We Are Stardust: Synthesis of the Elements Essential for Life

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Cosmology Review

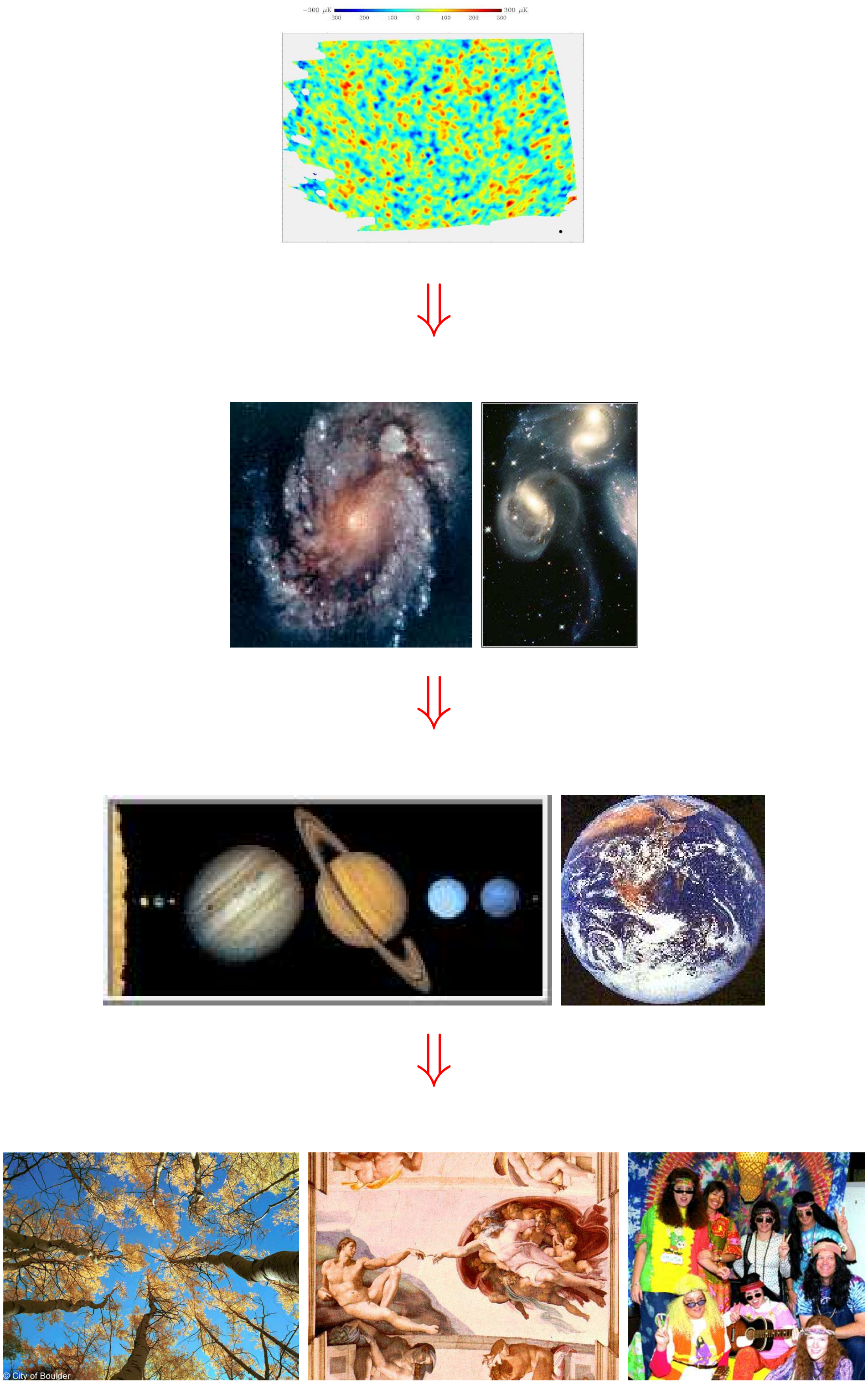
• The universe began about 14 billion years ago as an extremely hot dense fireball which we refer to as the Big Bang.

• The nucleosynthesis that occurred in the first three minutes after the Big Bang made only hydrogen, helium, and trace amounts of deuterium and lithium.

• Thus, all the other elements that we observe on Earth and in the universe were made subsequently.

• We believe, from theoretical models and from strong observational evidence, that stars and supernovae have created the large number of observed chemical elements, starting with just hydrogen and helium. Astronomers refer to all elements which are heavier (of greater atomic weight than helium) as "metals".

• The first stars are believed to have formed when the universe was about 100 million years old.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Conditions For Life As We Know It

• **Quality and quantity of a stable energy source – sunshine. [Mechanism by which matter can use this energy to become more ORDERED.]**

• **Liquid water, with hydrogen and oxygen.**

• **Amino-acids: small molecules containing various combinations of carbon, nitrogen and oxygen. Long chains of amino-acids → proteins → DNA. [Time for system to achieve COMPLEXITY.]**

All of these factors combine to make Earth our fertile, living and liveable home.

So, what gives us stable sunlight, and the elements of carbon, oxygen, and nitrogen?

Our Sun – The Closest Star

• About 6000 stars are visible in the night sky to the naked eye (without telescopes), and they are all "suns".

