Compton Lecture #2: Where Stars Come From

- Welcome!
- On the back table:
  - Lecture notes for today's lecture
  - Extra copies of last week's are on the back table
  - Sign-up sheets – please fill one out if you're not already on the Compton Lectures mailing list

Stars: Their Life and Afterlife

Where Stars Come From

Brian Humensky

68th Series, Compton Lecture #2

October 11, 2008

- Congratulations to Drs. Nambu, Kobayashi, and Maskawa!
  - Yoichiro Nambu has been at the UofC since 1954
  - His work was key to developing the Standard Model and understanding superconductivity

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"


Photo: SCANPIX


Photo: Kyodo/Reuters


Photo: Kyoto University

Yoichiro Nambu	Makoto Kobayashi	Toshihide Maskawa
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA	Japan	Japan
Enrico Fermi Institute, University of Chicago Chicago, IL, USA	High Energy Accelerator Research Organization (KEK) Tsukuba, Japan	Yukawa Institute for Theoretical Physics (YITP), Kyoto University Kyoto, Japan
b. 1921	b. 1944	b. 1940

Outline

- Introduction: Key Properties of Stars
- Molecular Clouds as Stellar Nurseries
- Formation of Stars
- The Eagle Nebula
- Summary

Introduction

Key properties of the Sun and stars

The Sun – A Starting Point

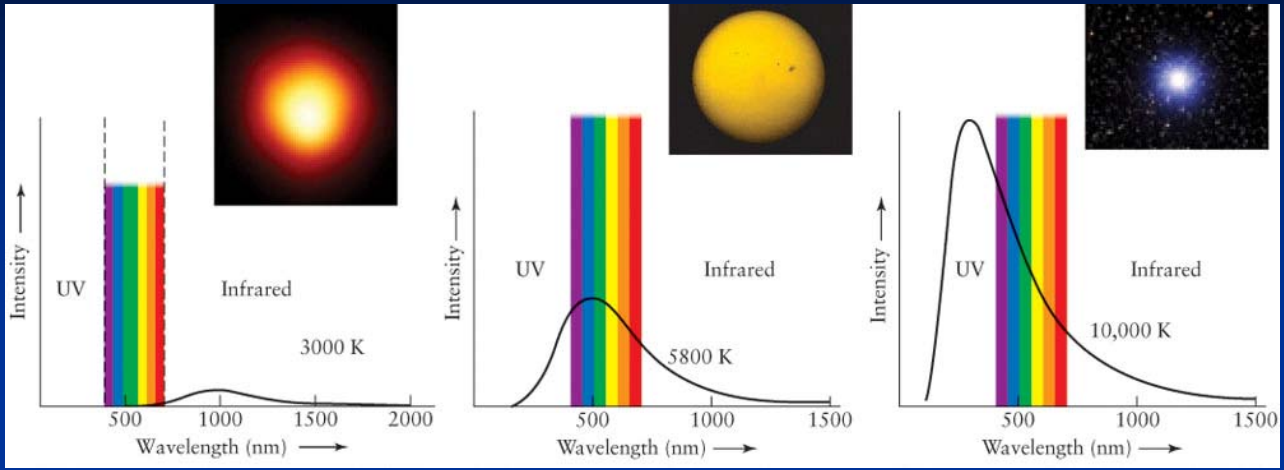
- A typical middle-aged Main Sequence star
  - average in mass, expected lifetime of ~12 Gyr (12 billion years)
- Powered by fusion of hydrogen into helium in its core

Mass	1.99×10^{30} kg = 1 $M_\odot$
Age	4.56 Gyr
Color	Yellow = G2 class
Temp	5800 K
Luminosity	3.85×10^{26} W = 1 $L_\odot$
Magnitude	-26.74 (vis) or 4.83 (abs)
Radius	6.96×10^{8} m

Stars Have Different Colors

- Some are distinctly yellow, others blue or red
- (sizes are an artifact of the star's brightness – they are not actually resolved!)

