Periodic Table

The Lives of Stars: Origins of the Chemical Elements

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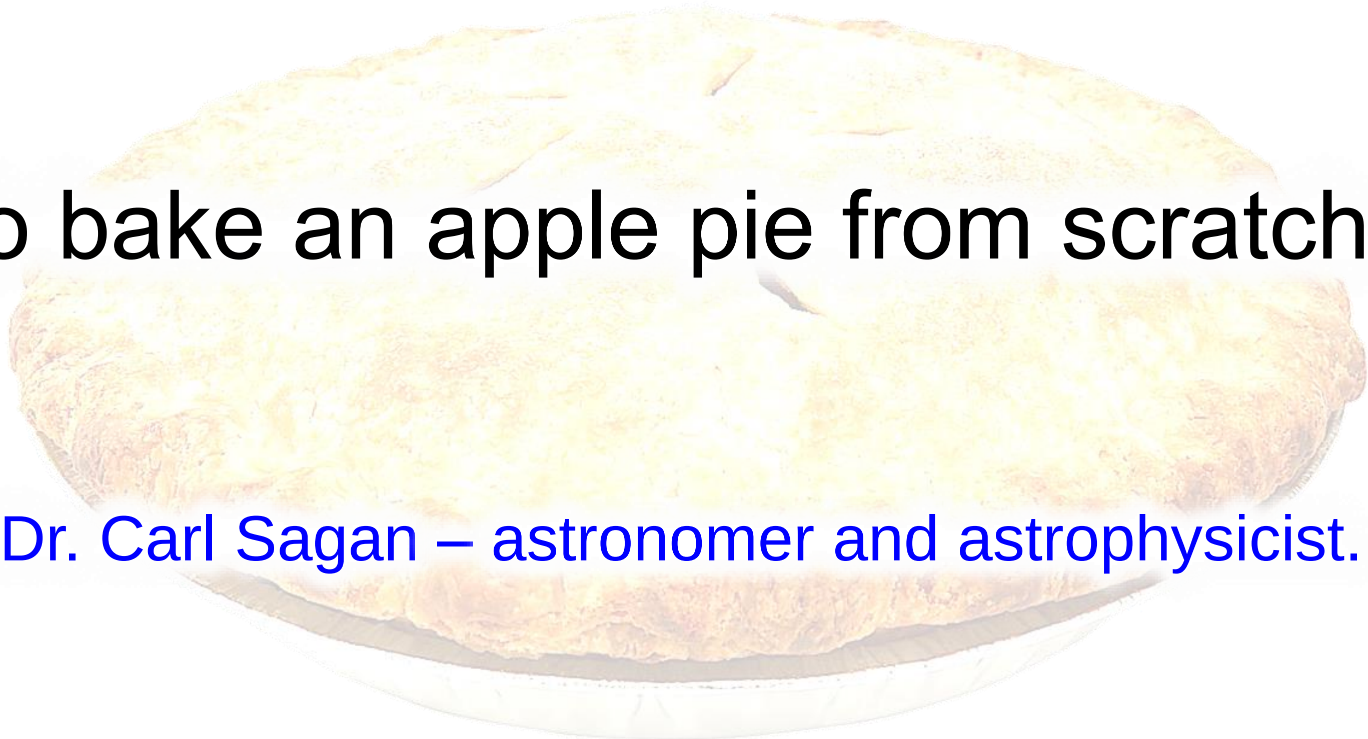

“To bake an apple pie from scratch…

Dr. Carl Sagan – astronomer and astrophysicist.

Periodic Table

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“To bake an apple pie from scratch…
…you must first invent the universe.”

Dr. Carl Sagan – astronomer and astrophysicist.

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What are the origins of the chemical elements?

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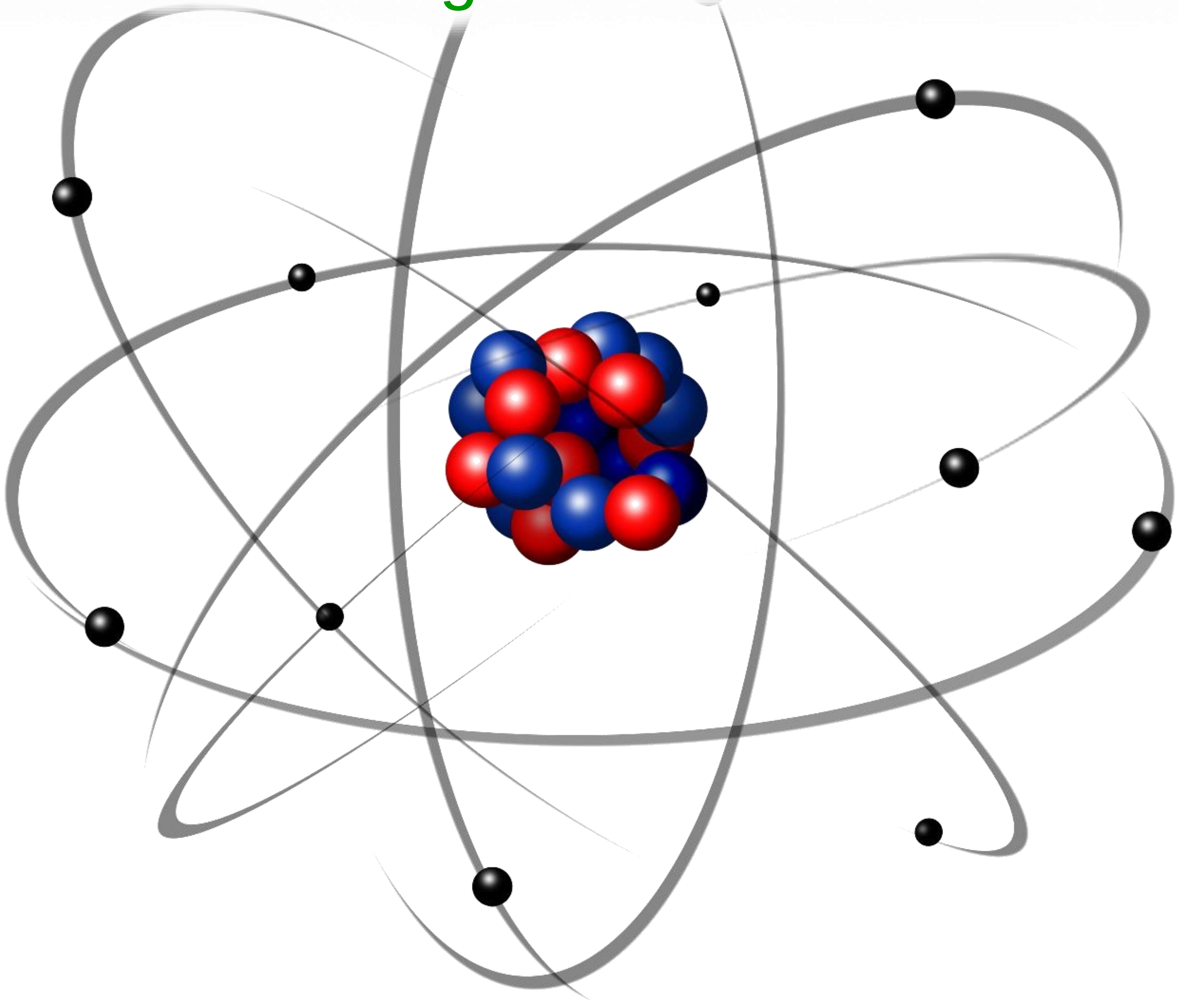

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- A long time ago the atoms in your body were spread across trillions of kilometers of otherwise empty space. Billions of years in the past there was no hint that they would eventually come to be configured as your eyes, your skin, your hair, your bones or the 86 billion neurons of your brain.

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- Many of these atoms came from deep inside a star – perhaps several stars, themselves separated by many more trillions of kilometers. As these stars exploded, they hurled parts of themselves outward in a flood of scorching gas that filled a small part of one galaxy out of hundreds of billions of other galaxies, arrayed throughout a gaping span of space and time almost a trillion trillion kilometers across.

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- Taurus (Latin for “the bull”) is a large and prominent constellation, visible in the northern hemisphere’s winter sky. It is one of the oldest constellations.

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- In 1054 , Chinese astronomers recorded what they called a “guest star” in the constellation of Taurus, the bull. This star had never been seen before, and it became the brightest star in the sky. Easily visible in broad daylight, the observers could read by its light at night. Today we know that the Chinese astronomers had witnessed a the huge explosion of a star – a *supernova*.