• Our Sun is the closest star to us and hence has been studied the most in detail. Sunlight takes 8 minutes to reach us on Earth from the Sun.

• The Sun is roughly made up of: 70% hydrogen, 28% helium and 2% metals.

• Relative to Earth, the Sun is 300,000 times more massive and about 100 times larger in radius. Such an enormous mass implies tremendous interior pressures. We can calculate that the Sun's central temperature is about 15 million degrees, or equal to about 100 billion times the Earth's atmospheric pressure.

• Under such conditions, the interior of the Sun is opaque, so we can only see a little way into it. What we see is the Sun's surface or "photosphere", about 0.1% of the Sun's radius and 5500 degrees Celsius, corresponding to yellow-green light.

• Internal conditions in our Sun (and other stars) are basically that of a scalding inferno with madly rushing particles and photons of light smashing violently into each other. This implies a slow outward progress of the photons created in the Sun: a typical photon takes 100,000 years to reach the "edge" of the Sun from the center, rather than the 2 seconds that it would take if the photon could travel freely at the speed of light. When the photons reach the surface, they go from "crawling" to "flying".

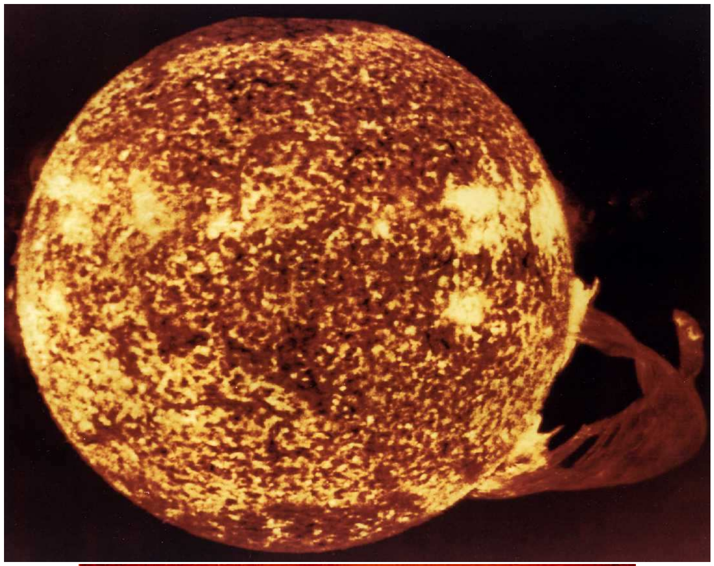
• This extremely slow outward progress of photons leads to two important consequences: a photon at the Sun's center (very hot, so X-rays) becomes a less harmful optical wavelength photon by the time it leaves the Sun; and, this has a tremendous stabilizing effect on the Sun's generated light (or luminosity), which is essential for the stability of life.

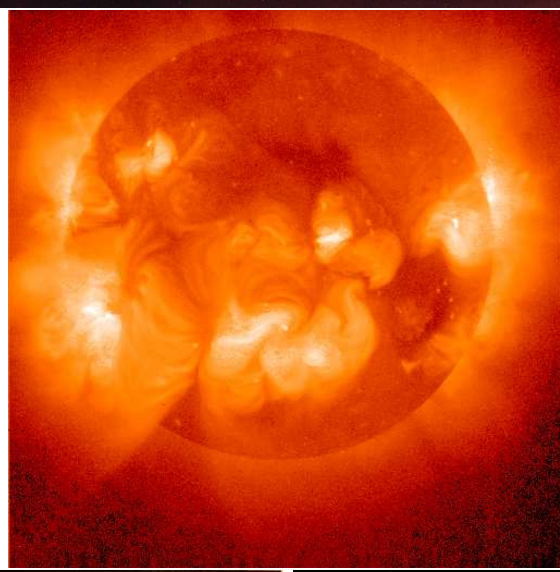
What Powers the Sun?

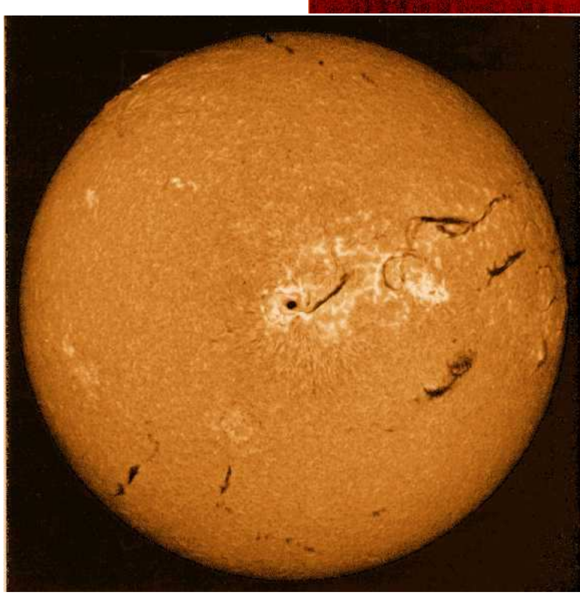
• In the 19th century, there was a conflict between the findings of geology and the theoretical models of the Sun's energy source from astrophysics.

