Section 4: Star Formation

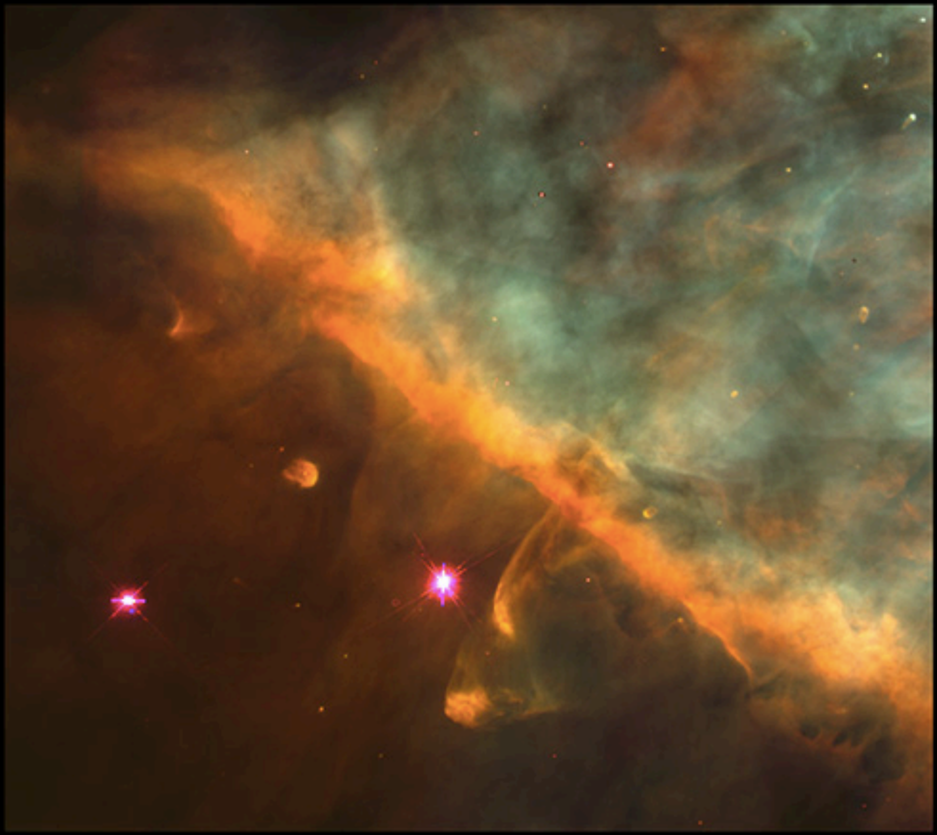

Pillars: Hubble vs Webb

Is star formation currently on-going in the Milky Way?

$$\tau = \frac{fuel}{power} = \frac{0.1\varepsilon Mc^2}{L} = 10^{10}\left(\frac{M}{M_s}\right)\left(\frac{M}{M_s}\right)^{-\alpha} y = 10^{10}\left(\frac{M}{M_s}\right)^{1-\alpha} y$$

$\varepsilon = 0.007$ and for solar-type stars, $\alpha = 3.1$. We see *O* and *B* stars! Star formation is on-goingl

Hubble (color)



Credits : NASA, C.R. O'Dell and S.K. Wong (Rice University)

JWST (color)

Credits : NASA / ESA / CSA / PDRs4All team S. Fuenmayor

Where does star formation take place?

Star Formation takes place in condensed cores in *Giant Molecular Clouds (GMC)*. GMCs are large gas clouds composed primarily of H_2, molecular hydrogen. GMCs do contain some dust, they are about 2 % by mass of dust.

They have masses of *10^4 to 10^7 M_s* and large sizes, *a few light years*. GMCs are dense *100 to several million molecules per cm^3*. The density of air in this room is roughly 10^{18}-10^{19} molecules per cm^3, and the average density of particles in our Galaxy is around 1 atom per cm^3. GMCs are cold, *$T \sim 10\text{-}50$ K*.

The star formation process is amazing taking the condensed *ISM* clouds to Main Sequence stars -- objects with central T ~ 10^7 K, n ~ 10^{26} particles per cm^3, and Radii ~ million or so km (~ 3 light-seconds!)--the whole process driven by gravity.

Star forming clouds are initially in hydrostatic and thermal equilibrium, star formation must be triggered--clouds have low pressures due to their low n and T. *Triggers* compress the clouds which pushes all particles closer together and so increases the inward pull of gravity on the cloud. Many triggers have been proposed.

Why do the clouds continue to collapse after the trigger?

Although there are only tiny amounts of dust, dust is a emitter of light over a broad range of energy (strong continuous emission) and is an efficient absorber and scatterer of visible light.

This prevents us from seeing star forming regions in the optical; dust; it does not affect IR and microwaves as much as optical, though. IR and microwaves offer the best views of the star forming regions.