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- What these observers did not know is that during the explosion, the star not only emitted huge amounts of light – more light than a billion suns – but also released chemicals into space. Inside the star were most of the first 26 elements in the Periodic Table, from simple elements, such as helium and carbon, to more complex ones, such as manganese and iron; and the giant explosion sprayed them into space. during the explosion, other elements were created as well, and after the explosion, the chemicals in space combined with each other to form ions and molecules.

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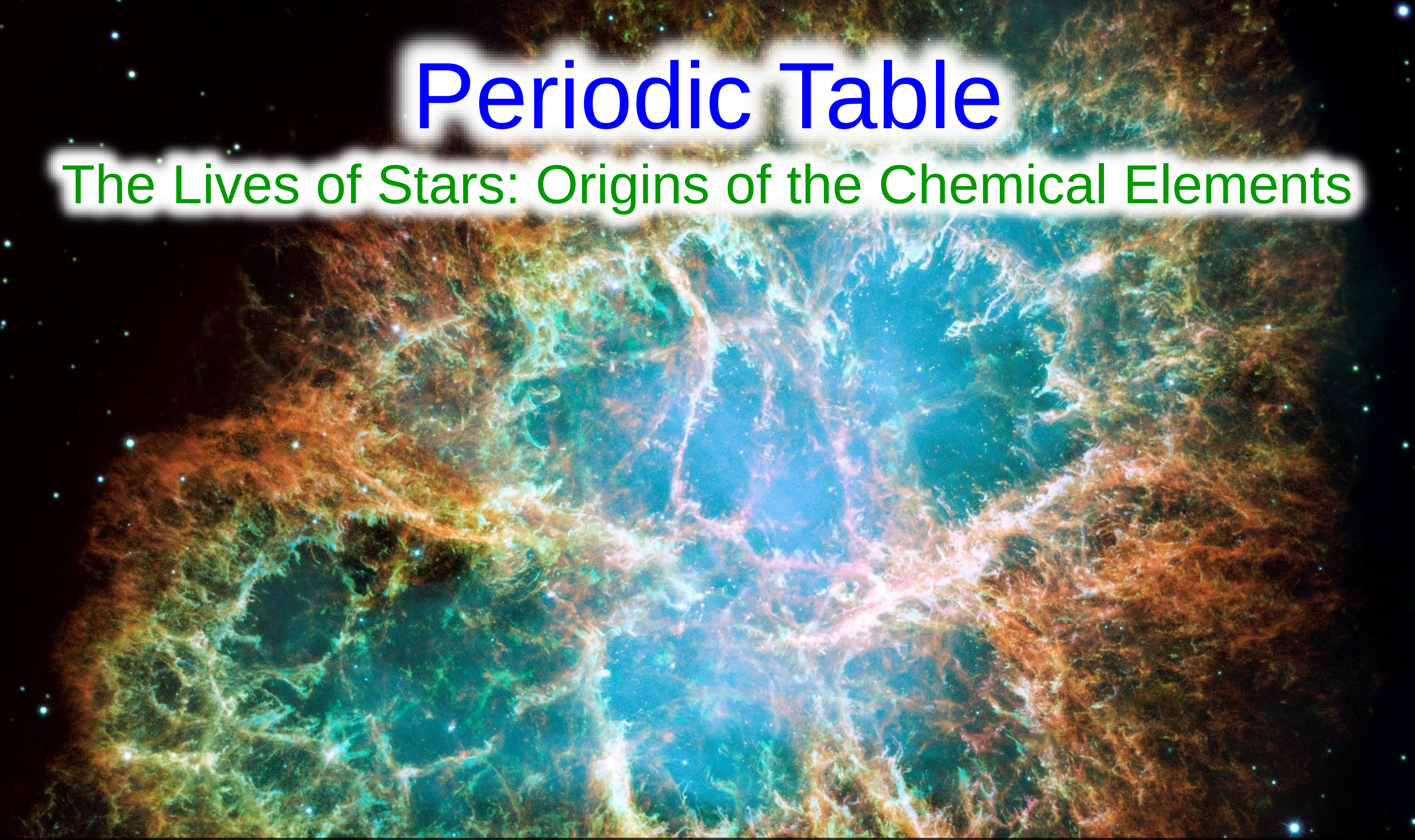

- The Crab Nebula is 6 500 light years from Earth. It is the remnant of a supernova that was observed by Chinese astronomers in 1054 AD.

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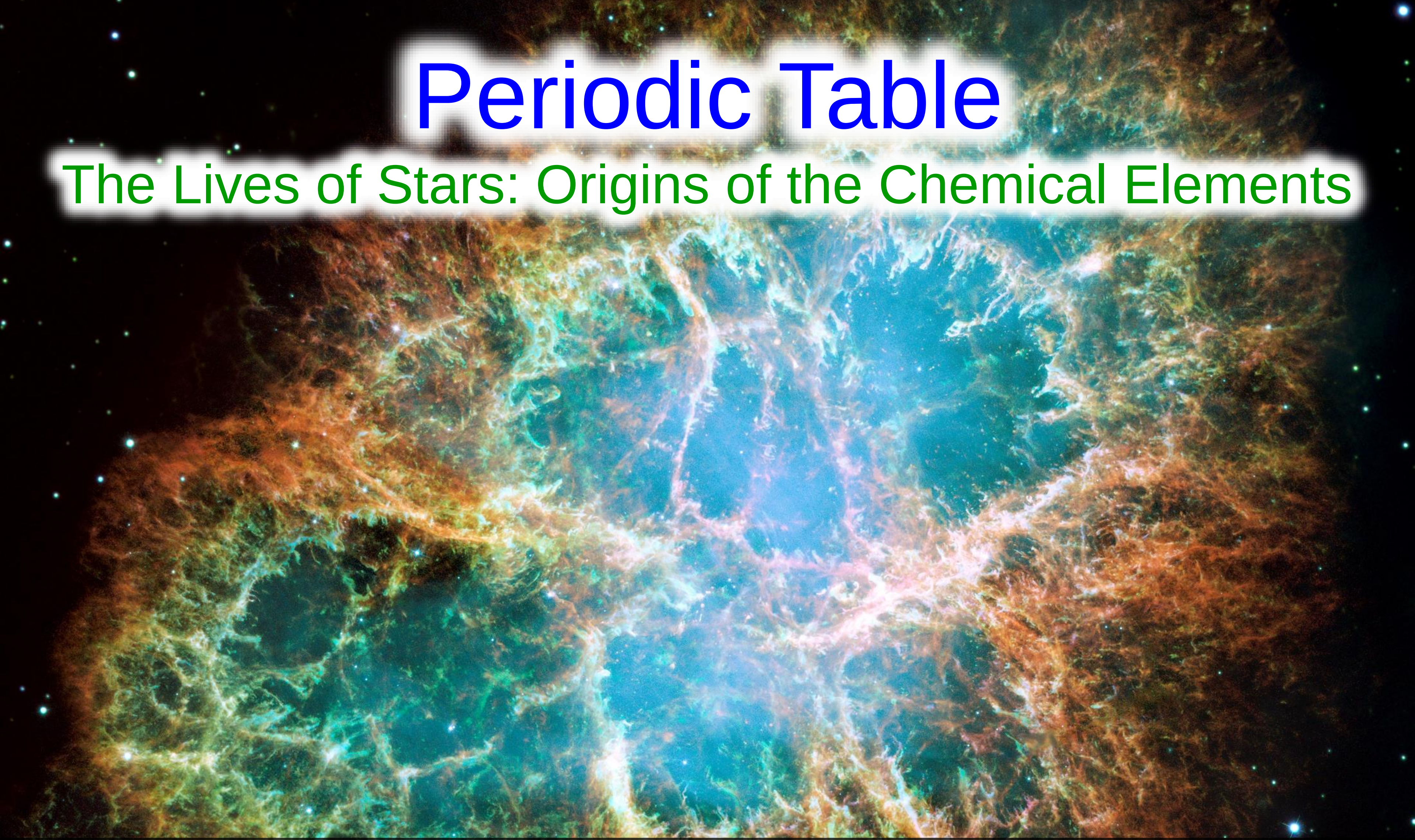

- At the centre of the nebula is a neutron star. The cloud of gas, expanding at 1 500 km per second, contains elements synthesised in the star.