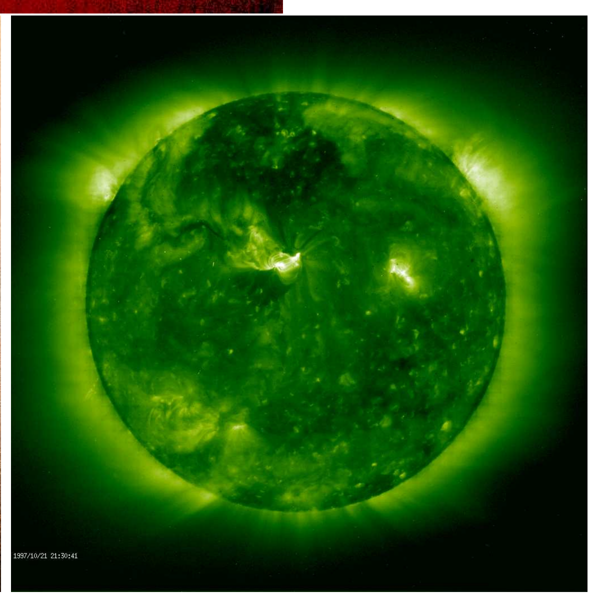
• Fossil evidence and radioactive dating showed that life on Earth had existed for over 3 billion years. Astrophysical calculations, based on the assumption that the energy source of the Sun came from gravitational contraction energy (50% of which goes into Sun's thermal energy), revealed that the Sun could shine at its current luminosity levels for only 30 million years. So what has been enabling the Sun to shine for the last few billion years?

• The Sun's source of energy is Thermonuclear Fusion, where heavier chemical elements are made from lighter elements through nuclear reactions at high temperatures, liberating energy in the process.





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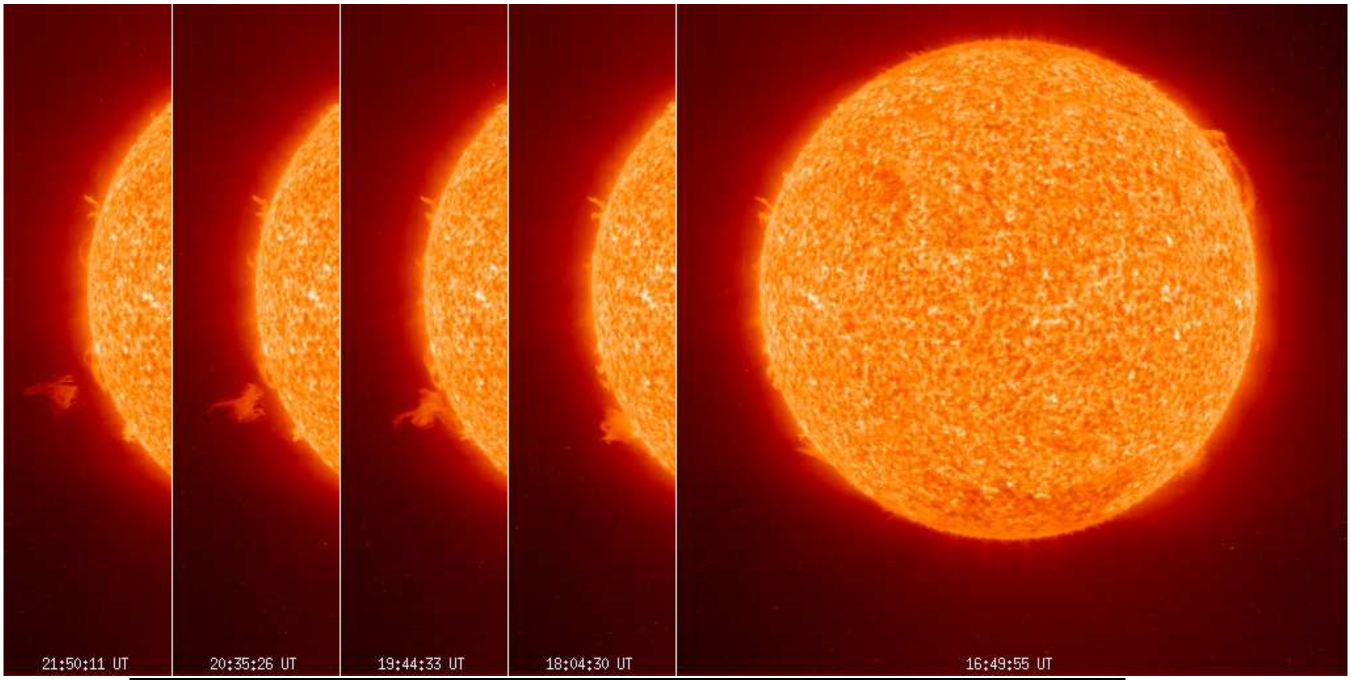
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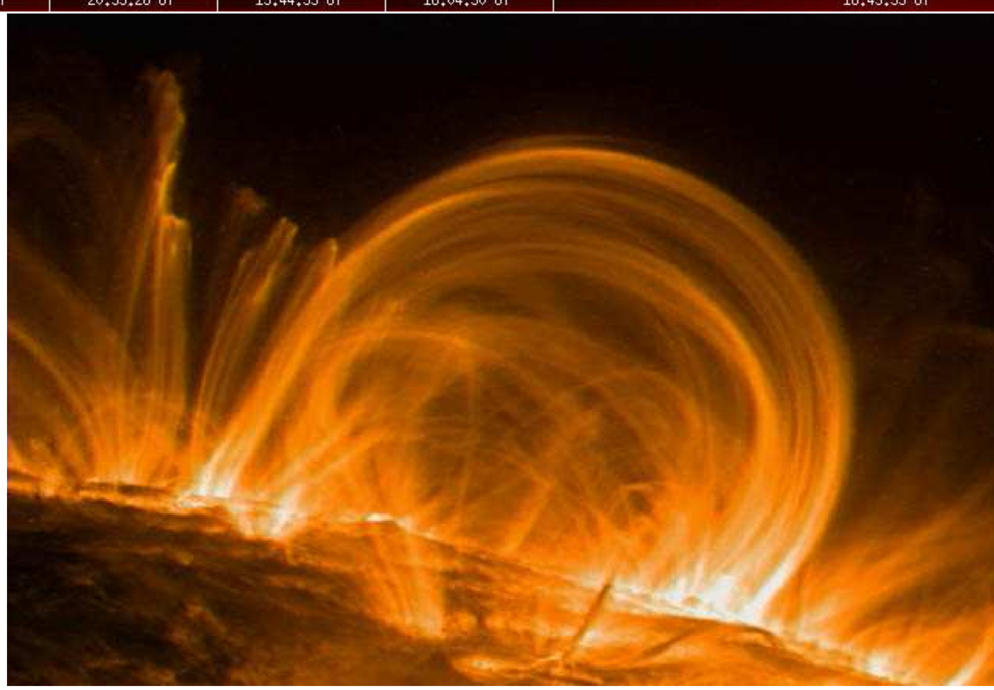


