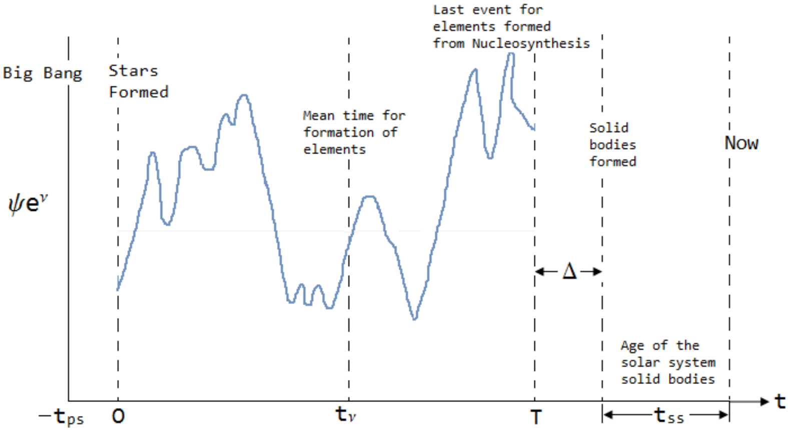


Figura : Rate of nucleosynthesis as a function of time.

In order to avoid the Ψe^{ν} dependence, Schramm and Wasserburg defined a normalized effective nucleosynthesis rate

$$\phi(t) = \frac{\Psi e^{\nu}}{\langle\Psi\rangle\, T} = \frac{\Psi e^{\nu}}{\int_0^T \Psi e^{\nu} dt} \tag{4}$$

from which one obtains an expression for the abundance

$$N_i(T + \Delta) = P_i T \langle\Psi\rangle\, e^{-\lambda_i \Delta} e^{-\nu(T)}(1 + \delta_i) \tag{5}$$

where

$$\delta_i \equiv \sum_{n=2}^{\infty} \frac{\lambda_i^n}{n!}\mu_n \text{ and } \mu_n \equiv \int_0^T (t - t_\nu)^n \phi(t) dt$$

μ_n is the nth moment of $\phi(t)$ around t_ν.

Meyer, B. S. and Schramm, D.N. Astrophys. J. 311, 406, 1986.

Tinsley, B. M. Astrophys. J. 198 145-50 (1975).

If we get the same Eq.(5) for other nucleus "j" and divide $\frac{N_i(T+\Delta)}{N_j(T+\Delta)}$ we get at the end

$$T - t_\nu = \frac{\ln\left(\frac{P_i/P_j}{N_i(T+\Delta)/N_j(T+\Delta)}\right)}{\lambda_i - \lambda_j} - \Delta + \frac{1}{\lambda_i - \lambda_j}\ln\left(\frac{1+\delta_i}{1+\delta_j}\right) \quad (6)$$

For long-lived cosmochronometers ($\lambda T << 1$), it can be rewritten as

$$T - t_\nu \sim \Delta_{i,j}^{max} - \Delta \quad (7)$$

Any cosmochronometer with a half-life relatively large sees the nucleosynthesis process as a single event in an average time t_ν.

Meyer, B. S. and Schramm, D.N. Astrophys. J. 311, 406, 1986.

Ψe^{ν} is relatively constant through the history of our galaxy. The estimate of the lower limit on the Galaxy's age for the pair $^{232}\mathbf{Th}/^{238}\mathbf{U}$ is

$$\left(\frac{N^{232}}{N^{238}}\right)_{ss} = \left(\frac{P^{232}}{P^{238}}\right)_{r-process} e^{-(\lambda_{232}-\lambda_{238})T} \tag{8}$$

where

$$\left(\frac{N^{232}}{N^{238}}\right)_{ss} = 2{,}32 \;\; \text{and} \;\; 1{,}40 \leq \left(\frac{P^{232}}{P^{238}}\right)_{r-process} \leq 1{,}90$$

Then, $T = 3{,}3 \pm 1{,}20$ Gyr which constrains the age of the galaxy to be

$$t_{Gal} = (T + t_{ss}) \geq 7{,}9 \pm 1{,}2 Gyr \tag{9}$$

Truran, J. W. Space Telescope Science Institute Symposium Series 10, 1997.

Anders, E. and Ebihara, M.*Geochem. Cosmochem. Acta* **46** 2363-2380 (1982).

Anders, E. and Grevesse, N. *Geochem. Cosmochem. Acta* **53** 197-214 (1989).

Assuming no gain or loss of matter $\omega(t) = 0$ one can simplify

$$N_i(t) = \frac{P_i}{\lambda_i}(1 - e^{-\lambda_i t})$$

which take us to

$$\left(\frac{N^{232}}{N^{238}}\right)_{ss} = \left(\frac{P^{232}}{P^{238}}\right)_{r-process} \frac{\lambda_{238}(1 - e^{-\lambda_{232} T})}{\lambda_{232}(1 - e^{-\lambda_{238} T})} \tag{10}$$

$$T = 8{,}2 \pm 3 \text{ Gyr}$$

$$t_{Gal} = 12{,}8 \pm 3{,}1 Gyr \tag{11}$$

is model-dependent.