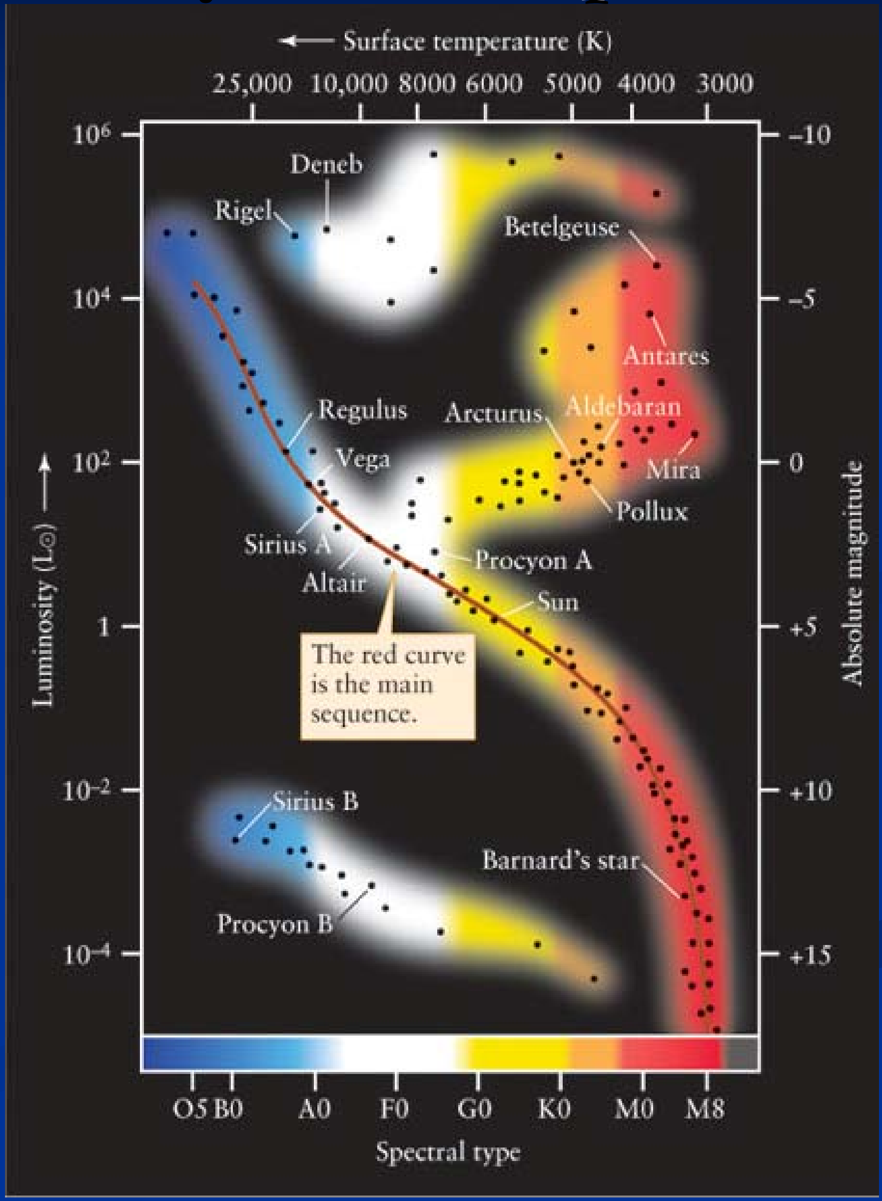
Color Arises from Surface Temperature



- All stars radiate with a spectrum that has a characteristic shape, a "blackbody" spectrum
- The peak wavelength depends on the star's temperature and is shorter (bluer) for hotter stars
- On the Main Sequence, a star's temperature and luminosity are set by its mass: more massive stars are both hotter and brighter
- Stars are assigned "spectral classes" according to their colors: the Sun is a class G star; blue stars fall in classes O and B and red stars in class M

Hertzsprung-Russell Diagrams Show the Relationship between Luminosity and Temperature

- The Main Sequence curves from lower-right to upper-left (cool/dim to hot/bright).
- Stars do NOT travel along the Main Sequence!
  - Their location on the Main Sequence is determined by their mass.
  - Stars form a "sequence" of colors/luminosity as a function of their mass.
- Note the enormous range of luminosities!
- Stars spend most of their lifetime on the Main Sequence.



Molecular Clouds as Stellar Nurseries

Molecular Clouds and the Interstellar Medium

- The Interstellar Medium (ISM) is the gas and dust that fills the spaces between stars.
  - SN 1006 is developing in this kind of medium.
- Various other states of gas pervade the galaxy.

Medium	Phase	State	Density (cm^{-3})	Temp (K)	Comments
Mol Clouds	Cold	H_2	>1000	10-50	SF Regions
H I Clouds	**Cold**	**H**	**30**	**100**	**Diffuse ISM**
Warm H I	**Warm**	**H**	**0.1**	**8000**	**Diffuse ISM**
Warm H II	Warm	H^+	0.03	10^4	Ionized
H II Regions	Warm	H^+	>100	10^4	Transient
Hot ISM	Hot	H^+	0.001	$10^{6.5}$	SNe shocks
SNRs	Hot	H^+	Varies	10^7	Dynamic

Molecular Clouds and the Interstellar Medium

- Star formation generally occurs in molecular clouds.
  - Short-lived massive stars can explode while still in or near cloud – as in the case of IC 443.

Medium	Phase	State	Density (cm^{-3})	Temp (K)	Comments
Mol Clouds	**Cold**	**H_2**	**>1000**	**10-50**	**SF Regions**
H I Clouds	Cold	H	30	100	Diffuse ISM
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Molecular Clouds and the Interstellar Medium

- Ultraviolet (UV) radiation from massive stars heats and ionizes nearby gas.
- Over several million years, stellar winds and supernovae expel this gas.

Medium	Phase	State	Density (cm^{-3})	Temp (K)	Comments
Mol Clouds	Cold	H_2	>1000	10-50	SF Regions
H I Clouds	Cold	H	30	100	Diffuse ISM
Warm H I	Warm	H	0.1	8000	Diffuse ISM
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Molecular Clouds and the Interstellar Medium

- Perhaps half the volume of the galaxy is filled with a very thin, very hot (several million degrees) gas produced by supernova shocks.
- The interiors of supernova remnants can be still hotter.

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SNRs	**Hot**	$\mathbf{H^+}$	**Varies**	$\mathbf{10^7}$	**Dynamic**

Molecular Clouds and the Interstellar Medium

- The Interstellar Medium (ISM) is a complex, dynamic environment.
- Let's focus on Molecular Clouds.