• This method of self-sustenance by the Sun (and all stars) against total collapse under their own gravity not only generates the energy but the very elements required for life as we know it. Furthermore, the Sun and other stars are extremely stable in this phase of their lives, because they have a built-in safety valve to prevent runaway thermonuclear reactions.

• Therefore, a star (like our Sun) contracts until it reaches a core temperature that generates sufficient energy through nuclear reactions to generate photons whose radiation pressure holds up the star. The rate of energy leakage of the photons from the star's surface exactly balances the nuclear energy generation rate in its core.

• Calculations indicate that the Sun should be able to shine at its present level for about 10 billion years. Radioactive dating of lunar rocks and meteorites show that the first objects solidified in the solar system about 4.6 billion years ago. This makes the Sun a middle-aged star.

• Thus the solar system is appreciably but not greatly younger than the oldest objects in the universe.

Humans, having been around for about 4 million years on Earth, are a relatively recent phenomenon.

The Life Cycle of Stars

• Stars are born in cool dense nebulae and clouds of interstellar gas and dust, that collapse under their own gravity.

• The dividing line between stars, which shine by their own light, and planets, which shine by reflected light, occurs at about one tenth of the Sun's mass.

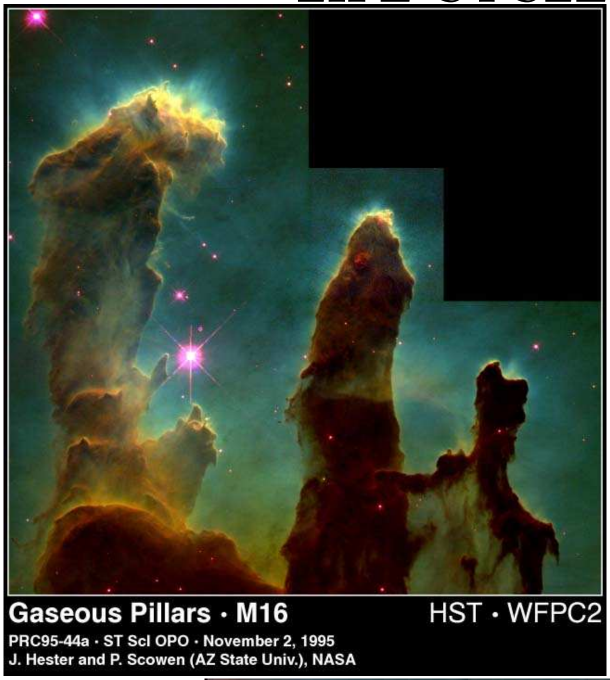
• The critical factors that determine a star's fate (structure and evolution) are its mass and initial chemical composition.

• The lifetime of stars goes as the inverse cube of the star's mass: that is, a star that is 10 times as massive as the Sun lives for a period that is 1000 times shorter!