Meyer, B. S. and Truran, J. W. *Physics Reports* **333-334** 1-11 (2000).

For the pair $^{235}\mathbf{U}/^{238}\mathbf{U}$

$$\left(\frac{N^{235}}{N^{238}}\right)_{ss} = \left(\frac{P^{235}}{P^{238}}\right)_{r-process} e^{-(\lambda_{235}-\lambda_{238})T} \tag{12}$$

where

$$\left(\frac{N^{235}}{N^{238}}\right)_{ss} = 0{,}317 \text{ and } 0{,}89 \leq \left(\frac{P^{235}}{P^{238}}\right)_{r-process} \leq 1{,}89$$

Then, $T = 1{,}75 \pm 0{,}25$ Gyr which constrains the age of the galaxy to be

$$t_{Gal} \geq 6{,}3 \pm 0{,}25 Gyr \tag{13}$$

Truran, J. W. Space Telescope Science Institute Symposium Series 10, 1997.

Anders, E. and Ebihara, M. *Geochem. Cosmochem. Acta* **46** 2363-2380 (1982).

Anders, E. and Grevesse, N. *Geochem. Cosmochem. Acta* **53** 197-214 (1989).

White Dwarfs are the end products of stellar evolution of the 97 % of the stars.

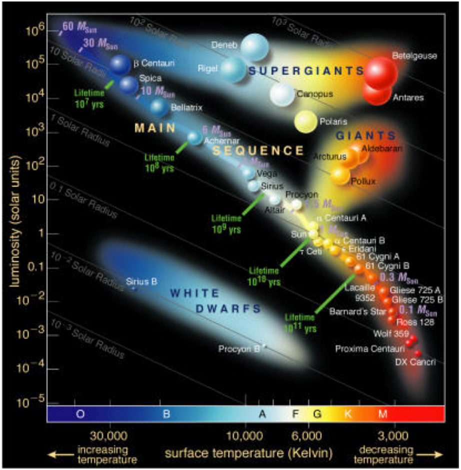
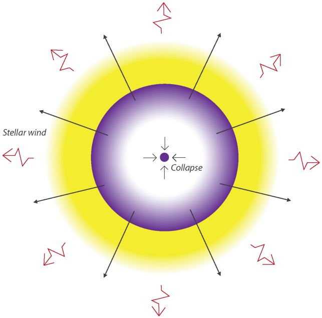


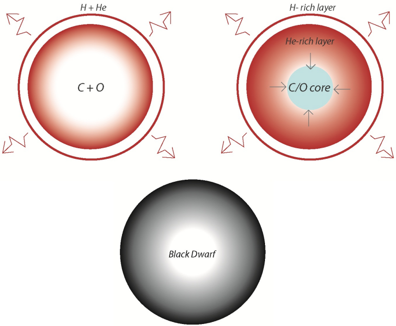
Figura : Hertzsprung-Russell diagram.

WD Formation

There are no nuclear reactions inside stars, hence the core contracts and heats up.
Due to the pressure of a degenerate electron gas the contraction stops and the electrostatic equilibrium in a White Dwarf is reached.



Cooling Sequence



- Outer layers of H and He ($m \leq 10^{-14}$M) regulate the energy that comes from the white dwarf.
- An internal convection couples the core and the surface in order to increase the radiated energy.
- As the thermal reservoir is depleted, the star becomes a cold and crystallized object called black dwarf.

Calculation of the cooling rates of white dwarfs depends on:

1. The amount of thermal energy stored inside.
2. Velocity of the energy transferred from the nucleus to the interstellar medium.

For a homogeneous star the luminosity function is

$$L(t) = \int_0^M \left(\varepsilon - T \left. \frac{\partial S}{\partial \rho} \right|_T \frac{\partial \rho}{\partial t} - C_v \frac{\partial T}{\partial t} \right) dm \qquad (14)$$

For a WD: $\frac{\partial \rho}{\partial t} \to 0$, $T = T_C$ and the residual energy sources are $\varepsilon \to 0$.

G. Fontaine, P. Brassard, P. Bergeron. The Potential of White Dwarf Cosmochronology. Publications of the Astronomical Society of the Pacific 113 (782). p. 409-435, 2001.