Medium	Phase	State	Density (cm^{-3})	Temp (K)	Comments
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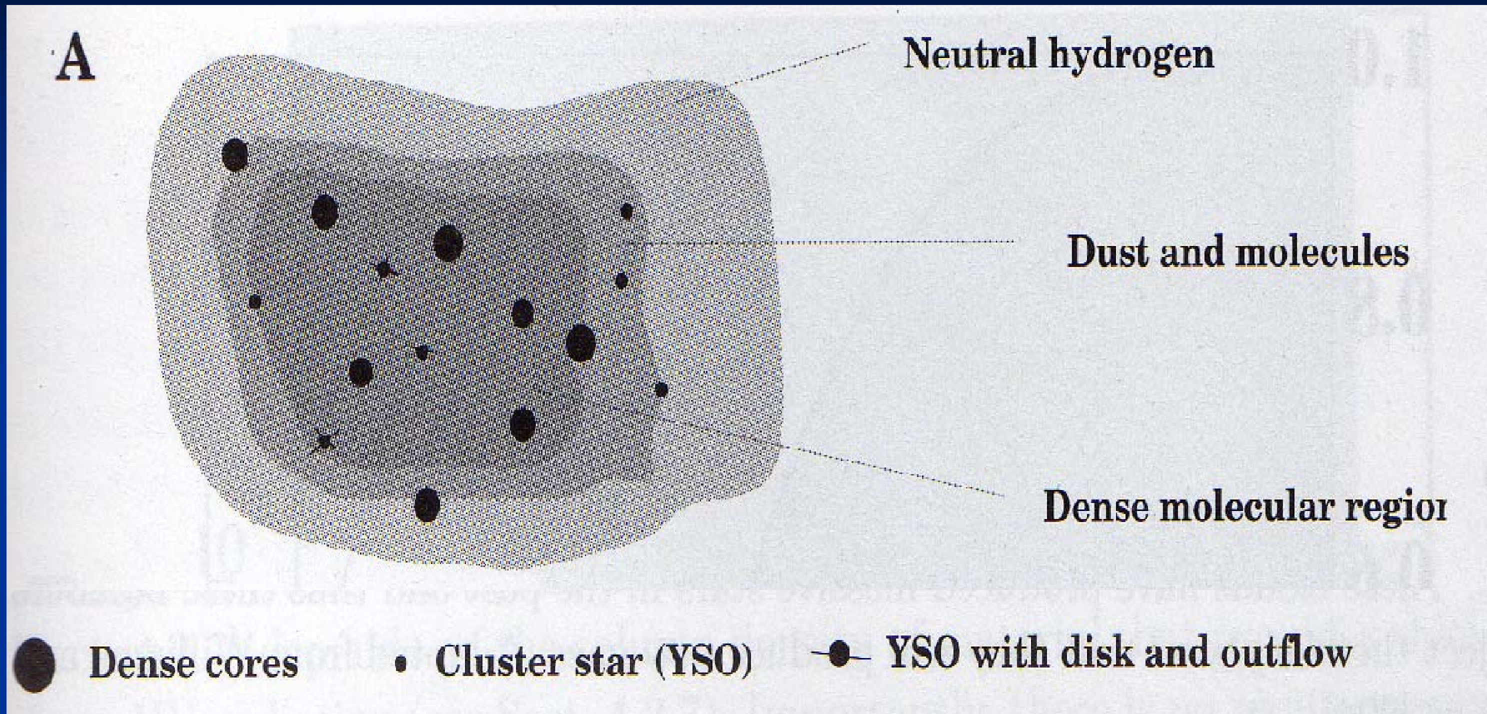
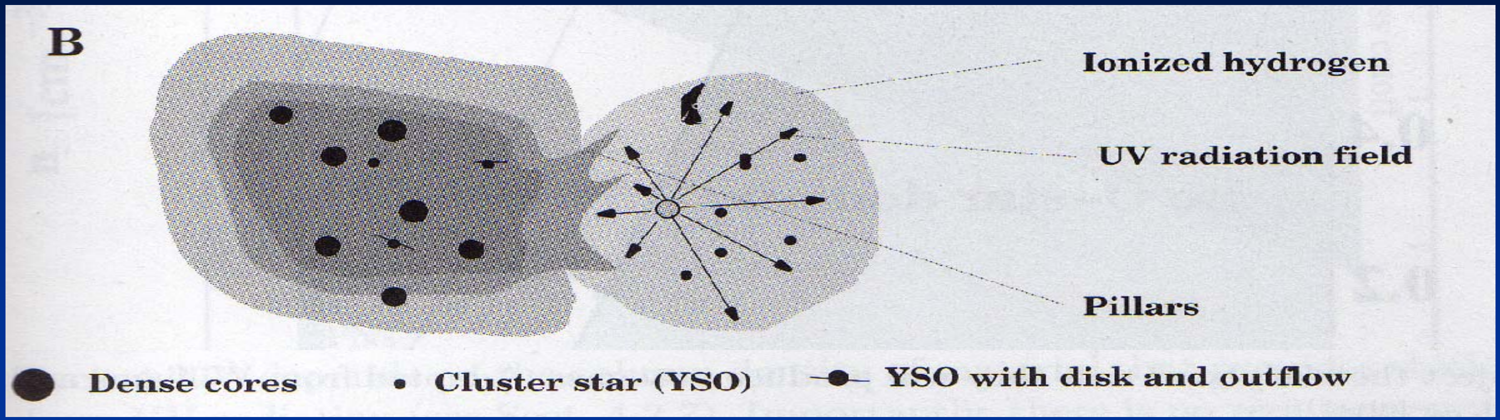
Phase A: Dense Cores in a Structured Cloud



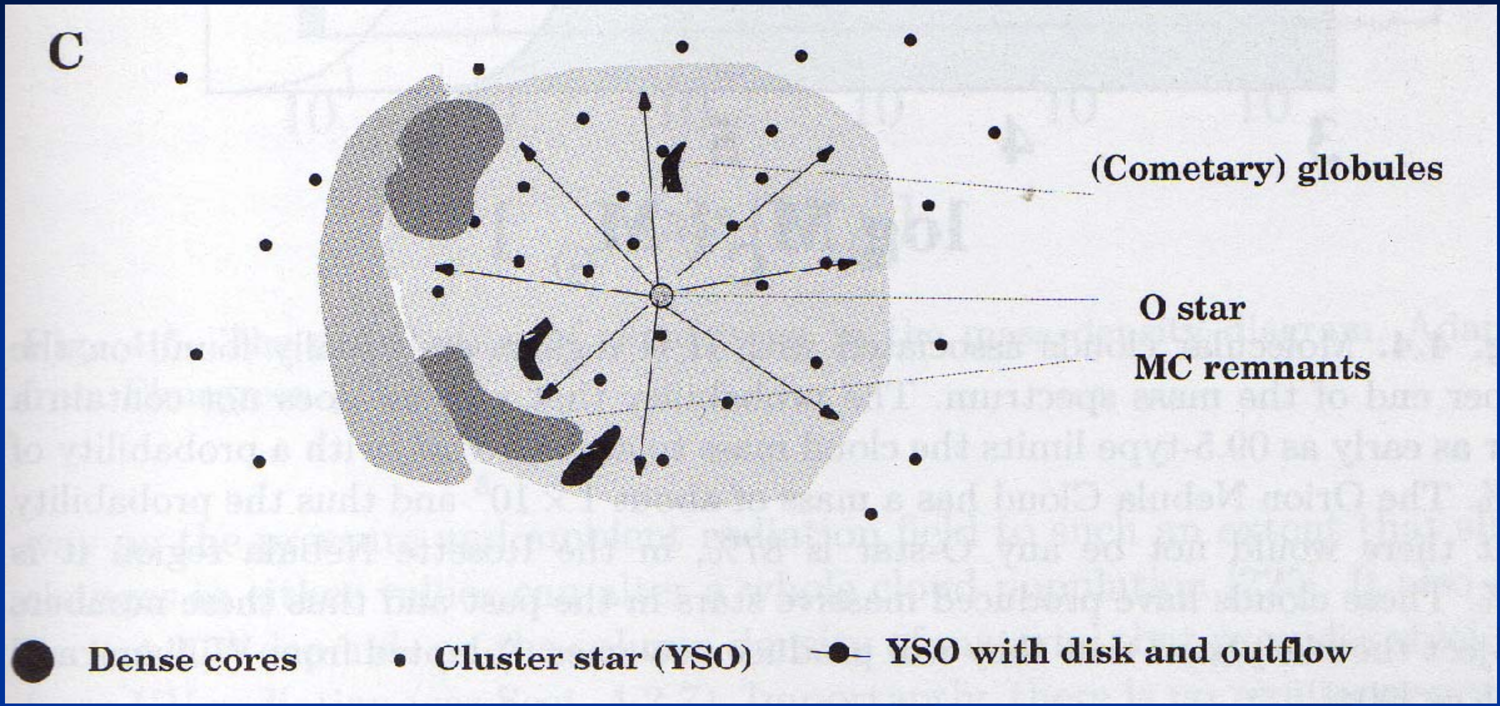
- H I shell protects against ionizing radiation.
- Cloud contains dense clumps and cores in a thinner background medium.
- Some clumps and cores will contract under gravity and begin to form stars.

