Chapter 21:
Stellar Explosions

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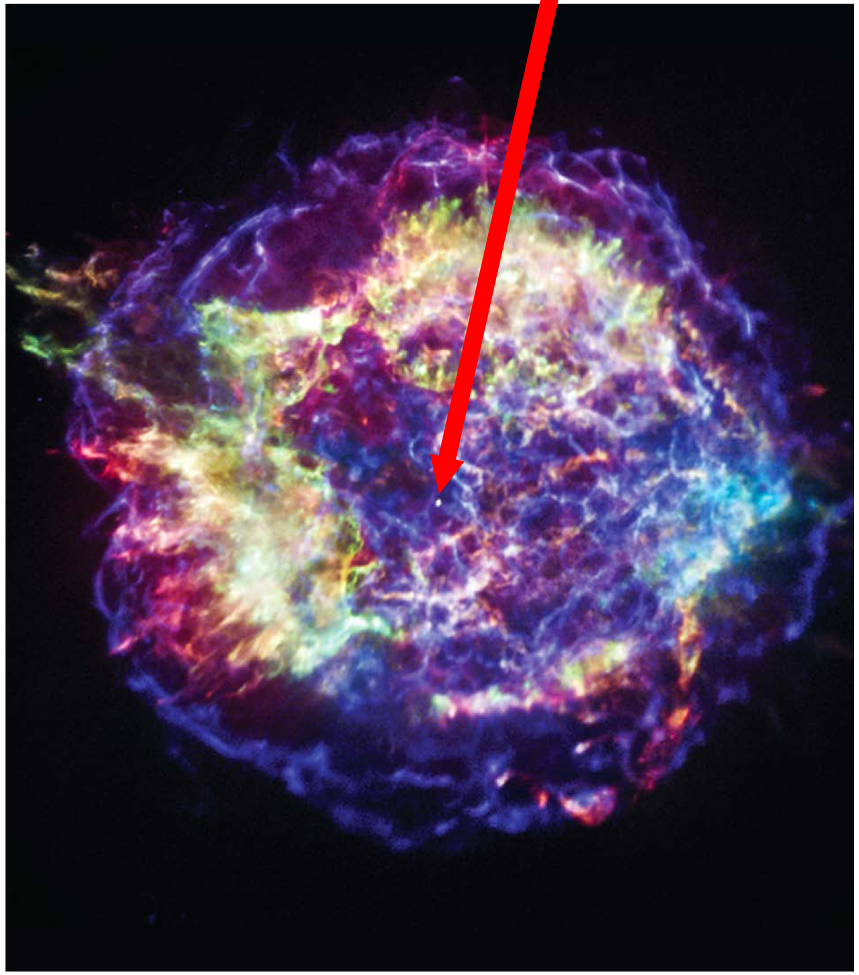
What are Stellar Explosions?

- When stars above a certain mass die (run out of fuel at their core), they will *literally* explode in **novae**, **supernovae**, or **hypernovae**
- The explosions "blows away" some of the star, leaving a **stellar remnant**, which can be:
  - A white dwarf
  - A neutron star
  - Or a black hole

Stellar remnant, probably a neutron star.

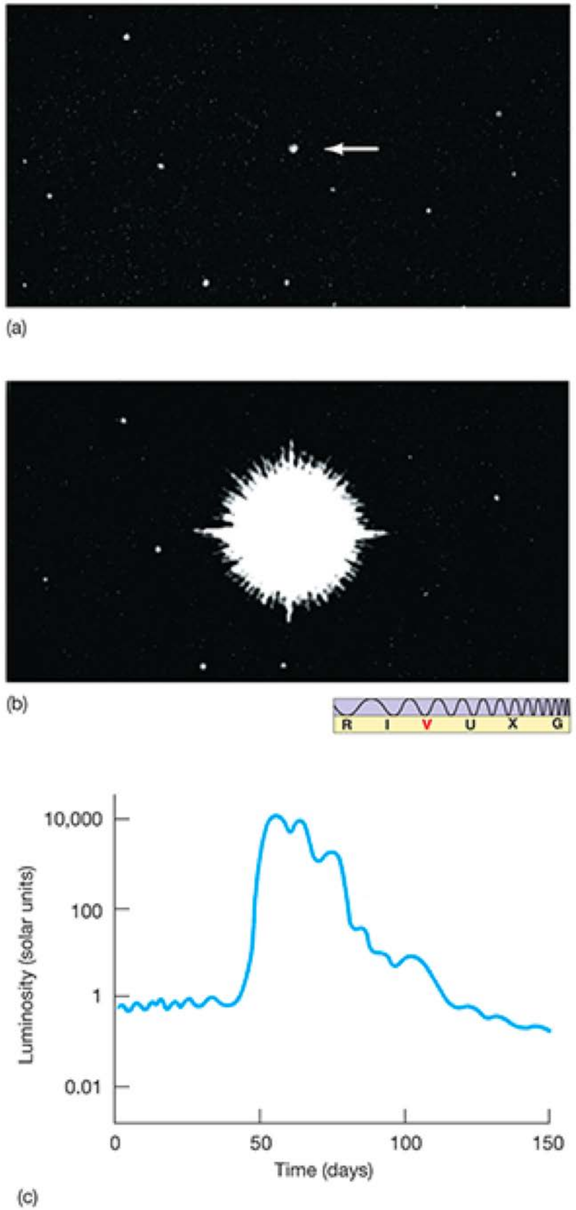


Stellar and Remnants Masses

- Stars with a (main sequence) mass $< 8M_\odot$ will eventually become white dwarfs.
  - White dwarfs have a remnant mass $< 1.4M_\odot$, known as the **Chandrasekhar limit**.
- Stars with a mass $< 25M_\odot$ will eventually become neutron stars.
  - Neutron stars have a remnant mass $< 3M_\odot$, known as the **Tolman-Oppenheimer-Volkoff (TOV) limit**.
- Stars with mass $> 25M_\odot$, or remnant mass $> 3M_\odot$, become black holes.
- What a star becomes is **determined by the remnant mass**; remnant masses trend with main sequence masses, but they're the decider.
  - A star with a very large mass can have a dramatically lower remnant mass after a stellar explosion, if the explosion blows away much of the star's mass.