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- These elements travel in space and ultimately end up in planets like Earth, being part of everything we see around us, including ourselves. The carbon in our cells, the oxygen in the air, the silicon in rocks, and just about every element, were all forged inside ancient stars before being strewn across the universe when the stars exploded.

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- During the past century, scientists have been studying how chemical elements form in stars and in outer space. Like genealogists – experts who study the origins of people and families – these scientists can track down where most chemical elements came from and how they descended from each other. And, similar to forming a family tree, studying the links between the chemical elements has brought – and keeps bringing – many surprises and interesting discoveries.

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- A young star is composed primarily of hydrogen, the simplest chemical element. This hydrogen ultimately leads to all known elements. first, the two constituents of each hydrogen atom – its proton and electron – are separated. The high pressure inside the star can literally squeeze together two protons, and sometimes, a proton will capture an electron to become a neutron.

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- When two protons and two neutrons fuse together, they form the nucleus of helium, which is the second element in the Periodic Table. Then, when two nuclei of helium fuse with each other, they form the nucleus of another element, beryllium. In turn, the fusion of beryllium with helium produces a carbon nucleus; the fusion of carbon and helium nuclei leads to an oxygen nucleus, and so on. This way, through successive fusion reactions, the nuclei of most elements lighter than iron can be formed. Scientists call this process *nucleosynthesis* (for "synthesis of nuclei").

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- The nucleosynthesis of helium-4, ^{4}He.

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}e^{+} + 2\,\nu_e + 2\,\gamma$$

→ e^{+} = positron.

→ ν_e = electron neutrino.

→ γ gamma ray.

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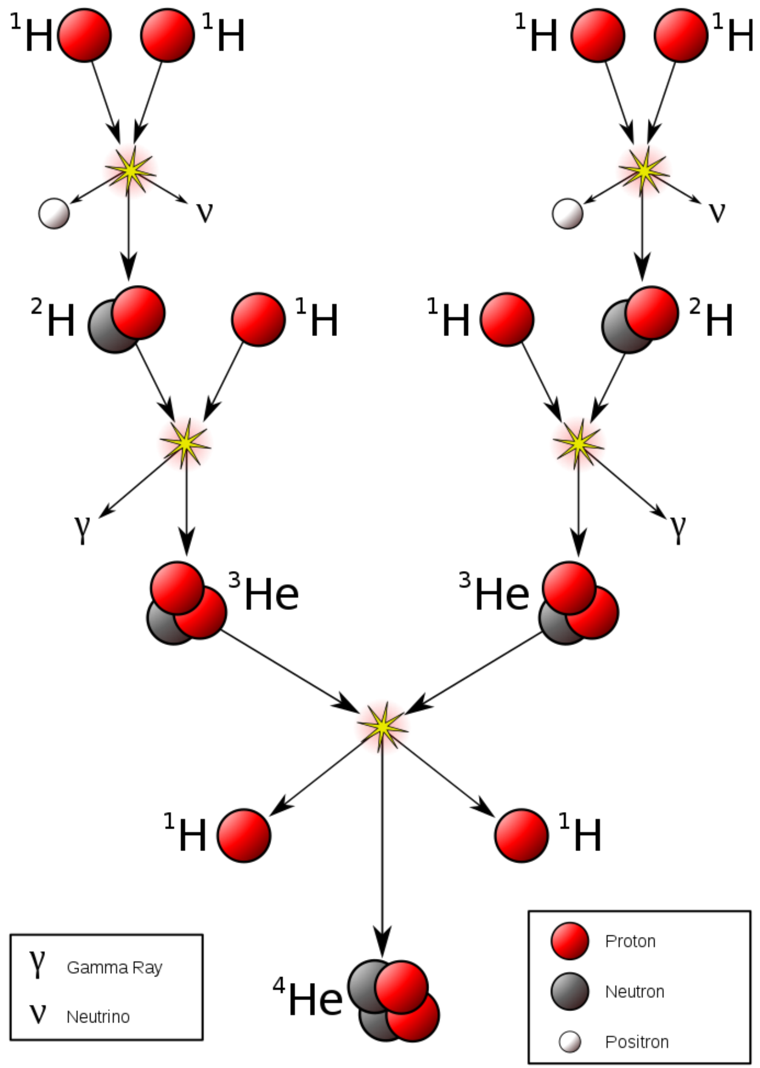

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- The nucleosynthesis of carbon-12, ^{12}C.

$$^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be + \gamma$$

$$^{8}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + \gamma$$

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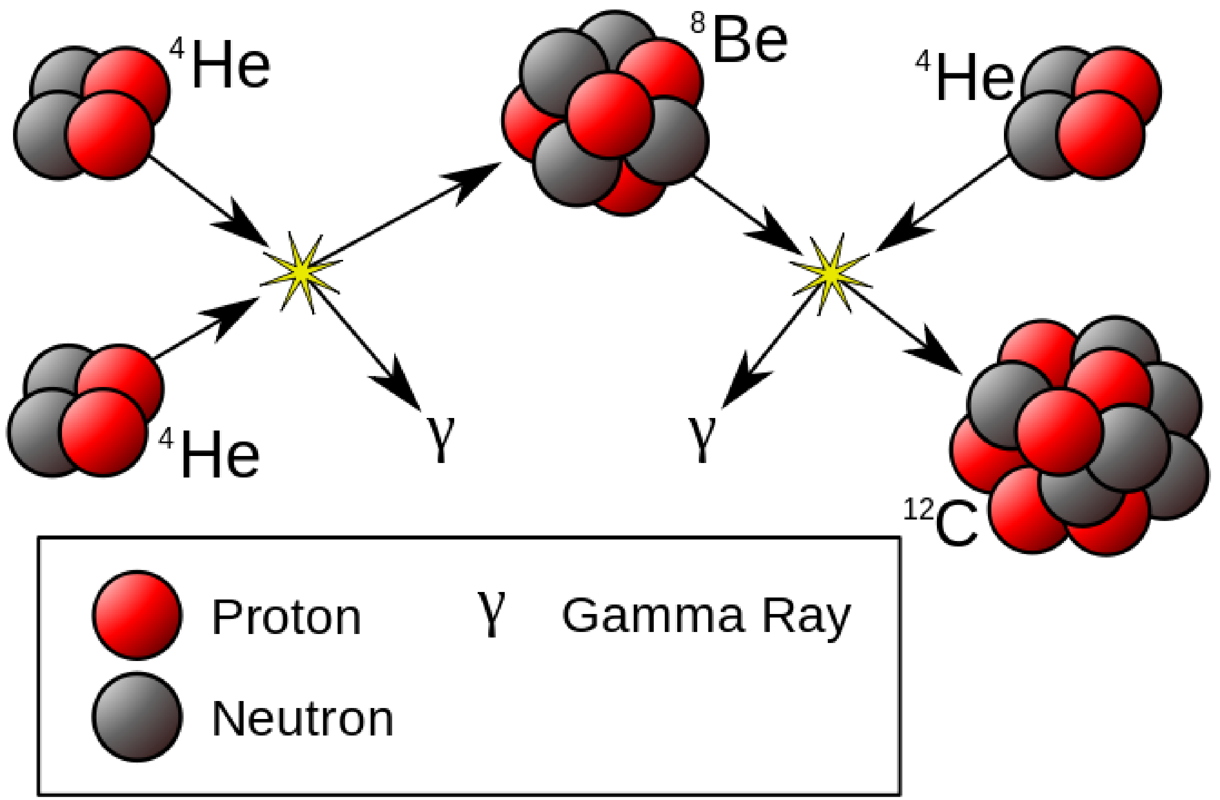

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- The nucleosynthesis of nitrogen-14, ^{14}N and oxygen-16, ^{16}O.