Phase B: First Massive Star



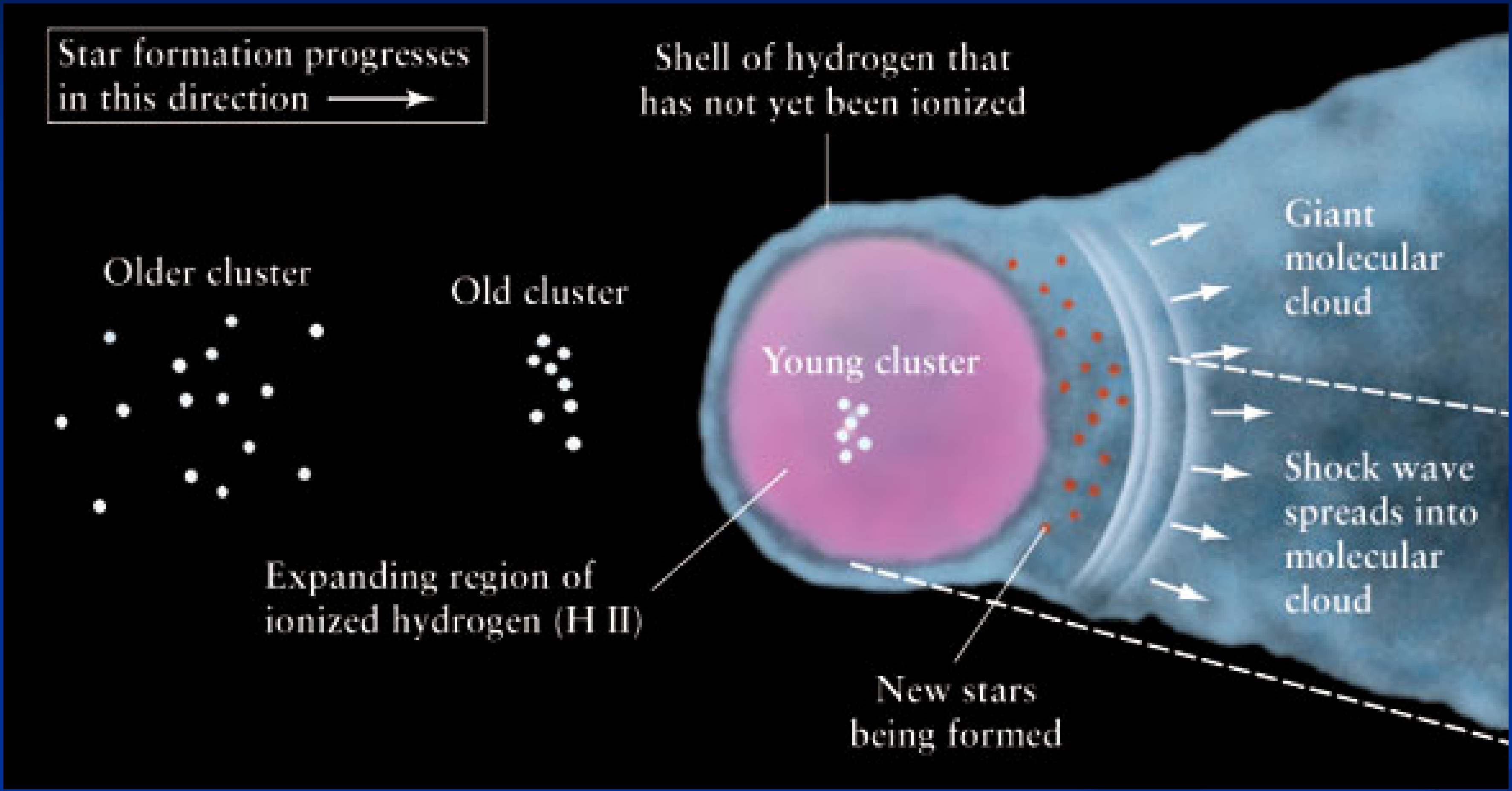
- Massive stars (Classes O and B) are the first to form.
- Blue stars – UV radiation.
- Nearby regions of MC begin to heat, ionize, evaporate.
  - Formation of an H II region.
- Clumpy nature of MC promotes formation of structures like pillars, filaments, cometary globules.

Phase C: Stars Expel MC Remnants



- O, B stars continue to ionize, evaporate MC and H II region grows.
- Smaller stars join Main Sequence.
- Fragments of MC and cometary globules remain for a time.

Sequential Star Formation in GMCs



Formation of Stars

From Dense Cores to Protostars

- Dense cores within molecular clouds have the high density ($10^2 - 10^4$ cm^{-3}) and low temperature (~10 K) needed to begin contracting into protostars.
  - Barnard objects contain a few thousand solar masses of gas and dust in a region ~ 30 light years across.
  - Bok globules are smaller, more spherical dense regions (few light years).