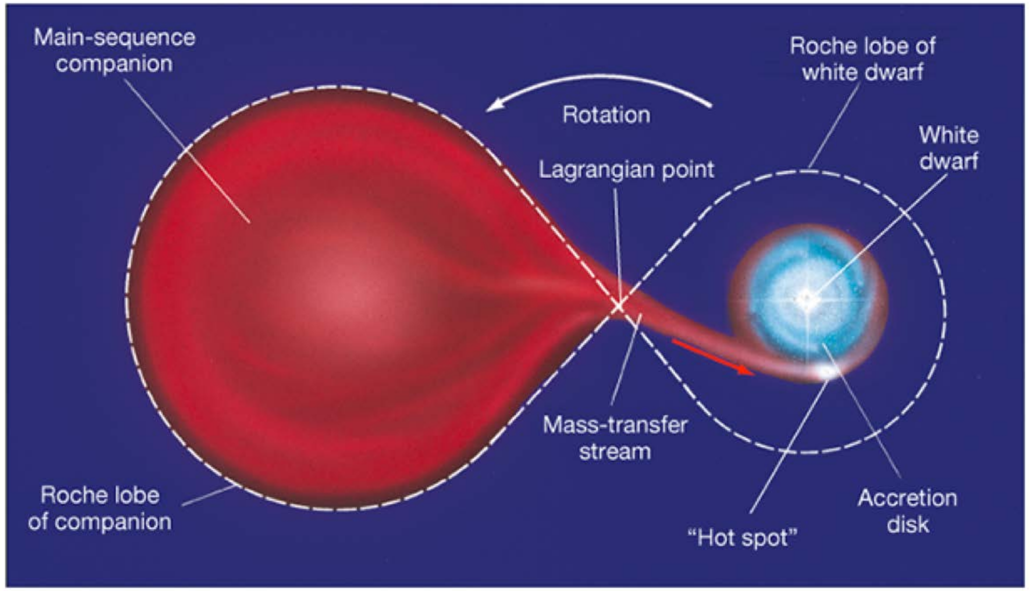
Novae and White Dwarfs

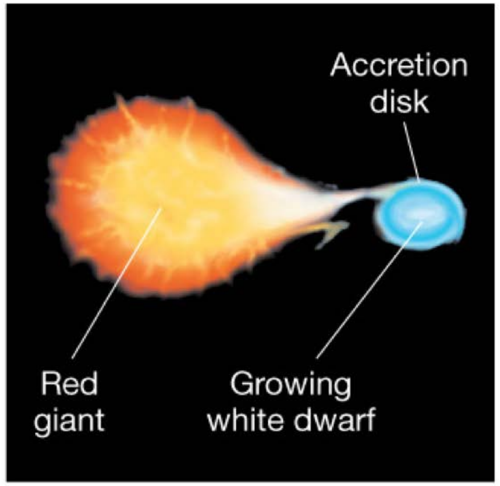
- **Very little mass is ejected** by a nova, so it will not affect the type of stellar remnant left behind (which will invariably be a white dwarf.)
- Novae can increase brightness by 10,000 times.
- Some novae repeat themselves, becoming what are called **recurrent novae**.

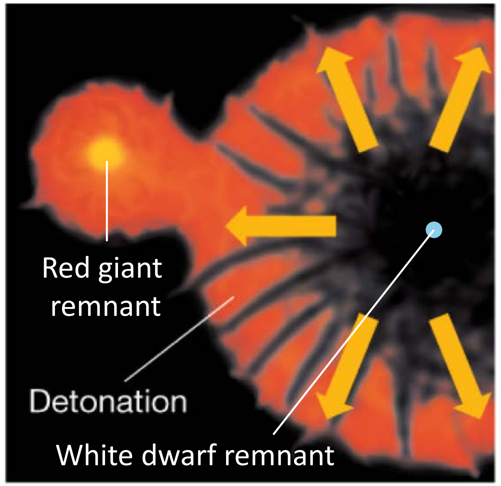


Mechanism of Nova Production

- Novae occur in **binary systems** between a red giant and a white dwarf.
    - White dwarf is formed by planetary nebula.
    - Novae don't produce white dwarfs.
- White dwarf accretes gas from red giant.
    - This gas "parked" in the accretion disk gets really hot, eventually hot enough to spark hydrogen fusion.
    - The sudden fusion increases brightness dramatically, blowing away accretion disk.
    - This process can repeat itself until the red giant runs out of gas: a recurrent nova.







Nova Summary

White Dwarf
+
Red Dwarf

$\xrightarrow{\text{Leads to}}$

Nova

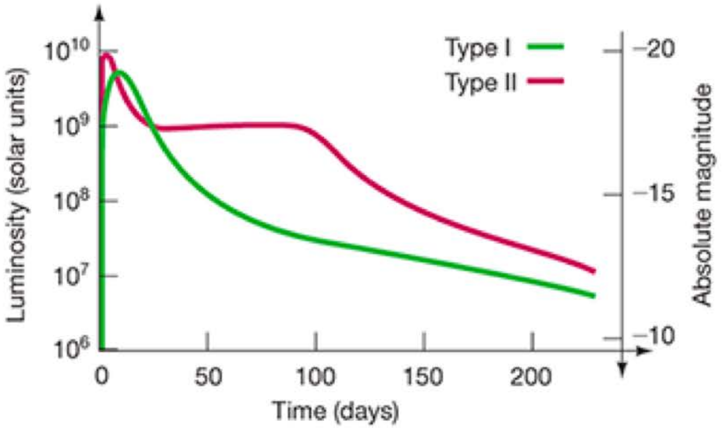
$\xrightarrow{\text{Leaves Behind}}$

White Dwarf
+
Red Dwarf

Nova vs. Supernovae

- A nova can get 10 thousand times brighter than the star, but a supernova can get 10 **billion** times brighter (a million times brighter than nova).
  - Supernova can be as bright as galaxies.
- A star may become a recurrent nova, but a star will only ever supernova **once**.
- There are **two types of supernova**, distinguished by their emission characteristics. The graphs to the right are known as **light curves**.
  - Type I are critically important in the study of cosmology because they have predictable light curves.