$$^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + \gamma$$

$$^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{1}e^{+} + \nu_e$$

$$^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + \gamma$$

$$^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$$

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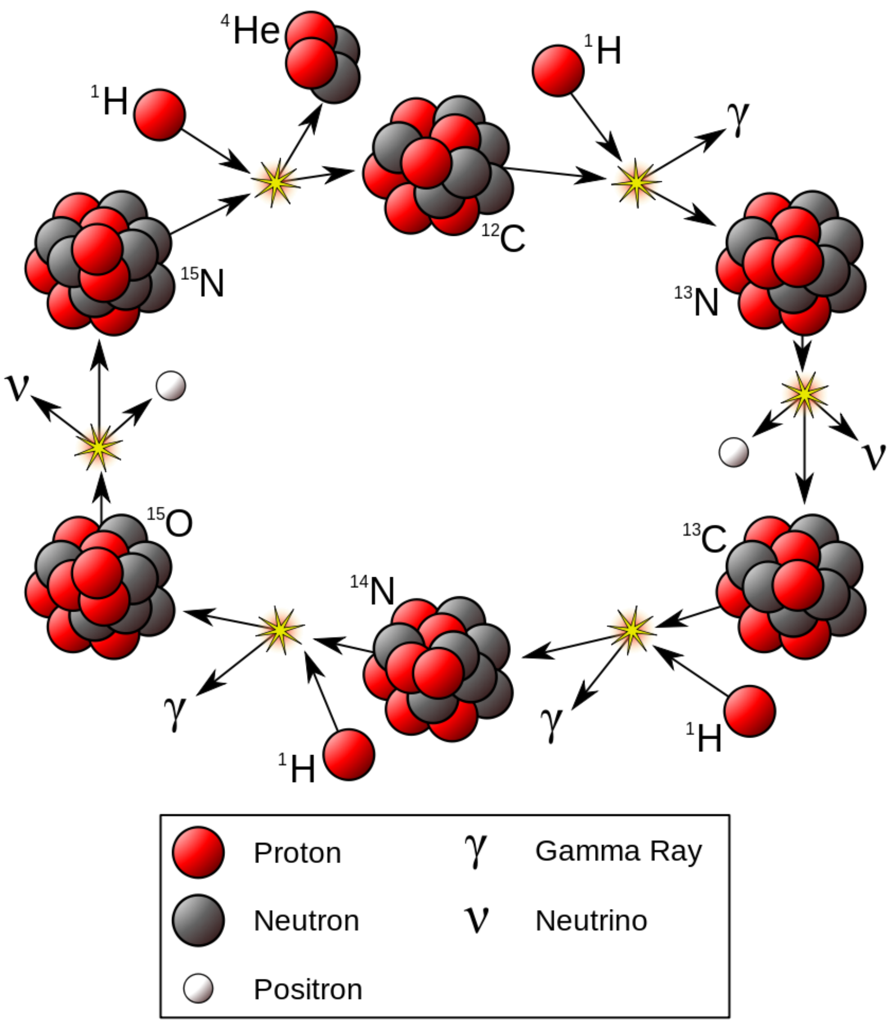

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- In stars, these fusion reactions cannot form elements heavier than iron. up until the formation of iron nuclei, these reactions release energy, keeping the star alive. But nuclear reactions that form elements heavier than iron do not release energy; instead, they consume energy. If such reactions happened, they would basically use-up the star's energy, which would cause it to collapse.

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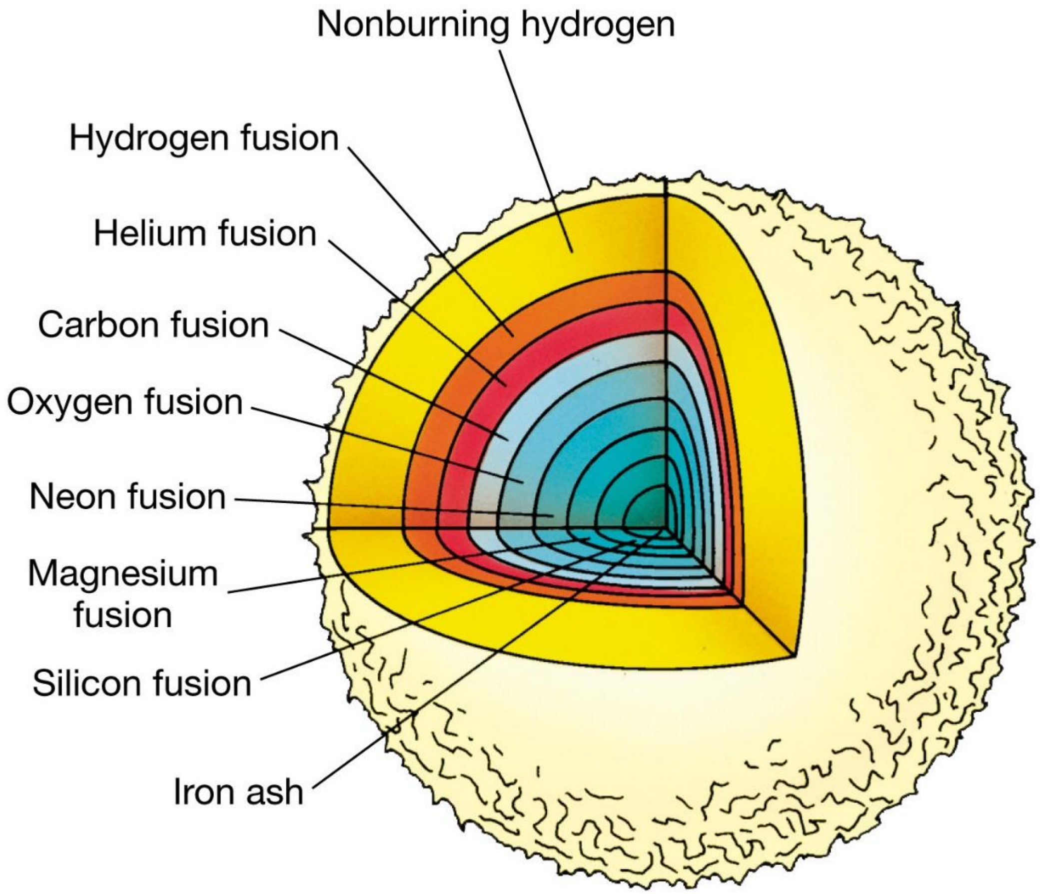

- Nucleosynthesis in different regions of a star.

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- Not all stars form iron, though. Some stars explode before creating that many elements. In stars less massive than the sun, the reaction converting hydrogen into helium is the only one that takes place. In stars more massive than the sun but less massive than about eight solar masses, further reactions that convert helium to carbon and oxygen take place in successive stages before such stars explode. Only in very massive stars (that are more massive than eight solar masses), the chain reaction continues to produce elements up to iron.

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- A star is a balancing act between two huge forces. On the one hand, there is the crushing force of the star’s own gravity trying to squeeze the stellar material into the smallest and tightest ball possible. On the other hand, there is tremendous heat and pressure from the nuclear reactions at the star’s centre trying to push all of that material outward.

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- The iron nucleus is the most stable nucleus in nature, and it resists fusing into any heavier nuclei. When the central core of a very massive star becomes pure iron nuclei, the core can no longer support the crushing force of gravity resulting from all of the matter above the core, and the core collapses under its own weight.

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- The collapse of the core happens so fast that it makes enormous shock waves that blow the outer part of the star into space – a *supernova*. It is during the few seconds of the collapse that the very special conditions of pressure and temperature exist in the supernova that allow for the formation of elements heavier than iron. The newly created elements are ejected into the interstellar dust and gas surrounding the star.

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- "The amount of elements released through a supernova is truly phenomenal," says Stan Woosley, professor of astronomy and astrophysics at the university of California at Santa Cruz. "For example, SN 1987A, a supernova seen in 1987, ejected 25,000 Earth masses of iron alone."