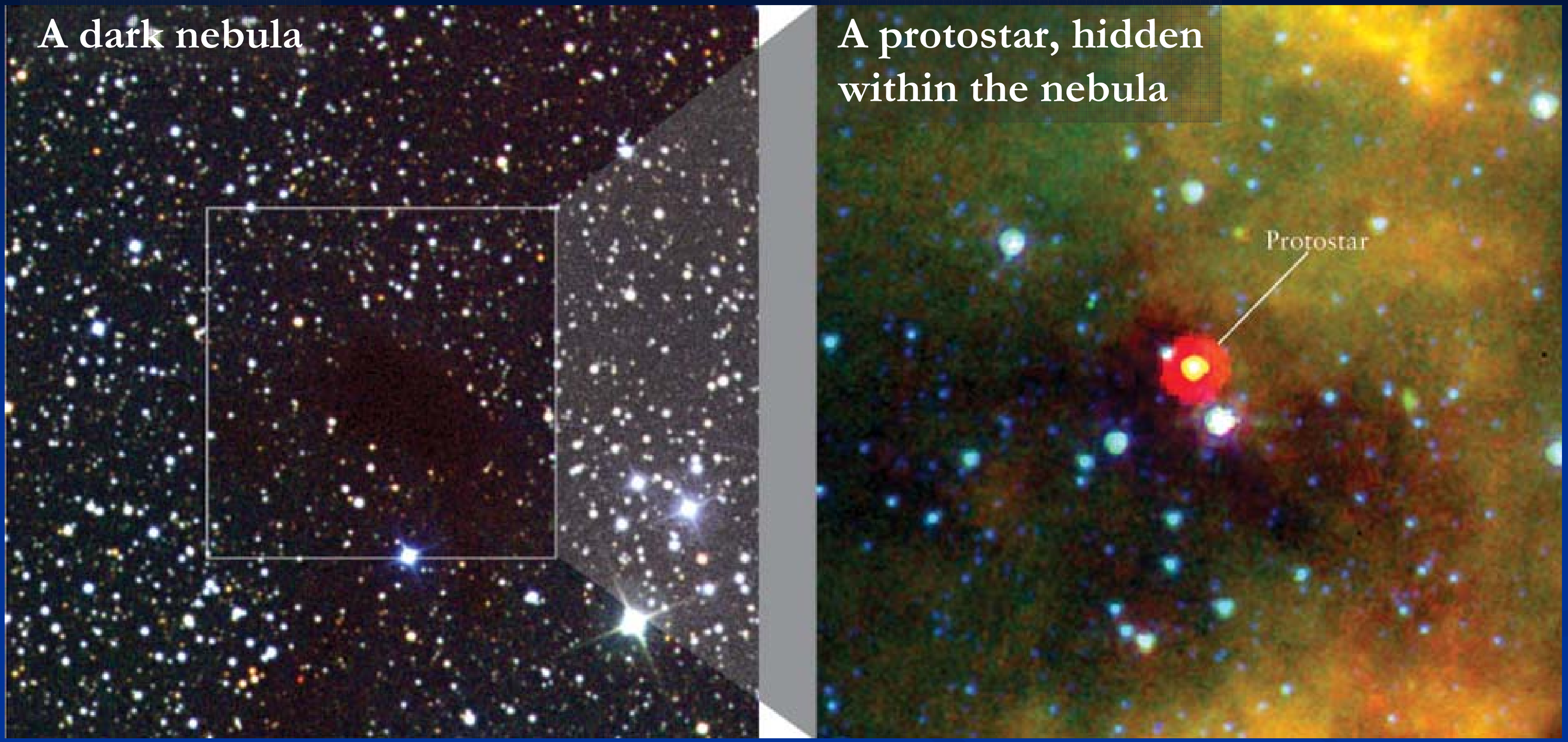
From Dense Cores to Protostars

- Densest regions of these cores are able to contract under gravity to form protostars.
- A single Barnard object can host many protostars, forming a stellar cluster.

Contraction, Heating, and Cooling

- Protostars tend to heat up as they convert gravitational potential energy into kinetic energy.
- Initially need to radiate this heat away – key role of dust in the early phases of the contraction.
- Rate of contraction depends strongly on mass – massive protostars can ignite hydrogen fusion in as little as 10^5 years but stars like the Sun take ~20 Myrs to ignite.
- After fusion ignites, stellar winds clear remaining gas away, revealing new star.

Protostars Would Be Bright If We Could See Them!



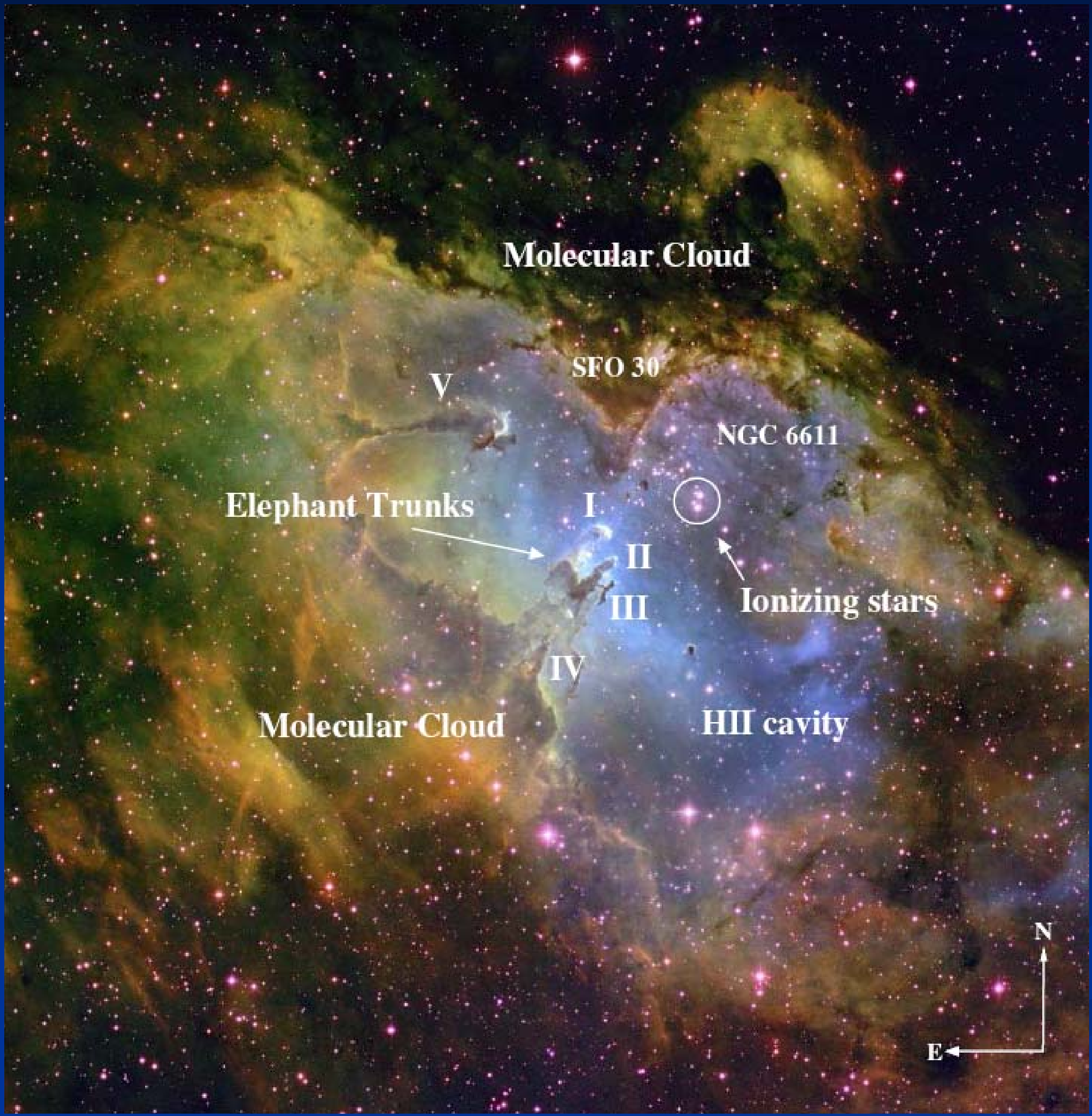
- Protostars form hidden inside dense nebulae – Bok globules.
- For a Sun-like star, after ~1000 years of contraction, surface heats to ~2000 – 3000 K.
- At this point it is 20 x larger than the Sun and 100 x more luminous!