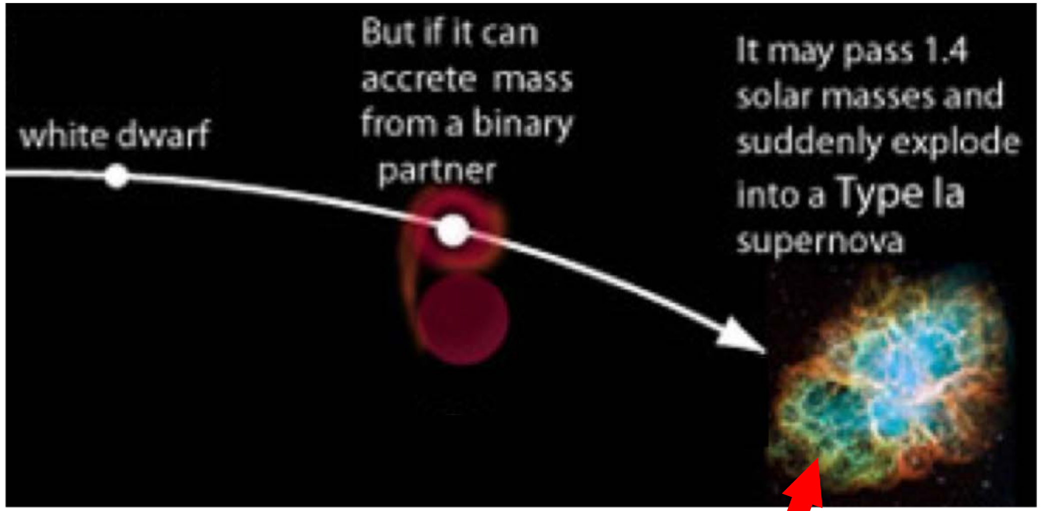
(a)



(b)

Type I Supernova

- Type I supernovae are *near-identical* to novae:
  - A white dwarf will accrete mass from a nearby red dwarf, triggering an explosion.
  - In novae, explosion from heating accreted matter to the point of hydrogen fusion.
- In a Type I supernova, the accreting white dwarf can actually accrete **too much mass**, putting it above the Chandrasekhar limit.
  - Rapidly, now too-massive star collapses, and carbon fusion occurs everywhere
  - This causes a massive explosion. These are also known as **carbon-detonation supernovae**. These are typically so violent that **no remnant remains**.



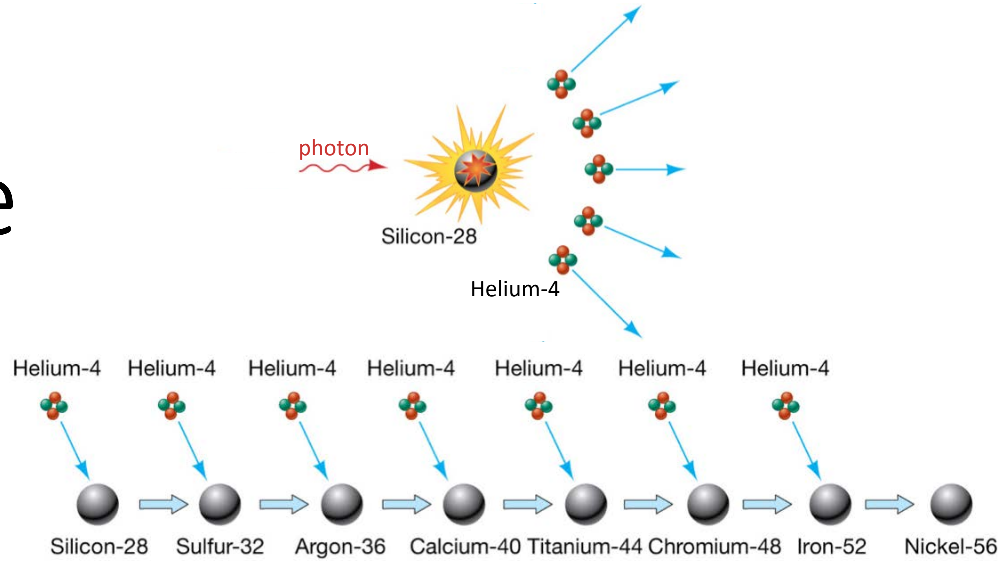
Actually a picture of a Type II supernova, but you get the idea.

Link Between Novae and Type I Supernovae

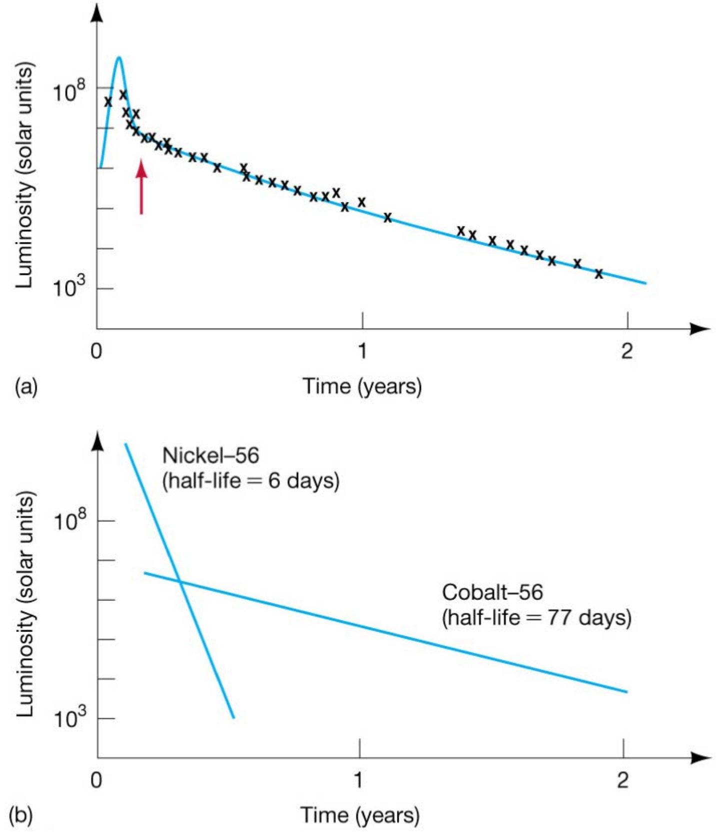
- Recall, a nova expels **very little mass** from a white dwarf.
- A recurrent-nova white dwarf will **grow in mass with each nova**.
- Eventually, the white dwarf will accumulate enough mass to grow beyond the Chandrasekhar limit, **igniting a Type I supernova**.

Recurrent Novae $\xrightarrow{\textbf{Leads to}}$ **Type I Supernovae**

Type I Supernova Light Curve



- Incredible heat allows photodisintegration and **alpha capture** of Si-28 to produce large quantities of Ni-56.
- Ni-56 is responsible for producing light-curve:
  - As Ni-56 builds up, the curve is initially very bright.
  - Ni-56 decays to Co-56 with a half-life of 6 days
  - Co-56 decays to Fe-56 with a half-life of 77 days, resulting in a stable, iron core.
- The explosion of the white dwarf, which has almost no hydrogen, means spectrum is **hydrogen-poor** (weak hydrogen lines).