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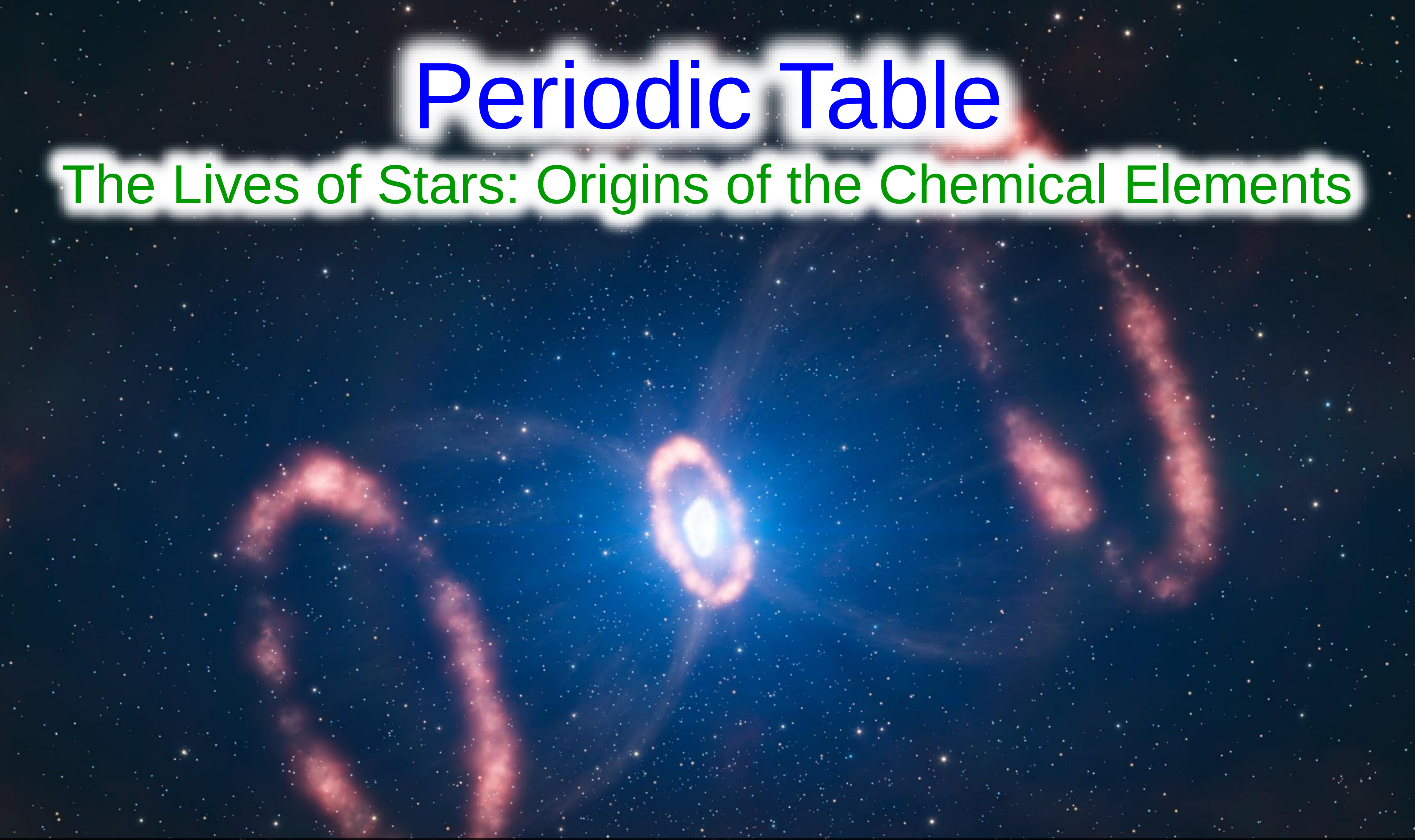

- SN 1987A was a supernova in the outskirts of the Tarantula Nebula in the Large Magellanic Cloud, 168 000 light years from earth.

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- Elements that are heavier than iron can be assembled within stars through the capture of neutrons – a mechanism called the “s” process. The process starts when an iron nucleus captures neutrons, thus creating new nuclei. These nuclei can be either stable, that is, they do not change, or radioactive, meaning that they transform, or decay, into another element after a certain amount of time, which can be as short as a fraction of a second and as long as a few million years.

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- Also, the newly formed nuclei can be different versions of a given element. These different versions of an element are called *isotopes*. They all contain the same number of protons in their nucleus but have different numbers of neutrons. Some isotopes are radioactive, while others are stable and never change.

- For example, nickel can appear in the form of 23 different isotopes. They all have 28 protons, but each isotope contains between 20 and 50 neutrons. Of these 23 isotopes, only five are stable, while the others are radioactive.

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- If a nucleus produced through the “s” process is stable, it may capture another neutron. If it is radioactive, it transforms into another nucleus. This other nucleus can, in turn, absorb another neutron, leading to a heavier nucleus.

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- For example, nickel-64, which contains 28 protons and 36 neutrons, can absorb a neutron, leading to nickel-65, which contains 28 protons and 37 neutrons: nickel-65 is radioactive. It exists for only 2 and a-half hours, and then transforms into copper-65 – the next element in the Periodic Table, which contains 29 protons and 36 neutrons. This is a process called beta decay, in which a neutron transforms into a proton and an electron: copper-65 is stable, so nothing happens after that.

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- This neutron capture mechanism, called the “s” process, is extremely slow. Hundreds or thousands of years might elapse between neutron strikes. but another process, called the “r” process, which stands for “rapid,” allows for the rapid capture of neutrons. unlike the “s” process, which occurs inside a star before it explodes, the “r” process happens only during the explosion of a star.

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- When a star explodes into a supernova, it produces a huge amount of light and releases an extremely high number of neutrons (on the order of 10 thousand billion billion neutrons per square inch per second). These neutrons are then rapidly captured by the various nuclei that are also released by the exploding star, producing new nuclei through the “r” process. In this process, even though many neutrons are available, only a limited number can be added to a given nucleus; otherwise, a nucleus becomes radioactive and breaks up.

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- Neutrons in a nucleus are thought to occupy shells similar to successive shells on a hard candy. When a nucleus gets “saturated” with neutrons, that is, when its shells are filled up, it undergoes a beta decay process to become the nucleus of the next element on the Periodic Table. This new nucleus, in turn, absorbs as many neutrons as it can hold, and then decays when it is “saturated” with neutrons, and the cycle starts again. When an element formed through the “r” process becomes really heavy (total number of protons and neutrons close to 270), it spontaneously breaks apart through a process called nuclear fission.

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- "The neutrons add very rapidly at a temperature of a few billion degrees, going from iron to uranium in less than 1 second," Woosley says. Elements created this way include transuranium elements – elements whose number of protons is higher than that of uranium – such as curium-250, californium-252, californium-254, and fermium-257.

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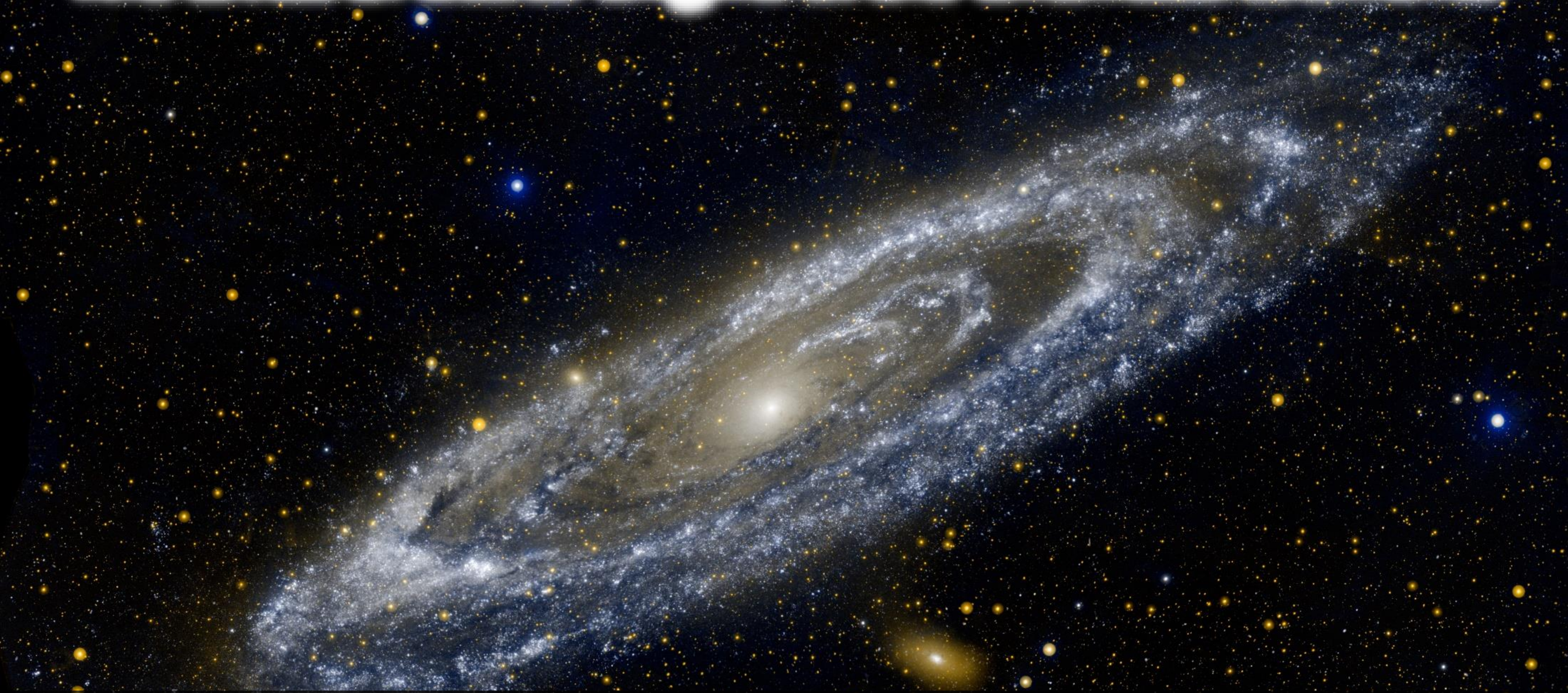

- The Andromeda Galaxy is 2.5 million light years from Earth and contains approximately one trillion stars.