Dust strongly cools contracting clouds. Initially, the clouds are optically thin to IR and dust cools the collapsing clouds. Only when the clouds become dense enough is heat trapped and collapse halts.

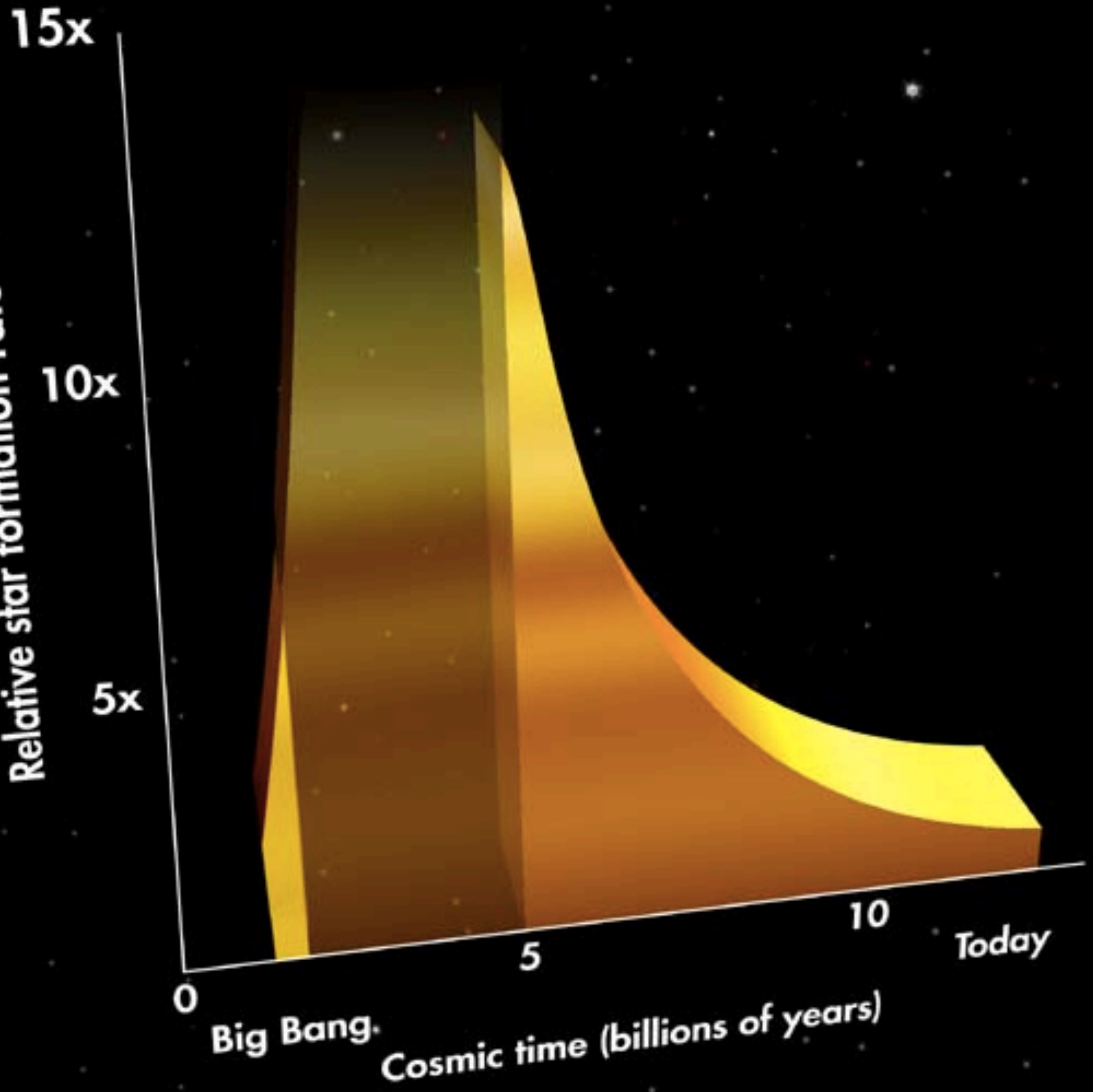
What is the rate for star formation?

There are ~200 billion stars in the Milky Way. The Milky Way is roughly 10 billion years old. The average mass of a Milky Way star is somewhat less than the mass of the Sun, 0.3 or so M_s. The exact value is not important for this argument as any star a little less massive than the Sun has an age longer than the lifetime of the Milky Way. We estimate an average star formation rate of *20 stars per year*.

What is the longevity for star formation?