Becoming a Neutron Stars

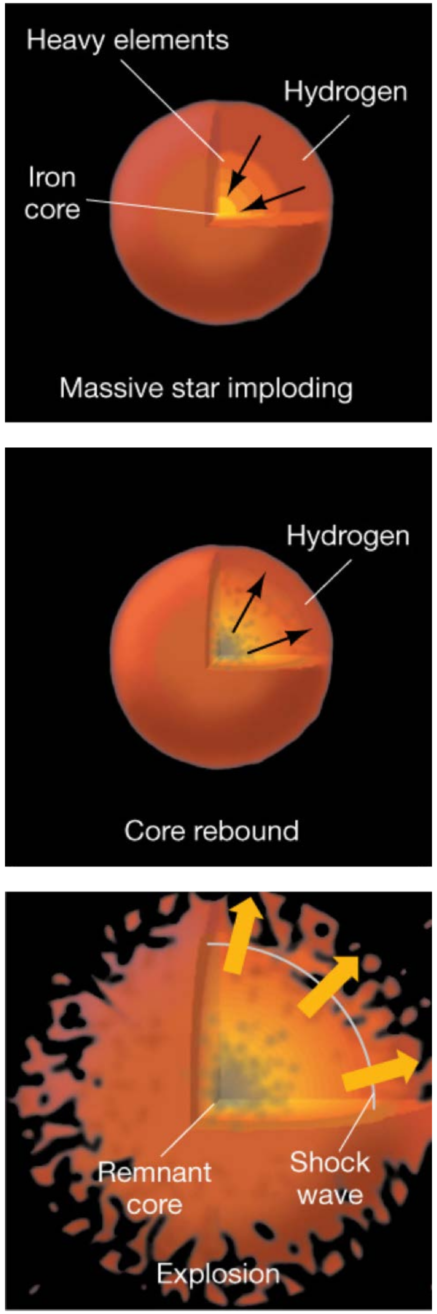
- Once the core runs out of fuel, it will collapse. If it’s mass is too large, it will collapse beyond the support of electron degeneracy pressure.
  - At this point, the star will be extremely hot, allowing for **photodisintegration of all nuclei into protons and neutrons**.
  - The temperature is also high enough for **electron capture**, the reverse of beta decay

$$p^+ + e^- \rightarrow n + \nu_e$$

  - This rapidly converts all protons in the gas to neutrons, known as **neutronization**.
- If the resulting mass is low enough, the neutron degeneracy pressure will prevent it from collapsing further. This is known as a neutron star.

Type II Supernovae

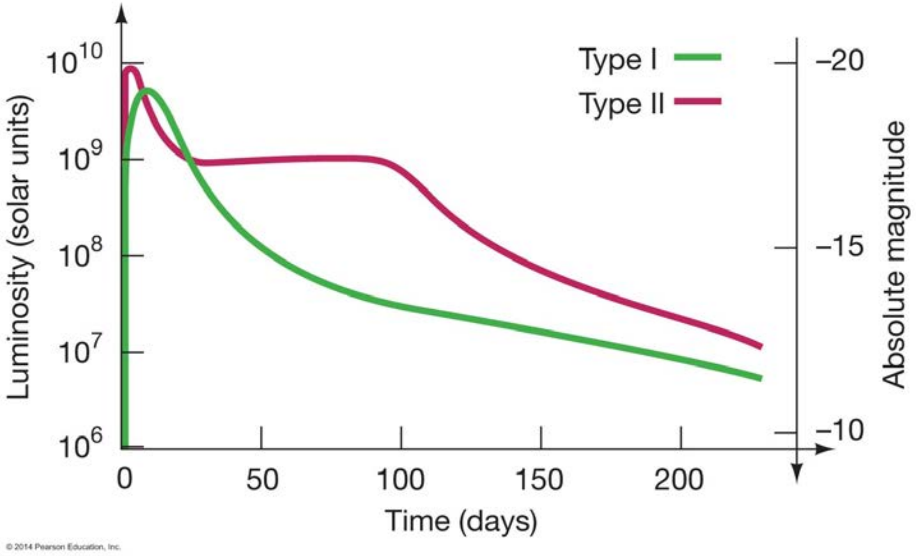
- As a high mass star collapses, and all its nuclear material becomes neutrons, the outward neutron degeneracy pressure becomes very large, resisting any further collapse of the star.
  - However, the star is **already** moving in that direction, and it can’t stop instantly!
  - The momentum of the star carries it **past** the radius it should have been, given the neutron degeneracy pressure, so the star violently pushes back.
  - The explosion also **crushes the core** to a neutron star or black hole, depending on the remnant mass.
  - This violent push-back is a type II supernova, also known as an **implosion-explosion supernova**, or a **core-collapse supernova**.



Type II Supernova Light Curve

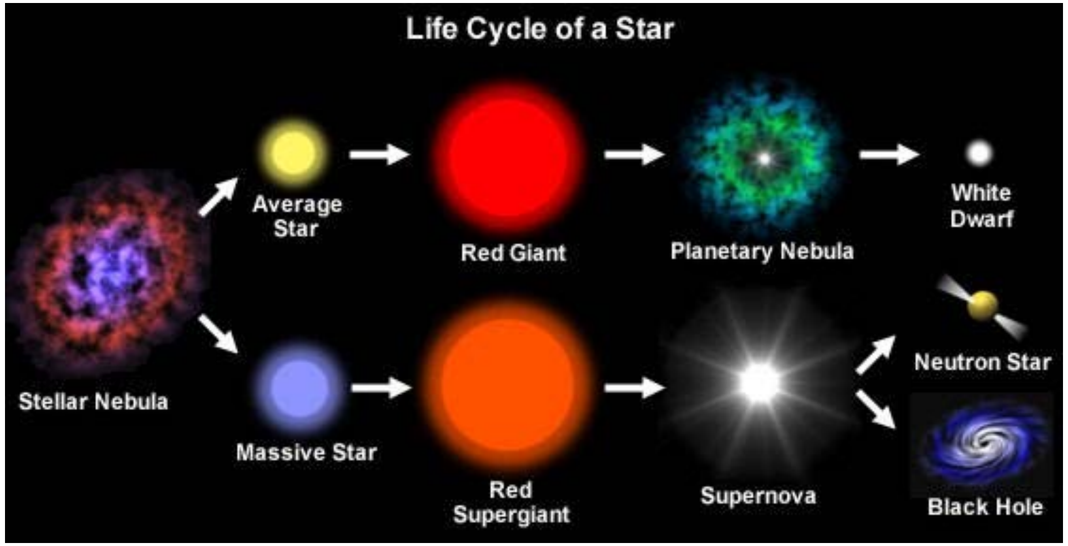
$$L = 4\pi R^2 \sigma T^4$$

- Remember Stefan-Boltzmann law!
  - Radius rapidly increasing with shock wave
  - Temperature rapidly decreasing with expansion
  - Luminosity is overall constant, hence the plateau, which **occurs during the expansion**
  - The **initial peak** is due to the incredible temperatures reached when the star initially over-collapses.