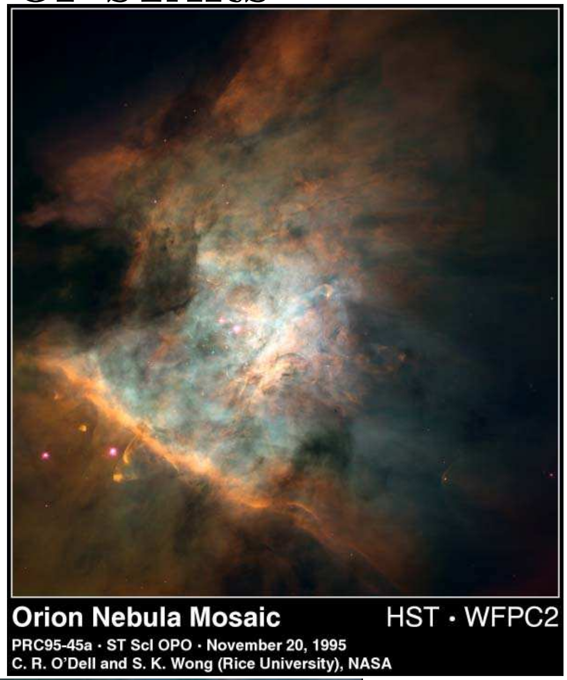
• The Sun is an average star, in terms of mass, age and chemical composition. From both its age (about 5 billion years) and its composition, we know that it is not a first generation star, but formed from a pre-enriched nebula.

• Stars less than twice as massive as the Sun power themselves by fusing 4 H nuclei into a ^{4}He nucleus in their cores, liberating energy.

LIFE CYCLE OF STARS



Gaseous Pillars · M16 HST · WFPC2
PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA



Orion Nebula Mosaic HST · WFPC2
PRC95-45a · ST ScI OPO · November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

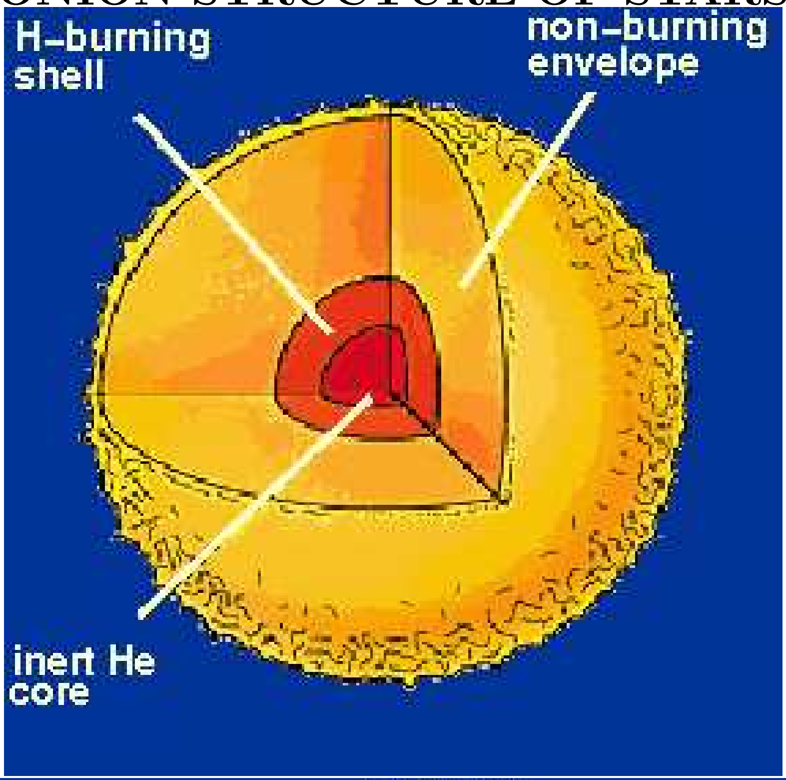
• More massive stars utilize the "CNO" cycle: 3 $^{4}He \rightarrow {}^{12}C$ at temp. = 100 million degrees; carbon → nitrogen and oxygen at temp. = several hundred million degrees.

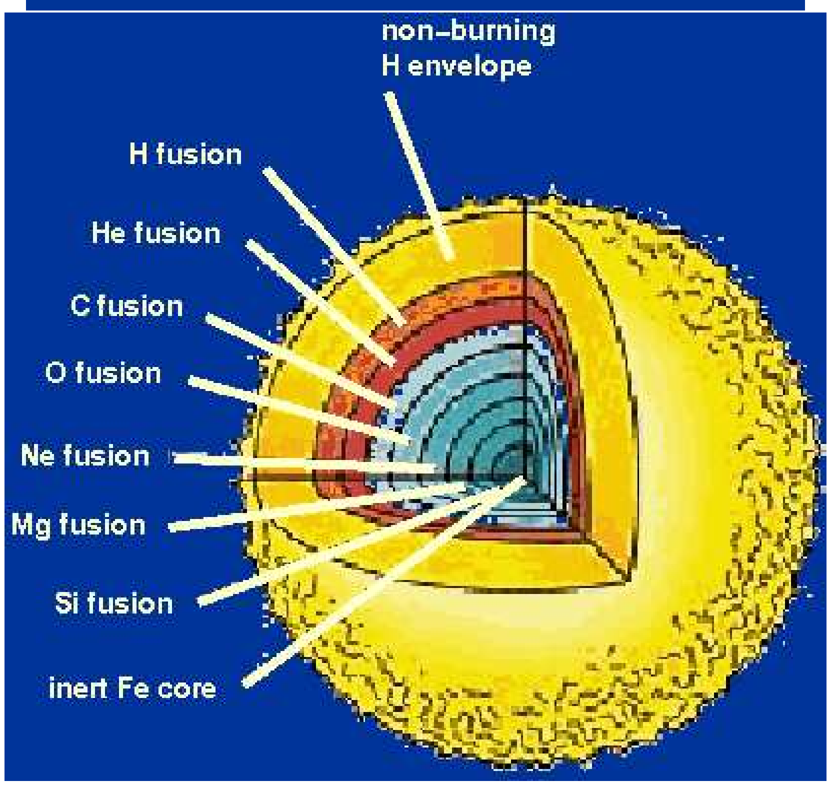
• Thus, a general pattern emerges: when the star exhausts one fuel, it can no longer support itself against gravity, so it contracts until it reaches a core temperature that can ignite the product of the previous fuel. Since this product is a heavier element than the initial fuel, this process requires successively higher temperatures. In this way, the most massive stars "burn" through carbon, oxygen, neon, sodium, magnesium, silicon, sulphur, etc., all the way up to iron. The inside of a very high-mass star looks like an onion!