The estimated cooling time is

$$t_{cool} \sim -\int_0^M C_v dm \times \int_{L_1}^{L_2} \frac{\partial T_C}{\partial L} \frac{dL}{L} \tag{15}$$

Mestel (1952)

$$t_{cool}^{Mestel} \sim \frac{7{,}6 \times 10^7}{A} \left(\frac{K_0}{4^{23}} \frac{\mu_e^2}{\mu} \right)^{2/7} \left(\frac{M}{M_\odot} \right)^{5/7} \left(\frac{L}{L_\odot} \right)^{-5/7} \tag{16}$$

μ is the average molecular weight of the material in the outer layer.

Mestel, L. MNRAS **112** 583 (1952).

However, the model of Mestel just works for relatively high effective temperatures.
A complete model would include:

- The crystallization process.
- The diffusion of the various atomic species.
- The convective mixing
- Nuclear processes

$$L(t) = -L_\nu - \int_0^M \left[\frac{du}{dt} + P\frac{d(\rho^{-1})}{dt} \right] dm \qquad (17)$$

Lamb, D.Q. and Van Horn, H.M. *Astrophys. J.* **200** 306-323 (1975).

G. Fontaine, P. Brassard, P. Bergeron. Publications of the Astronomical Society of the Pacific 113 (782) 2001.

Winget et al. (1987) computed the ages shown in Table 21

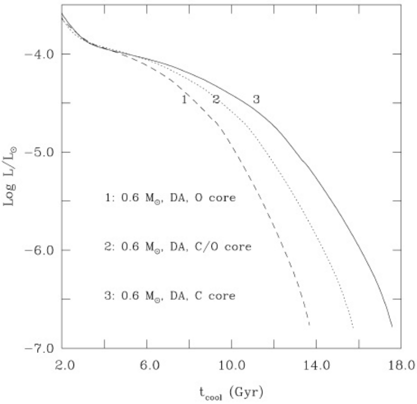
	t(Gyr)					
$log(L/L_\odot)$	0.4 $M_\odot$ C	0.6 $M_\odot$ C	0.8 $M_\odot$ C	1.0 $M_\odot$ C	0.6 H/He	0.6 H/He/C
-1.00	0.034	0.026	0.025	0.042	0.018	0.018
-1.50	0.070	0.074	0.085	0.120	0.062	0.062
-2.00	0.155	0.176	0.207	0.274	0.197	0.197
-2.50	0.325	0.382	0.456	0.590	0.484	0.484
-3.00	0.680	0.885	1.084	1.428	1.090	1.090
-3.50	1.568	2.060	2.846	3.234	2.234	2.211
-4.00	3.186	4.836	5.430	5.045	5.440	5.718
-4.50	7.161	8.693	8.371	6.919	10.571	10.453
-5.00	12.574	12.829	11.054	8.268	14.668	14.165

The cooling age for the WD population is $t_{cool} = 9{,}0 \pm 1{,}8$ Gyr. Thus, the age of the galaxy disk is

$$t_{disk} = t_{cool} + t_{ms} = 9{,}3 \pm 2{,}0 \; Gyr \tag{18}$$

with $t_{ms} \sim 10M^{-2{,}5}$ Gyr.

Winget, D. E. et al. *Astrophys. J.* **315** L77 (1987).



Fontaine et al. found the age for the *WD 0346+246* to be $\sim 12{,}7$ Gyr and for the halo to be $t_{halo} \sim 13$ Gyr.
At the end the age of the universe can be calculated from

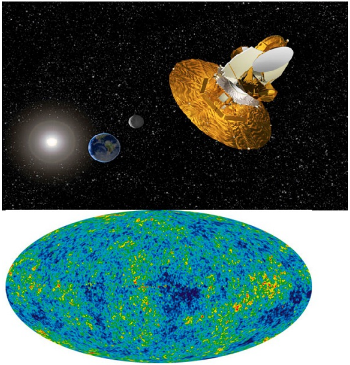
$$t_{universe} = t_{ps} + t_{disk} \tag{19}$$

where $t_{ps} \sim 1$ Gyr is the prestellar interval.

G. Fontaine, P. Brassard, P. Bergeron. Publications of the Astronomical Society of the Pacific 113 (782) 2001.

The Hubble Age

Measure the rate of expansion of the universe and extrapolate back to the Big Bang.
In 2010, NASA with the WMAP data found $t_{universe} = 13{,}75 \pm 0{,}11$ Gyr.



WMAP. Taken from http://map.gsfc.nasa.gov/

Summary of results from literature

- For the cosmochronometers ^{232}Th, ^{235}U and ^{238}U one gets values around $12{,}8 \pm 3{,}1$ Gyr for the age of the galaxy.
- The age of a WD can be determined by calculating its cooling time. The age of one of the coolest WD known is $\sim 12{,}7$ Gyr and recent calculations give $t_{halo} = 12{,}07$ Gyr.
- These results represent lower limits for the age of the universe.
- From both techniques one obtains ages which are consistent with the results found by NASA.
- Many work still remains in this field.

Thanks!