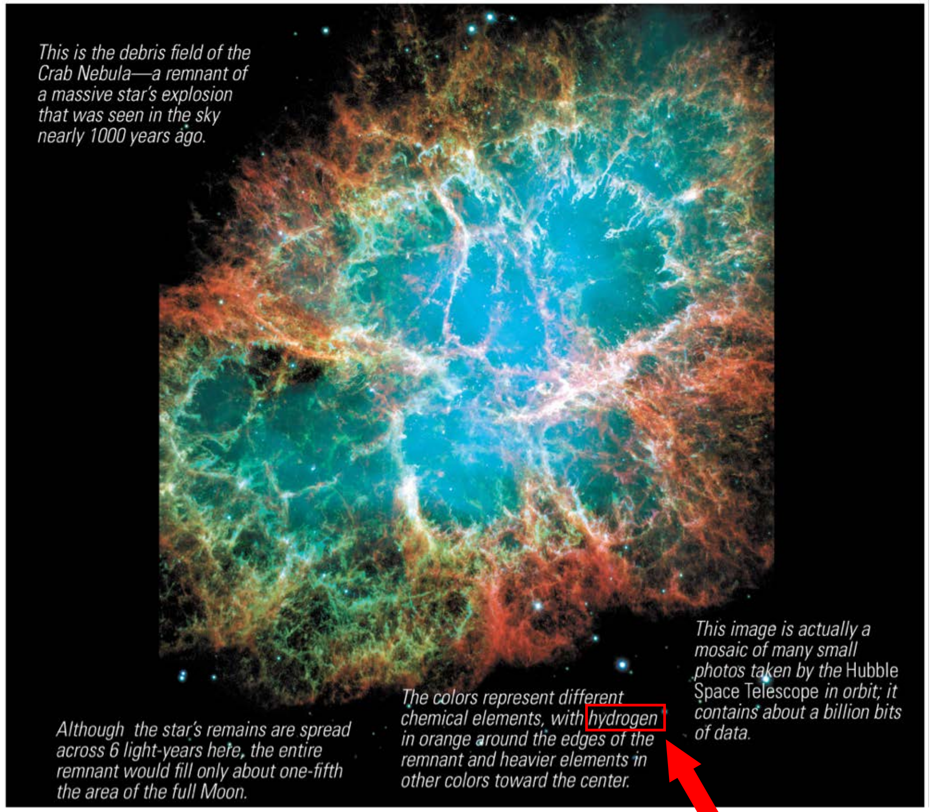
- Explosion contains much unburnt hydrogen, meaning spectrum of Type II supernova should be **hydrogen-rich** (strong hydrogen lines).

Summary of Explosions



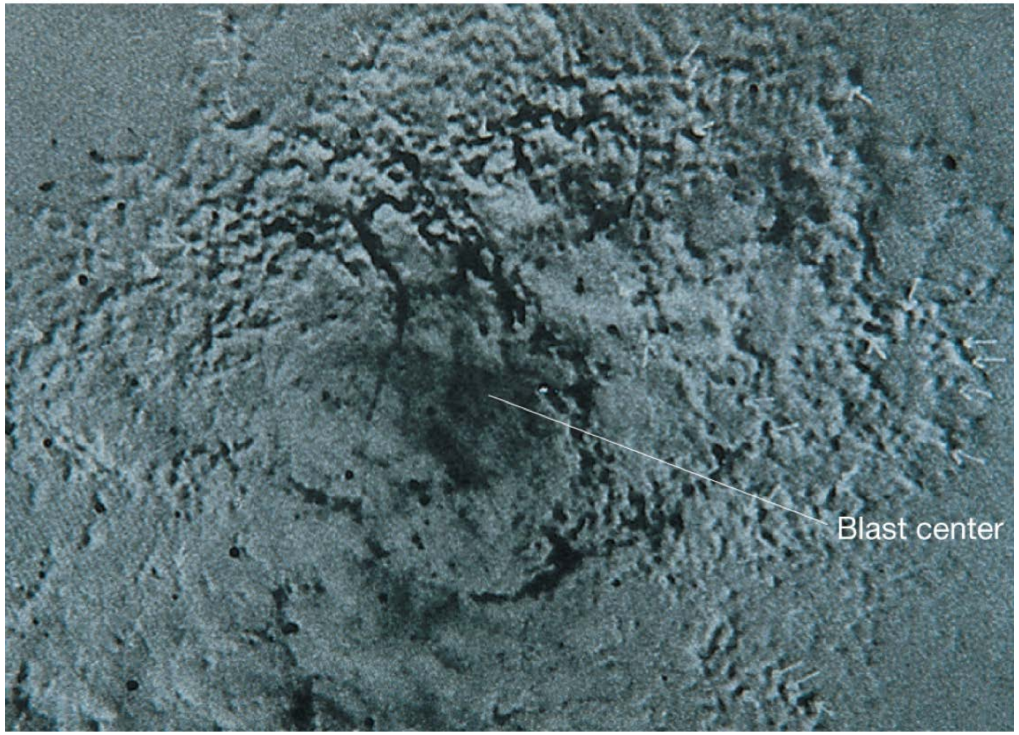
- **Novae** occur when remnant white dwarfs accrete gas from a red giant, heating the gas to spark fusion and blowing the gas away. Novae can become recurrent, leading to more-and-more mass accumulating on the white dwarf.
- This can lead to **Type I supernovae**, in which the white dwarf's mass exceeds the Chandrasekhar limit, it collapses until carbon detonates, and then it violently explodes. These are hydrogen-poor.
- **Type II supernovae** occurs due to over-collapse, causing neutron degeneracy pressure to push-back on the envelope of the star, causing a dramatic explosion. These are hydrogen-rich.