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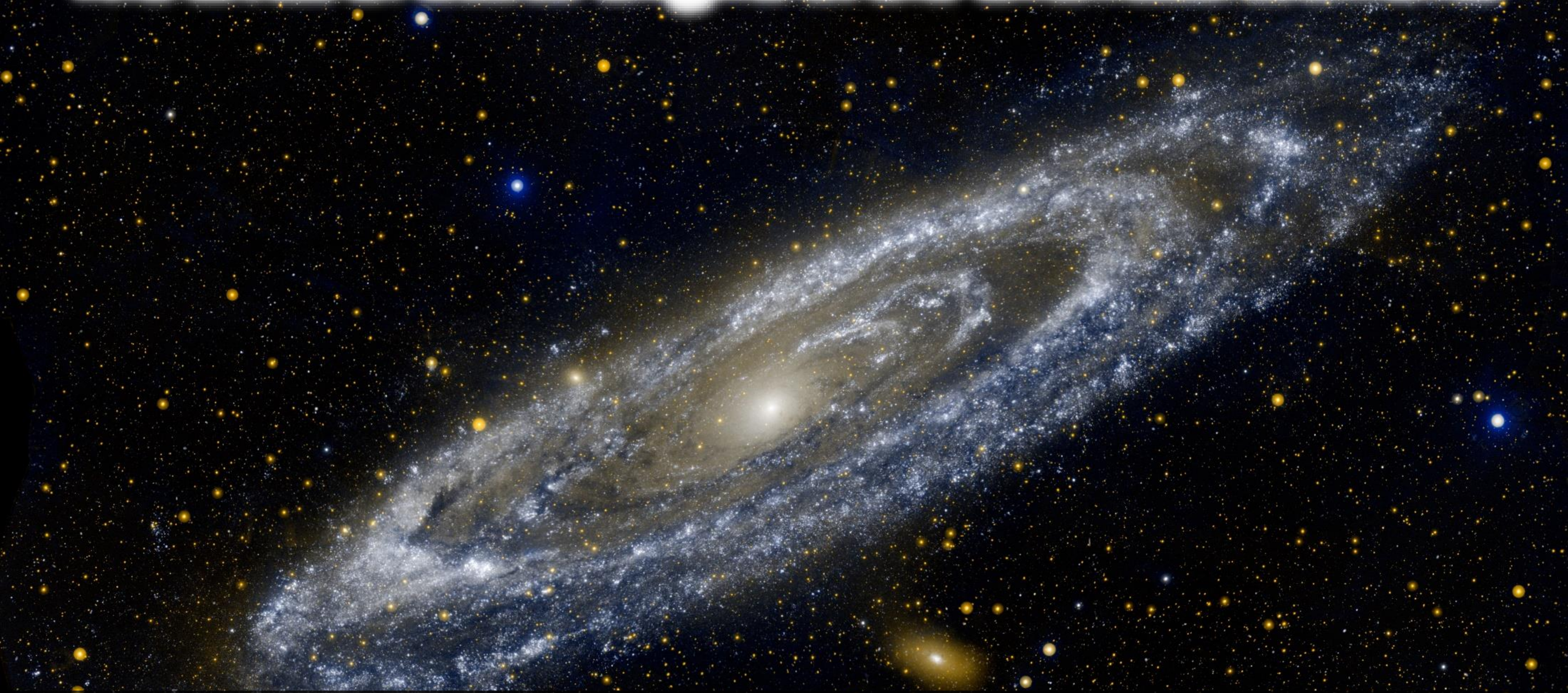

- The immense gravity at the centre of each star fuses the nuclei of atoms together, resulting In the synthesis of new chemical elements.

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- When a supernova spews its newly made elements into space, the elements become part of an enormous cloud of gas and dust, called an *interstellar cloud*. The gas is made of 90% hydrogen, 9% helium, and 1% heavier atoms. The dust contains silicates (compounds made of silicon), carbon, iron, water ice (H_2O), methane (CH_4), ammonia (NH_3), and some organic molecules, such as formaldehyde (H_2CO).

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- Such clouds are found so often between stars in our galaxy that astronomers think that all stars and planets have formed from them. Except for hydrogen, which appeared when the universe formed through the big bang explosion, all of the elements on Earth have been cooked for billions of years in stars and then released in the universe through supernova explosions. The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, and the carbon in our apple pies were all made in the interiors of stars. The gold in jewels, tungsten in light bulbs, and silver in cookware were all produced during stellar explosions. We ourselves are made of "star stuff."

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- The sun formed approximately 4.6 billion years ago. It is 73% hydrogen and 25% helium, with traces of heavier elements, *e.g.* carbon, oxygen, neon and iron.

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- Every second, the sun fuses 600 million tons of hydrogen to form 596 million tons of helium. The difference is lost as energy according to $E = mc^2$.

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- From Einstein's equation $E = mc^2$

where…

E = energy

m = mass in kilograms = 4 000 000 000 kg

c = speed of light in a vacuum = 300 000 000 m s^{-1}

- Energy produced by the sun every second

$= 4\ 000\ 000\ 000 \times 300\ 000\ 000^2$

$= 3.60 \times 10^{26}$ J s^{-1}

$= 3.60 \times 10^{26}$ W

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- To determine which chemical elements are formed inside stars, scientists use a technique known as *visible spectroscopy*. It is based on a device, called a spectroscope, which spreads visible light into its component colours by passing it through a prism or grating.

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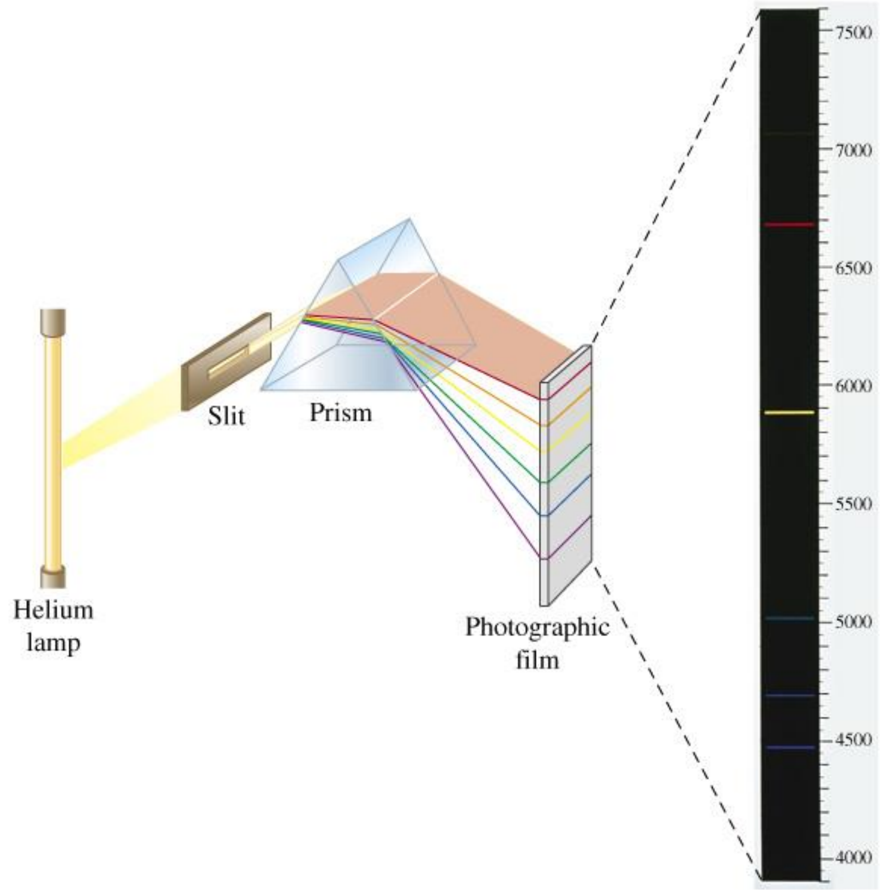

- There are six distinct bands in the emission spectrum of helium.

