Stellar species and evolution

3.3 Origin of Elements and Yield

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3.3 Origin of Elements and Yield

- Stars shine because they generate energy from inside.
- The heat source is the nuclear fusion reaction.
- main sequence → evolution progresses → Asymptotic giant branch stage

supernova explosion

Hydrogen to Helium（Center temperature↑）Elements heavier than helium

Elements heavier than iron

↓

After a star dies, it is scattered into space!

In this chapter, we learn about the end of stars and the origin of elements.

3.3.1 Star death and supernovae

- The end of a star can be broadly divided into two types depending on its mass M.
- When mass M is less than 8 solar masses

The star cools down through the asymptotic giant branch stage, becoming a carbon-oxygen white dwarf.
Since white dwarfs typically have a mass of 0.6 solar masses (with a range of 0.4 to 1.4 solar masses), most of the remaining mass (e.g., 7.4 solar masses) is ejected into interstellar space.

In the asymptotic giant branch (AGB) stage,
1. Carbon C oxygen O central nucleus has degenerate electrons
2. Outside of that, a helium combustion shell, a helium layer, a hydrogen combustion shell, and an outer layer where convection occurs are formed.
3. The helium burning shell becomes thermally unstable, causing a heat pulse

- What is a heat pulse? - A phenomenon in which heat changes suddenly in a short period of time.

Helium combustion → Carbon and oxygen are produced
Neutrons produced by the pulse are absorbed by iron to produce barium (Ba) and strontium (Sr).
This is called the neutron capture process, also known as the s-process.
S-process elements and carbon (C) are assembled into the outer convective zone (the outermost layer) through a process called pumping, and are observed on the surface of the star.

- Binary star systems are different

The mass of the white dwarf, made of carbon and oxygen, increases as hydrogen and helium gases that have fallen from the companion star burn on the surface of the white dwarf.
When the mass exceeds 1.4 solar masses, a Type Ia supernova explosion occurs! → Nickel is synthesized and transformed into iron

In other words, Type Ia supernovae are the main source of iron (Fe) and iron-group elements (nickel, Ni, etc.).

3.3.1 Star death and supernovae

- When mass M is greater than 8 to 10 solar masses
Stars end their lives by collapsing into supernovae due to gravitational collapse.
The carbon-oxygen core burns to produce heavier elements
- Furthermore, if the mass is greater than 10 solar masses
Combustion continues until the most stable iron (Fe) is formed at the center.
（It will look like Figure 3.11 on page 74 of the textbook.）

- When mass M is greater than 10 solar masses and less than 130 solar masses
The iron core undergoes gravitational collapse due to photolysis, resulting in a Type II supernova, leaving behind a neutron or black hole at the center.
photolysis→ The phenomenon in which a substance is decomposed by light energy

▶️In such a Type II supernova
Main elements produced during stellar evolution: Oxygen (O), Neon (Ne), Magnesium (Mg)
Created during a supernova explosion: Silicon Si, Sulfur S, Argon Ar, Calcium Ca, and Titanium Ti (alpha elements) are released in large amounts.

3.3.1 Star death and supernovae

- When mass M is between 140 and 300 solar masses

Electron-positron pairs are produced from photons during the burning process of the oxygen core.
The internal energy of the star is used to create these electron pairs.
→ The pressure to counter gravity is no longer supplied

the result

1. The star undergoes gravitational contraction
2. The temperature of the oxygen core rises
3. Oxygen combustion progresses explosively

The whole star explodes and scatters
All relatively heavy elements such as iron (Fe) and calcium (Ca) are released.

- When mass M is greater than 300 solar masses

The combustion energy of the oxygen core can no longer support the weight, so there is not enough force pushing back from the center,and it can no longer withstand gravity and collapses.
→ become a black hole

3.3.2 The origin of elements heavier than iron

- Elements produced by thermonuclear reactions in stars are up to the iron group elements (the most central core)

- Elements heavier than iron exist in nature
Strontium (Sr), barium (Ba), lead (Pb), uranium (U)

Figure 3.13 Relative composition ratio of the solar system to silicon (Si) expressed as 10 to the power of 6

Vertical axis: plus or minus from 10 to the power of 6 of silicon Si
Horizontal axis: Sum of the number of neutrons and protons (nuclear mass number)

3.3.2 The origin of elements heavier than iron

- In order to overcome the strong electrical repulsion of elements heavier than iron and create a nuclear fusion reaction, high temperatures are required to increase the speed.

But

Nuclei heavier than iron break apart through photolysis

therefore
The neutron capture process (a reaction in which an atomic nucleus captures one or more neutrons and transforms into a heavier atomic nucleus) is important. Beta decay is a phenomenon in which beta rays (electrons) are emitted from the atomic nucleus.