Example of Supernova: Crab Nebula



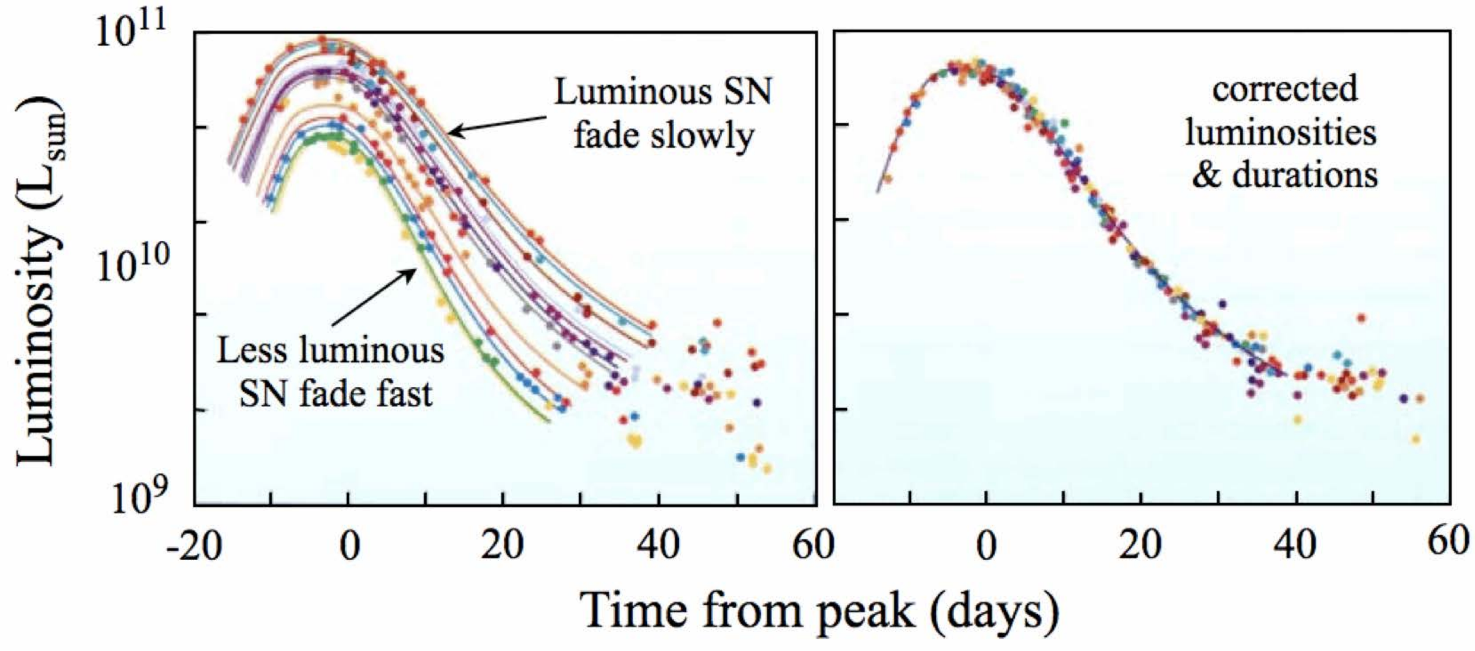
Hydrogen-rich → Type II

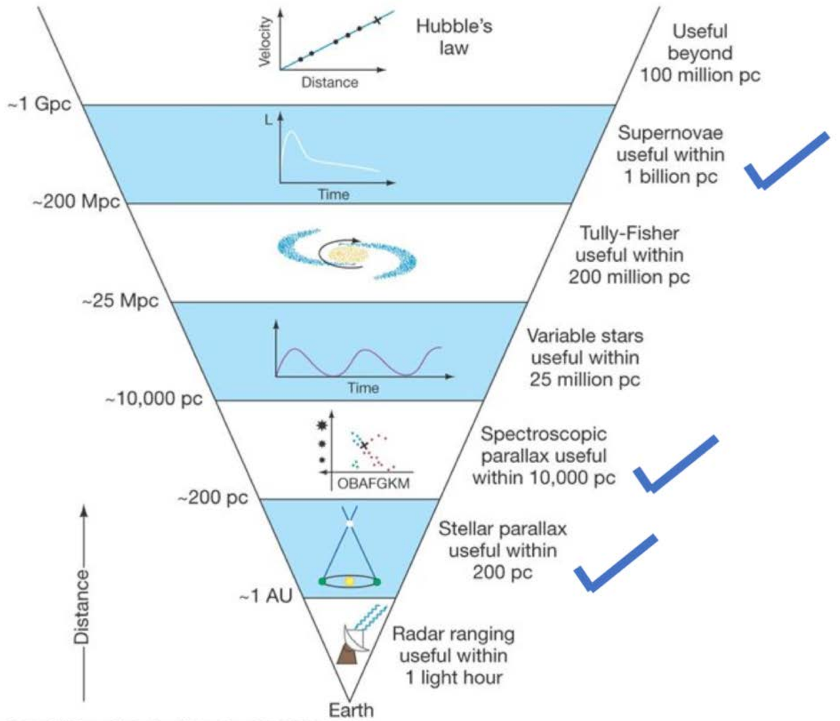
Positive photo (white) and negative photo (black) superimposed. Arrows indicate lack of overlap, meaning the nebula is still expanding.



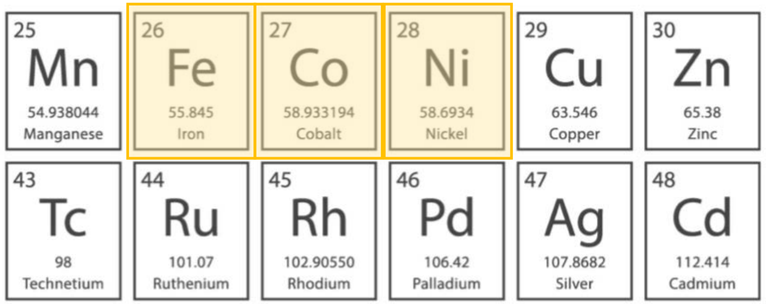
Type I Supernovae and the Distance Ladder

All Type I supernova are caused by Ni-56 and Co-56 decay, so all can be calibrated for brightness. This allows us to know how bright a supernova *should be*, and comparing that with how bright appears to be allows us to calculate distance.