• Nuclear fusion in stellar cores is energetically favorable only up to the element iron. Beyond iron, the star will not gain energy, but will rather have to give up energy to continue nuclear reactions.

• Thus, high-mass stars eventually reach the iron dead-end, at which catastrophic core collapse and heating up to several billion degrees occurs. At these temperatures, matter prefers to be in simple elements and the iron disintegrates into helium nuclei and neutrons. Eventually, a tremendous explosion of the outer star layers occurs– a supernova– while the core collapses into a neutron star or a black hole.

ONION STRUCTURE OF STARS





The Fate of Stars

• Stars of mass 1–3 solar masses burn up to helium in their cores, gently expel their outer layers as a planetary nebula and end their lives as a white dwarf.

• Stars of mass 3–10 solar masses burn up to carbon and oxygen in their cores, gently expel their outer layers as a planetary nebula and end their lives as a white dwarf.

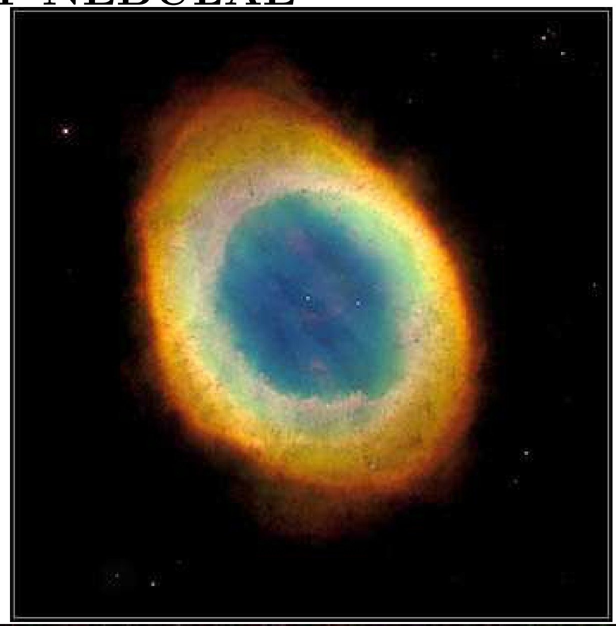
• Stars of mass greater than 10 solar masses burn up to iron in their cores, violently expel their outer layers as a supernova and end their lives as a neutron star or a black hole.

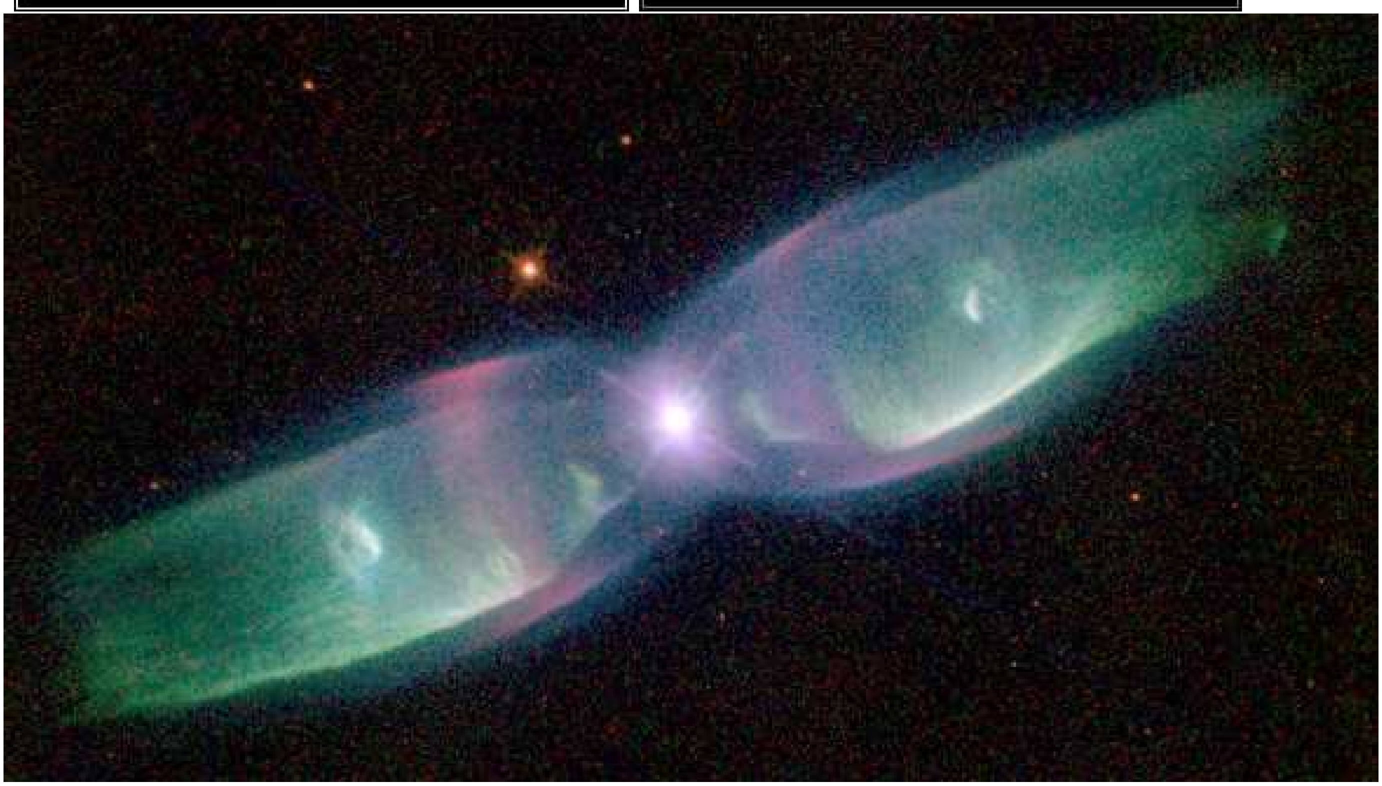
Therefore, elements like oxygen, silicon and sulphur come mostly from short-lived stars of mass greater than 10 times the Sun's mass.