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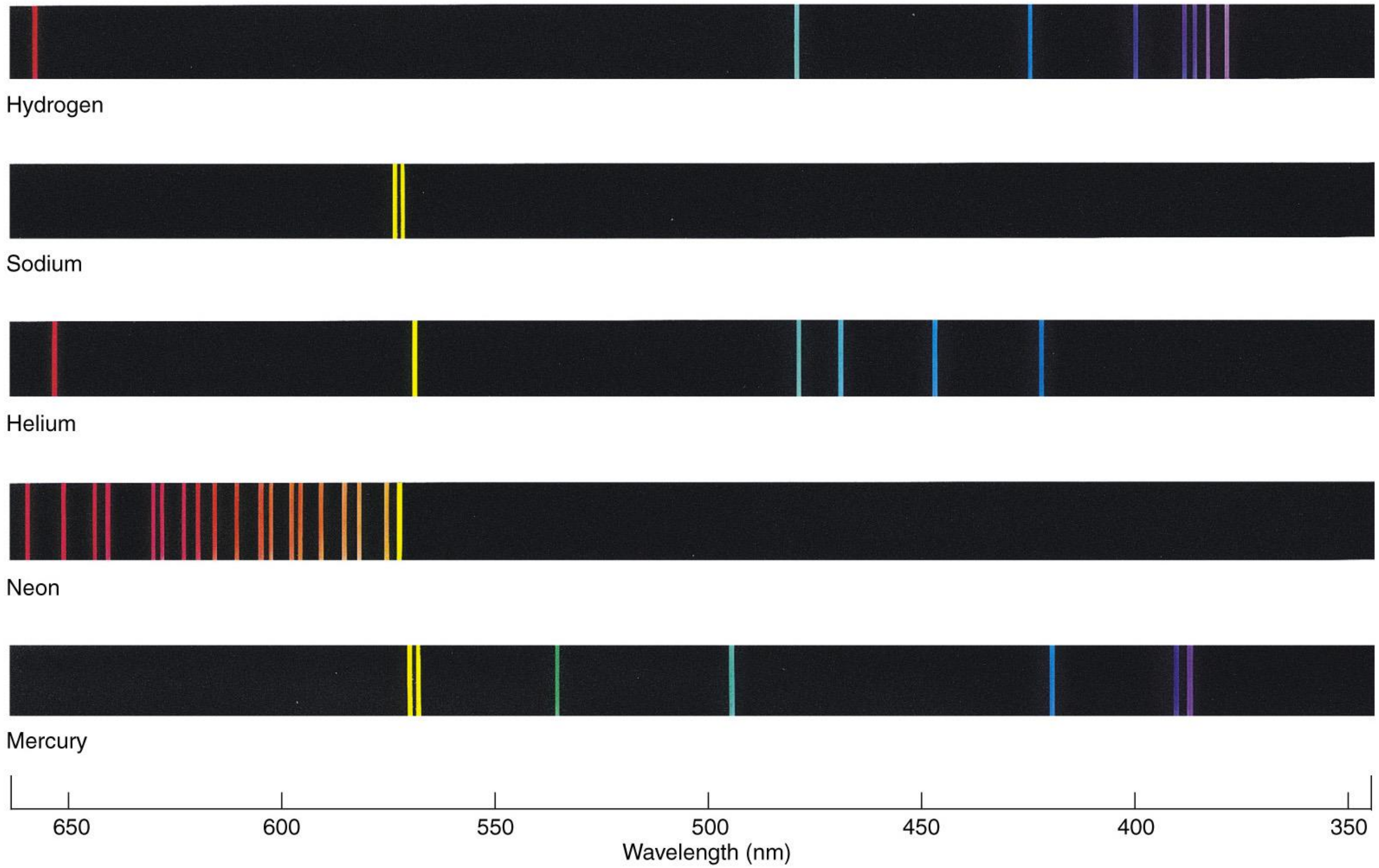

- Each chemical element has its own unique emission spectrum, from which it can be identified.

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- These colours are called an *emission spectrum*, and their position and intensity differ according to the chemical element that emits the light. For example, the hydrogen's emission spectrum consists of four lines: purple, blue, green, and red, located at positions that correspond to their wavelengths. The emission spectrum of helium consists of six lines that are purple, cyan, green, yellow, orange, and red. In other words, atoms and molecules produce their own "fingerprint" or "signature" when the light they emit is spread in a spectroscope.

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- Astronomers also measure how much light is present at each spectral line. The overall strength or weakness of all the lines of an element depends on the number of atoms of that element. The percentage composition of the atoms in a stellar body can also be determined. For example, by looking at the light emitted by the sun, scientists have been able to determine the relative number of atoms from specific elements and infer their percentage by mass.

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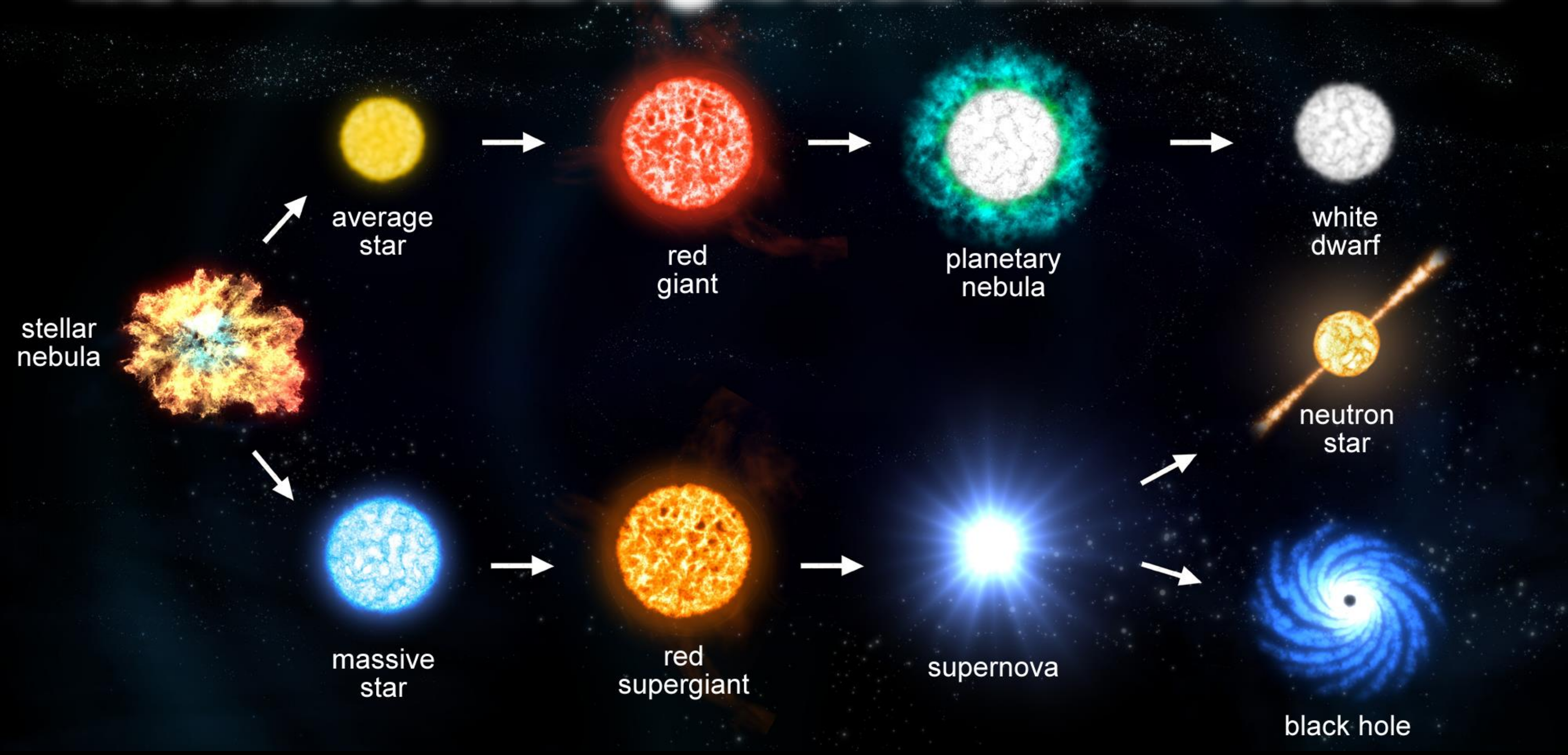

- The ultimate fate of a star depends upon its size (mass).