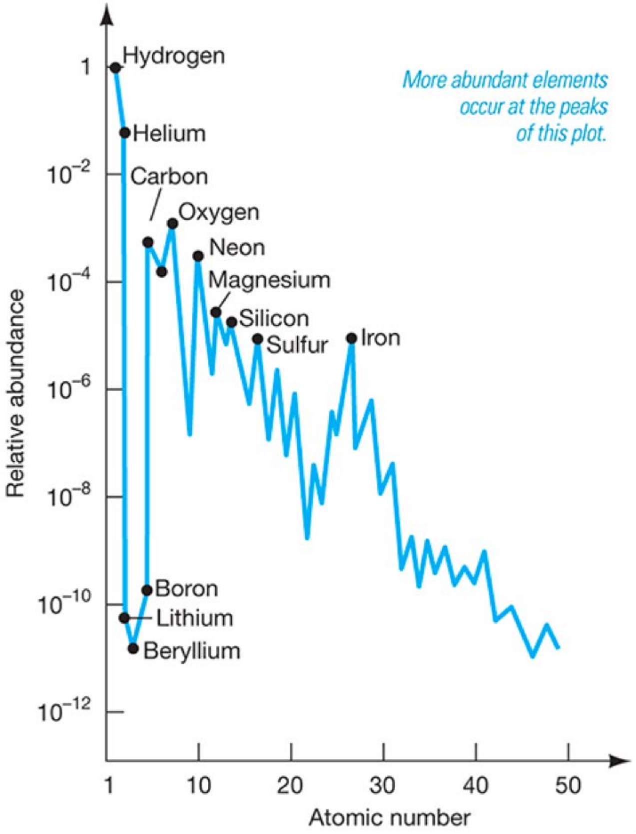




Elements Beyond Iron

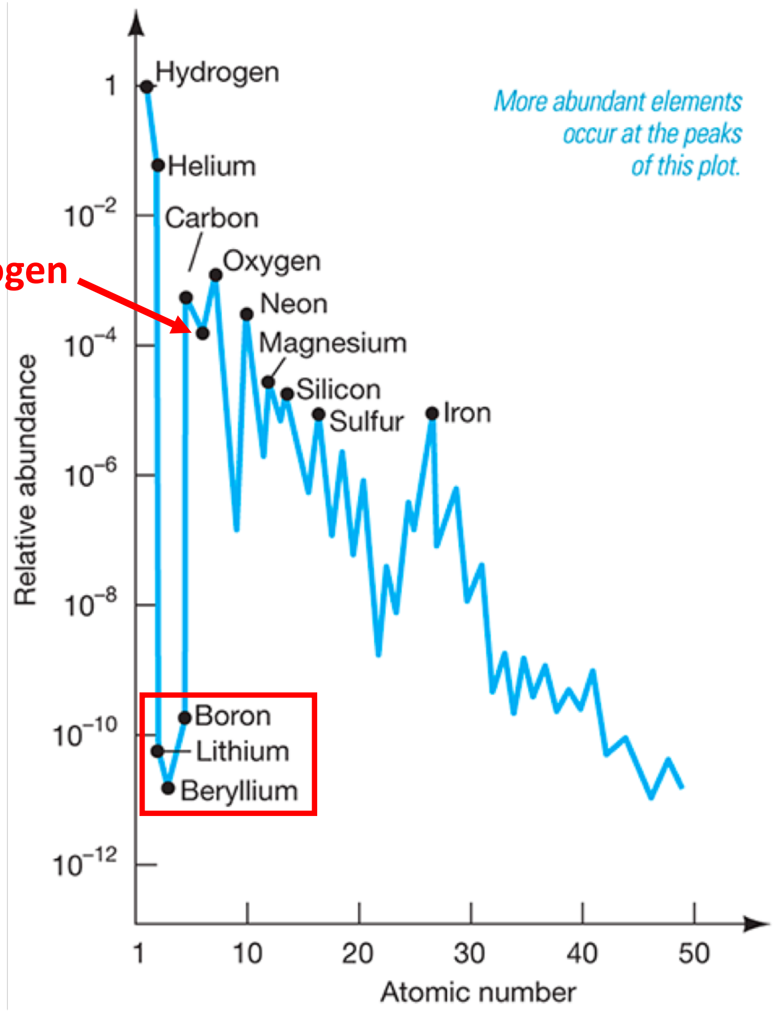


- Remember! Ni-56 in heavy stars, decays to Co-56, which decays to Fe-56.
- Photodisintrigration produces many free neutrons. At high temperatures of a **collapsing star**, nuclei can capture these neutrons.
  - Fe-56 captures a neutron to form Fe-57, which undergoes capture to form Fe-58, which undergoes capture to form Fe-59.
  - Fe-59 will decay into Co-59, which is stable, thus **cobalt has been produced**!
  - Co-59 will capture a neutron to form Co-60, which will decay into Co-60, which will decay into Ni-60, which is stable, thus **nickel has been produced**!
- This occurs one-at-a-time is very **slow**, so it’s called the **s-process**.

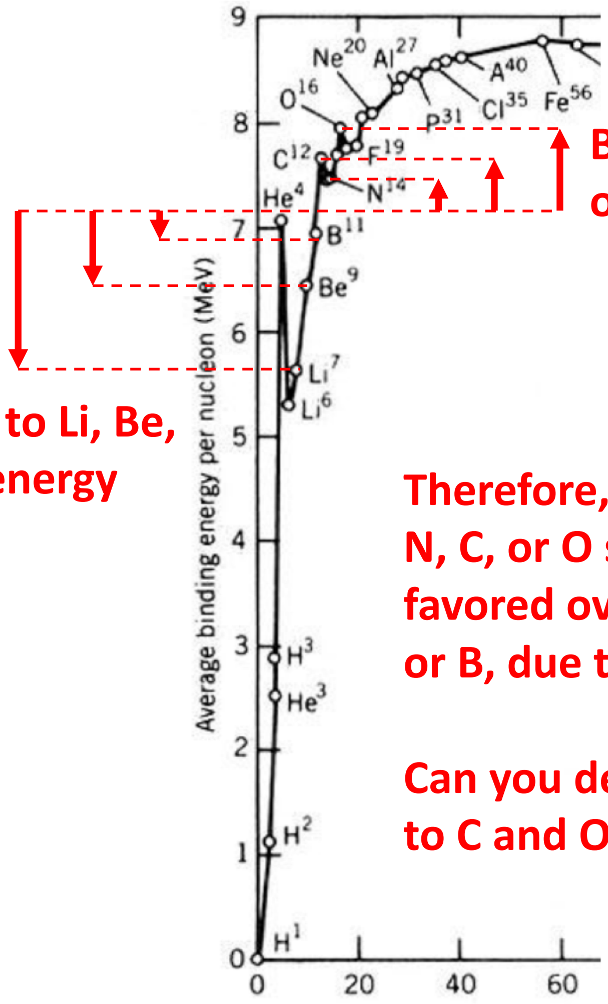


Question: Why is Li, Be, and B so Rare?