And elements like carbon and nitrogen come mostly from longer-lived stars of mass 3–6 times the Sun's mass.

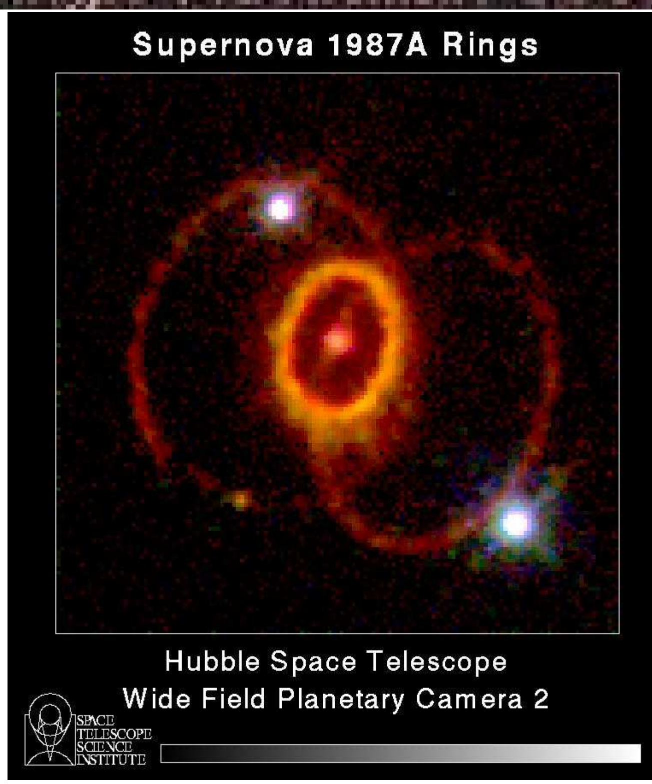
"We are stardust, billion year old carbon, we are golden..."
– Joni Mitchell, "Woodstock"

THE DEATH OF LOW-MASS STARS AS PLANETARY NEBULAE





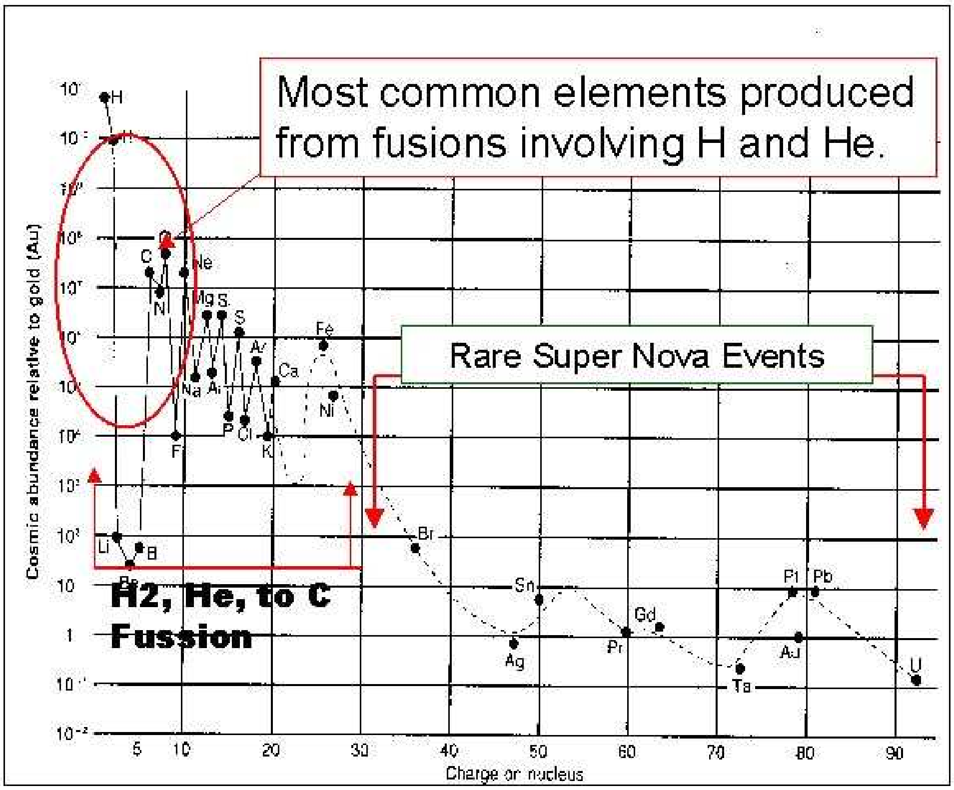
THE DEATH OF HIGH-MASS STARS AS SUPERNOVAE:



At its peak brightness, a supernova can outshine an entire galaxy.

Creation of Elements Beyond Iron

• Nuclear fusion in stellar cores is energetically favorable only up to the element iron. Beyond iron, the star will not gain energy, but will rather have to give up energy to continue nuclear reactions.



• We believe that all the known (naturally occurring) elements beyond iron, such as gold, silver, lead, uranium, etc. were made through reactions (not nuclear) involving elements lighter than iron and free neutrons. These take place in stellar interiors, or in the death throes of a star– in the supernova stage.

Stars as Parents:
Surviving a Violent Nursery

- **Stars and supernovae are the original recyclers: they continuously return energy, and substantial amounts of material and new chemical elements to the interstellar gas, from which new stars form.**

- **Over their lifetimes, the Sun and other stars are extremely stable in their average light production. But, over short timescales, they are also dynamic entities that strongly influence their environments. Our lives are directly impacted by e.g., solar flares, sunspot activity, and the solar wind (creates the aurora borealis).**

- **Stars provide the conditions and elements required for life as we know it on Earth. But they also frequently hinder and entirely disrupt the formation of other stars or proto-planetary disks near them, through their copious radiation, expelled material and explosive deaths.**

Favorable conditions seem to be rare enough, that in some basic physical sense, we really ARE lucky to be here!

The Frontiers of Cosmology and Stellar Evolution

THEORY:

- A model of supernovae that succeeds in getting them to blow up, as they clearly do in nature!

- Modelling detailed structure and evolution of primordial stars.

OBSERVATIONS:

- Search for a metal-free star: these must have formed at some point in the past, but they have not been found to date in our galaxy or in the distant universe. Theorists speculate that perhaps the first stars are very different from present day-stars: perhaps they were very massive, so that their lives were extremely brief. Role of James Webb Space Telescope in discovering these.

- First extrasolar planet discovered in 1995. Today, about 110 planets are known outside our solar system, with masses ranging from 35 to 5600 Earth masses. See http://exoplanets.org/ for latest updates and status of current planet searches. Future goals include finding Earth-sized extrasolar planets and the environments in which they occur.

• **Extraterrestrial Life and Astrobiology: origin and sustenance of life. Our Sun is an average star, and carbon is a very common and versatile element. Life may arise from ordinary chemical reactions, given the right conditions. BUT: Commonness of life materials does not guarantee commonness of life (recall complexity and orderedness issues).**

• **Search for Extraterrestrial Intelligence (SETI): recently exceeded 1 million hours of searching the sky! If and when it happens, communication with an alien civilization could (we hope!) advance our technology and social structure by 100s or 1000s of years into the future.**

The Big Picture

Some Historical Notes:

• Rapid developments in the studies of atomic structure and subatomic particles from nuclear physics led to the astrophysical understanding of what makes stars shine. This beautifully illustrated the connection between microscopic processes and the macroscopic conditions that are necessary for our lives.

• Paradoxically, it also led to the development of atomic bombs, which dramatically increased our capacity to end life.

Connections to Cosmology:

• The attempt to understand the energy source of stars reveals important clues about the creation of the universe. First, we have seen that the Sun's central temperature is about 15 million degrees, at which temperatures only hydrogen can be burned. Therefore, in order to be stable for over 3 billion years, the Sun must be made up of mostly hydrogen. Second, studies of the Sun's corona (at about 2 million degrees) first revealed emission lines from an element unknown on Earth at the time. Helium is rare on Earth but is the second most simple and abundant chemical element in the universe. Finally, no stars or pockets of galactic gas have been found with helium abundances ranging outside of 23–28%.

These all point to the universe having gotten not too far with making elements before the first stars and supernovae.

- **The general predominance of hydrogen and helium that is currently observed implies by itself that the universe had an extremely hot beginning, since matter prefers to be in simple elements rather than large complex ones at high temperatures.**

- **Looking at light from distant objects is equivalent to looking back in time, because of the time that it takes light to travel across space from its source. Since carbon is made primarily by stars which live longer than about a billion years, we can deduce that no carbon-based lifeforms are possible before the current observational edge of the universe in UV/optical light, when universe's age $\sim$ 1 billion years old.**