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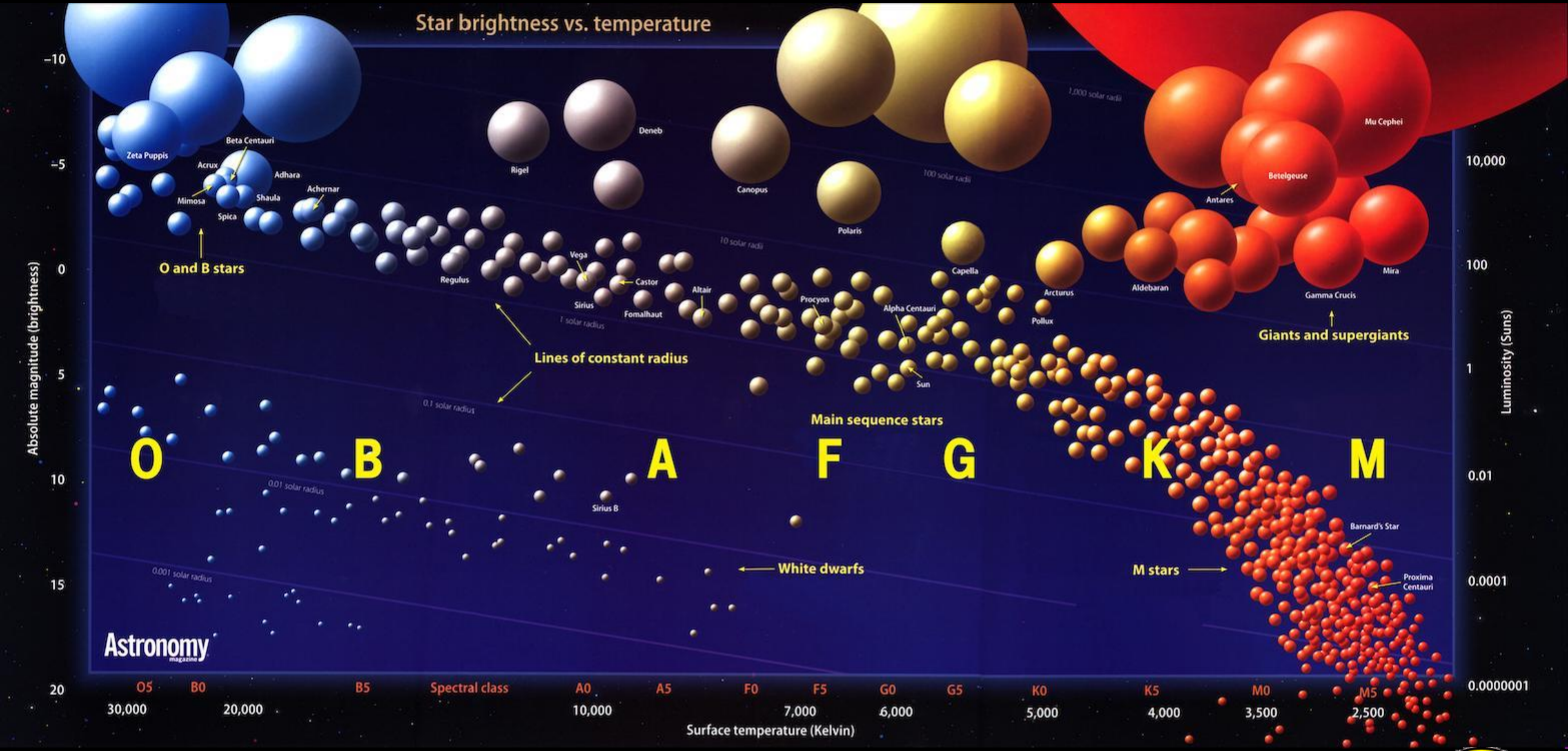

- Stars are classified based upon their size (mass), brightness and surface temperature.

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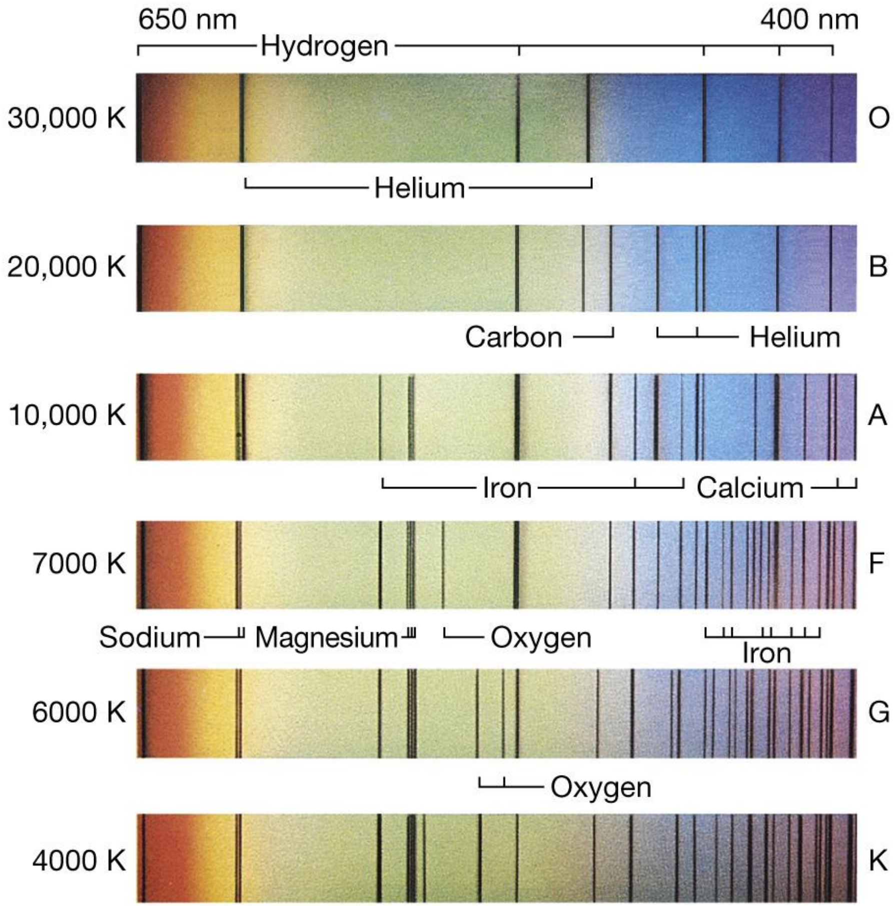

- Emission spectra for the different types of star; O, B, A, F, G and K (see previous slide).

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*First and Last Things

By weight, our bodies are 10 per cent hydrogen, 60 per cent oxygen and 20 percent carbon. The last 10 per cent is taken up principally by nitrogen, calcium, phosphorus, sulfur, sodium and magnesium, iron and copper. The atoms that constitute these substances were created not in our sun but by other stars long since dead, as we have seen. They are not our atoms. They do not belong to us, nor to our bodies. They are just passing through. Every moment of our lives, we exhale carbon dioxide. The atoms in that gas have existed for billions of years already, and they will continue to exist for billions of years more after we have gone; in soil, in leaves, in dogs, in cats, in flowers, and in the air breathed by our descendants.

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*First and Last Things

Our sun has burned for five billion years, and will burn for five billion more; after which, it will have used up a crucial proportion of its available hydrogen. The sun that has nurtured us for so long will turn into a violent and unpredictable monster prone to sudden nuclear shutdowns and re-ignitions, expansions and contractions, alternating over several millennia. It will end its days as a red giant so gigantic that its wayward mantle of gases will swallow up half the planets of the solar system, including the Earth. Everything on our planet that lives and breaths will be utterly vaporised. The grass, the trees, even the toughened lichen that clings to granite will be blasted to atoms.

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*First and Last Things

The oceans will boil away to the last drop. The ice caps will vaporise. The sand on every beach in the world will fuse into glass. Mercury and Venus will vanish. If Earth survives the storm, it will remain only as a scorched lump of rock. The sun's final life-giving service will have been to vaporise the thin sliver of biosphere on Earth's surface, blasting it into space once more so that the atoms might one day contribute towards new worlds and new forms of life. Perhaps, some day in the future, some intelligent and curious creature containing a few of our second-hand atoms will ask where they came from.

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Presentation on

The Lives of Stars:

Origins of the Chemical Elements

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11th November 2016

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