Mass Limits of Main Sequence Stars

- The physical processes involved in forming and powering stars limit their masses to a range of ~ 0.08 – 200 $M_{\odot}$.
- Lower limit: Protostars below ~0.08 $M_{\odot}$ are unable to form high enough pressures and temperatures in their cores to ignite hydrogen fusion.
  - These "brown dwarfs" continue to radiate via Kelvin-Helmholtz contraction
- Upper limit: Protostars above ~200 $M_{\odot}$ build heat and pressure too quickly.
  - Unable to cool efficiently enough, the pressure increases until it overcomes gravity and the protostar blows up.

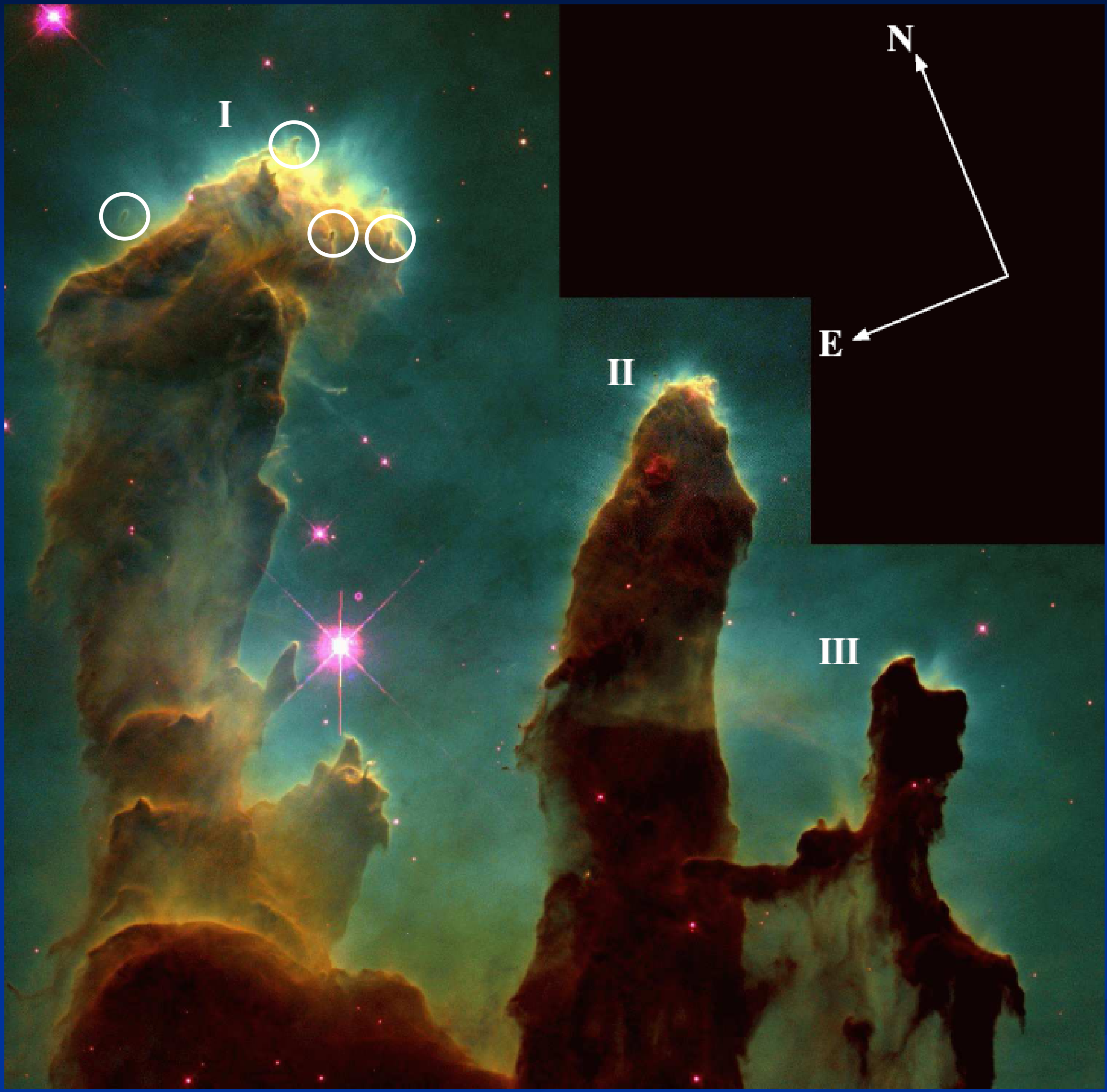
The Eagle Nebula

The Eagle Nebula



The Elephant Trunks

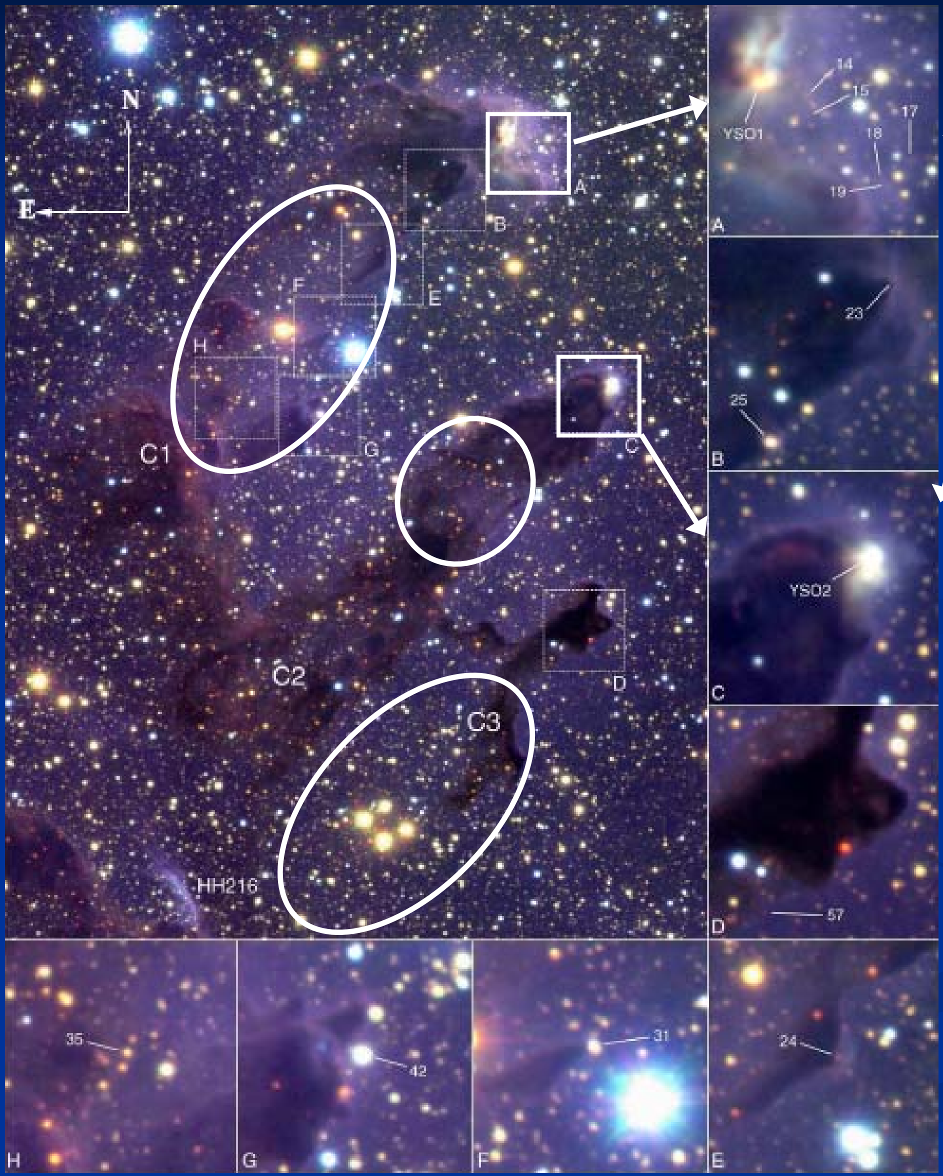
Evaporating Gaseous Globules (EGGs), some harbor protostars



Columns look solid, but…

Elephant Trunks in the Near IR

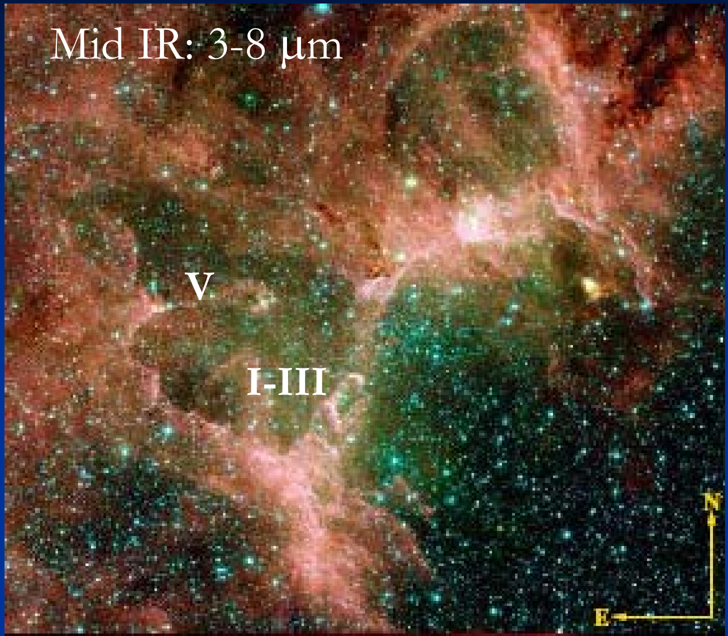
- Most of the trunk material is in the caps
  - Can see through trunks along much of their length