3.3.2 The origin of elements heavier than iron

Continuation of previous page

Neutron capture process → The mass number of the nucleus increases（Neutrons attach to the nucleus）

beta decay → Neutrons change into protons（Electrons are emitted）、becomes a stable nucleus

When the number of neutrons is 50, 82, or 126, the nucleus becomes stable, making it difficult to capture neutrons and allowing them to accumulate.
（Strontium Sr, Barium Ba, Lead Pb)

These nuclei represent the peak abundance in the solar system, which is thought to be the result of neutron capture processes and the stability of the nuclear structure.

- s process

occurs inside AGB stars
Reactions proceed by tracing stable nuclei
The neutron density is low, and neutron capture proceeds more slowly than in beta decay.

- r process

Occurs when a supernova explosion occurs due to gravitational collapse or when neutrons merge.
It progresses in a short time of just a few seconds
Heavy, unstable isotopes are produced → beta decay

→ Neutrons are converted into protons to form stable atomic nuclei

3.3.2 The origin of elements heavier than iron

- What can be read from Figure 3.13 (the vertical axis indicates the abundance ratio in the sun)

The sun contains elements created in both the s-process and the r-process. This is because it is thought that the sun was created through repeated births and deaths of stars, and that chemical evolution progressed. In other words, by simply examining the composition of the sun, we can roughly understand the events in the solar system.

The mass number of the nucleus produced in the r process is slightly smaller than that in the s process, and the atomic number is also slightly smaller.

- Composition peaks produced by the s process

Strontium Sr: mass number 88, barium Ba: mass number 138, lead Pb: mass number 208
We can also look at these compositions in dwarf galaxies. We can see trends depending on the mass of the dwarf galaxy.
Looking at the r-process and s-process reveals what events have occurred in the galaxy in the past.

- Composition peaks produced during the r process
Selenium (Se): mass number Se, Tellurium (Te): mass number 130, Platinum (Pt): mass number 195

3.3.3 Summary of the origin of elements

- weight: helium ＜element X＜iron

-weight: iron ＜element X

produced by neutron capture and subsequent beta decay

3.3.3 Summary of the origin of elements

-It is thought that the faster the beta decay, the more stable it tends to be. Lighter is the s-process, and heavier is the r-process.

https://en.wikipedia.org/wiki/Nucleosynthesis#/media/File:Nucleosynthesis_periodic_table.svg
Yellow is type II. A table showing the proportion of origins of each element.

3.3.3 Summary of the origin of elements

- 11Sodium Na, 13Aluminum Al

The production rate depends on the initial mass and metallicity of the star. It is produced in the burning shells of massive stars in hydrostatic equilibrium.

- 12 Magnesium (one of the alpha elements)

The production rate depends on the initial mass of the star. They are produced in the burning shells (carbon burning shells) of massive stars in hydrostatic equilibrium. They are rarely produced in Type Ia stars.

- Other alpha elements (8O, 14Si, 20Ca, 22Ti)

Oxygen (O) is produced in the burning shells (helium burning shells) in hydrostatic equilibrium. Heavier alpha elements are produced in the interiors of massive stars by explosive nucleosynthesis during supernova explosions.

3.3.3 Summary of the origin of elements

- iron peak element
(21 Scandium Sc, 23 Vanadium V, 24 Chromium Cr, 25 Manganese Mn, 26 Iron Fe, 27 Cobalt Co, 28 Nickel Ni, 29 Copper Cu, 30 Zinc Zn)
Scandium Sc, vanadium V, chromium Cr, manganese Mn, iron Fe, cobalt Co, and nickel N are produced in both Type I and Type II supernovae.
Cobalt Co is produced in a Type II supernova, while zinc Zn requires a Type II supernova and a hypernova? Since elements cannot be produced in one go, a Type II pathway is required. It is also possible that no quick progress can be made from hydrogen. The pathway for element synthesis is different. Alpha elements often have the same number of protons and neutrons.

- Light neutron capture elements (38 Strontium Sr, 39 Yttrium Y, 40 Zirconium Zr)
Both the s-process and the r-process are required. In stars with low metallicity, this is called the weak r-process.
- Representative s-process elements (56 Barium Ba, 82 Lead Pb)

More than 80% of barium (Ba) and lead (Pb) are produced by the s-process, but they can also be produced by the r-process in metal-poor stars.
- Representative r-process elements (63 europium Eu, 78 platinum Pt, 79 gold Au, 90 thorium Th, 92 uranium U)
More than 90% of europium (Eu), platinum (Pt), and gold (Au) are r-process, while thorium (Th) and uranium (U) are 100% r-process.