Nitrogen



To go from He to Li, Be, or B *requires* energy

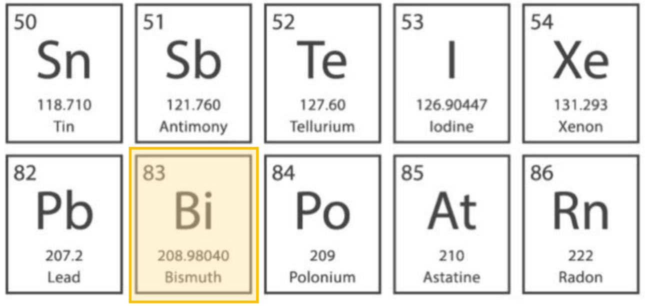


But, from He to N, C, or O *releases* energy

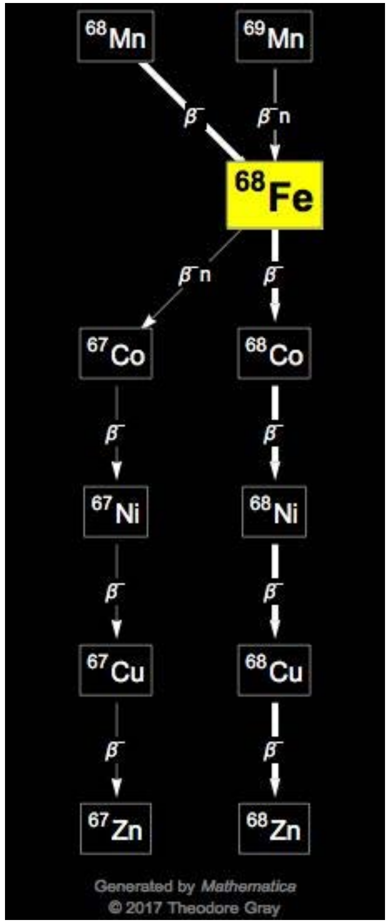
Therefore, the transition from He to N, C, or O should be dramatically favored over the transition to Li, Be, or B, due to energetic favorability.

Can you determine why, compared to C and O, N is less abundant?

Elements Beyond Iron (cont'd)

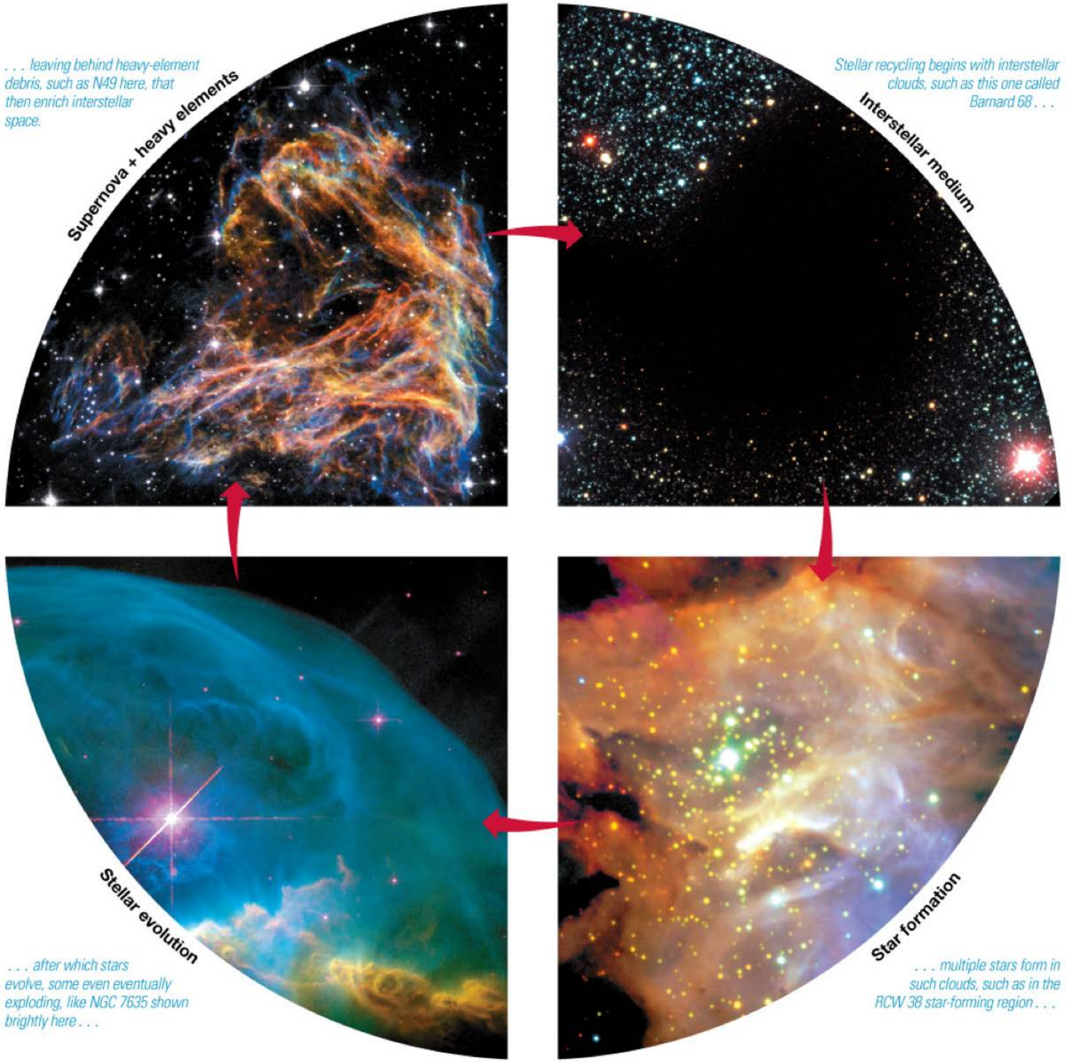


- The s-process allows for **production up to Bi-209**, the heaviest known stable nucleus, but not beyond it.
- When a star **explodes**, it releases so many neutrons that have such high energy, a single nucleus can capture multiple neutrons before there is enough time to decay.
  - In the s-process, Fe-58 capturing one neutron, decaying into Co-59, which captures one neutron, decaying into Ni-60, etc.
  - During an explosion, Fe-58 might be able to capture ten neutrons, decaying from Fe-68 to Co-68 to Ni-68 to Cu-68 to Zn-68, which is stable. (Zn-67 is also a stable end product.)
  - This occurs more **rapidly**, and is called the **r-process**.
- Heavy elements above Bi are produced by r-process.



Cycle of Stellar Evolution

4) Stellar explosions produce shock waves that are perfect for inducing star formation, and the cycle repeats itself.



1) Interstellar medium allows a gas cloud to fragment, initiating star formation in the region.

3) Stars spend their lives on the main sequence, eventually evolving off and dying.

2) Stars undergo the birth process after gas fragmentation is completed.