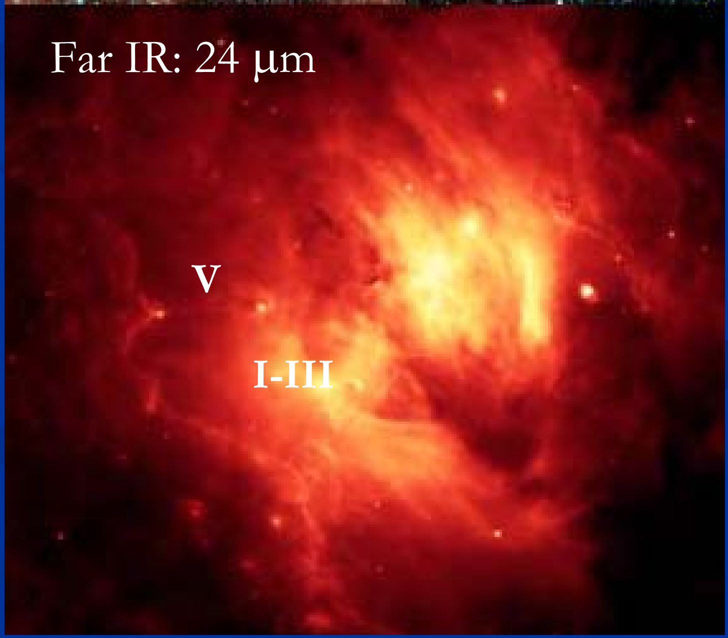


Young stellar objects forming in the dense cores of trunks I and II

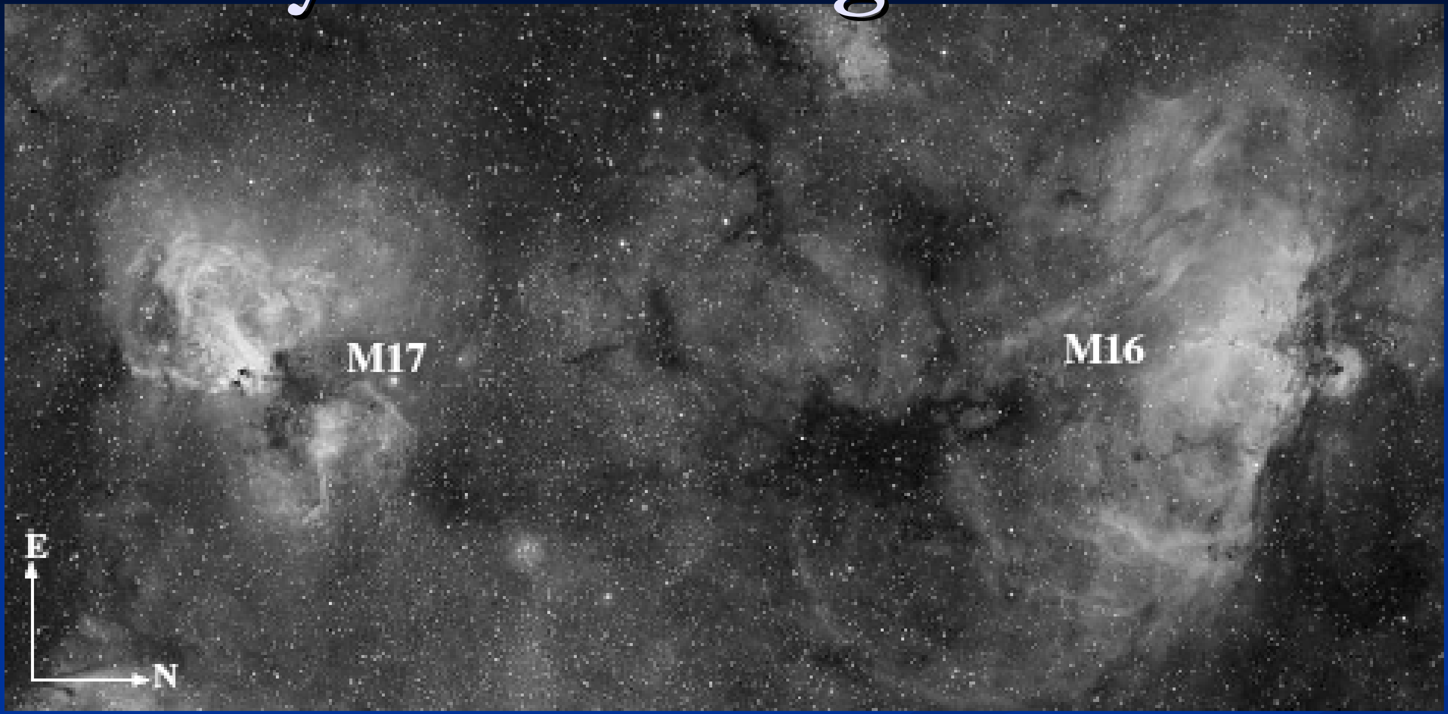
A Supernova Remnant in the Eagle?

- Recent work in the mid, far IR (Spitzer) reveals a region of warm dust in the middle of the Eagle Nebula.
- Starlight alone doesn't seem to account for how the dust was heated up.
  - Perhaps a SNR is expanding and heating the dust!
- If so, the Elephant Trunks will be blasted away by the SNR's shock wave.
  - The Trunks would be gone, but…
  - The young stars they are hiding would be revealed!





Beyond the Eagle's Nest



- The Eagle Nebula (M16) and M17: parts of a larger star-forming region in the Sagittarius arm of the galaxy?
  - possibly including NGC 6604 (not shown).
- The stars in NGC 6604 are older than those in the Eagle Nebula (4 Myr vs 2-3 Myr) and M17 (1 Myr).
- Open question: What drives the age sequence?
  - Natural evolution of the clouds during passage of the spiral arm?
  - SF in M16/M17 driven by stellar winds or SN-blown bubbles in NGC 6604?

Summary I

- Luminosity (brightness), temperature (color), and lifetime of a star are all determined primarily by its mass
- Stars usually form hidden in dense cores embedded inside Giant Molecular Clouds
  - Gravitational contraction only starts in cold, dense matter and initially requires efficient cooling to progress
  - In early stages, need shielding from interstellar radiation fields
- In a new star-forming region, the massive stars form first and shape their environment
  - Ionizing radiation can destroy molecular cloud, cutting off nearby star formation
  - Stellar winds and supernova blast fronts can introduce compression and turbulence in clouds, providing seeds for next generation of star formation

Summary II

- Many details of star formation are still being explored
  - How exactly do magnetic fields and rotation influence star formation?
  - Why do some clusters tend to form massive stars while others do not?
  - What drives initial formation of dense regions?
    - Spiral waves, stellar winds, SNe, galaxy-galaxy interactions…
  - And much, much more
- **No lecture Saturday, Oct 18th!** See you on the 25th when we explore stellar evolution and end times.