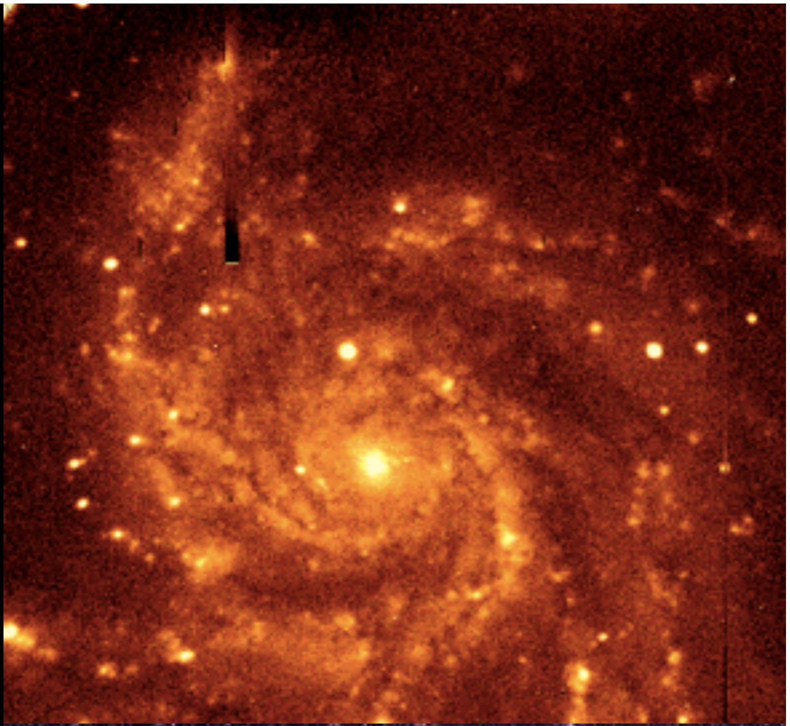
Roughly, 4 M_s of material goes into star formation every year (7 stars per year are thought to form in the *Milky Way* galaxy, based on study of $_{13}Al^{26}$ by *Integral*).

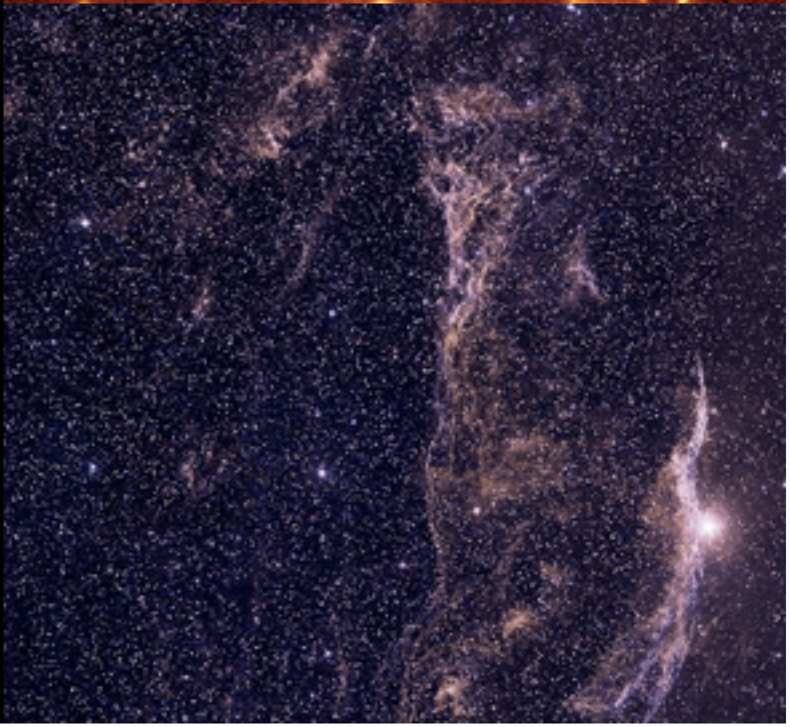
Stars return roughly 1 - 2 M_s per year back to the *ISM* ===> a net loss of gas of roughly 2 or 3 M_s per year. Currently, the *ISM* contains 10-15 % of the visible mass of the Milky Way ===> ten or so billion M_s of gas and dust, the materials out of which stars form. *Star formation will persist in the Milky Way galaxy for billions or more years. Has the rate been steady?*


15x
10x
5x
Relative star formation rate
0
5
10
Today
Big Bang
Cosmic time (billions of years)

Triggers

OPO • June 1, 1999
JPL/IPAC), Eva K. Grebel (Univ. Washington),
llinois, Urbana-Champaign) and NASA





What is the Jeans Mass, M_J?

I. Virial Theorem

$$\left(\frac{dP}{dr}+\frac{GM\rho}{r^2}\right)\bullet r=0\rightarrow\int\left(\frac{dP}{dr}+\frac{GM\rho}{r^2}\right)4\pi r^3 dr=0$$

$$(A)\int\frac{dP}{dr}4\pi r^3 dr=0,$$

$$dU=\frac{dP}{dr}dr, V=4\pi r^3$$

$$\rightarrow\int\frac{dP}{dr}4\pi r^3 dr=4\pi r^3 P\,|_0^{R_*}-\int 12\pi r^2 P dr=-3(\gamma-1)U$$

$$(B)\int\left(\frac{dP}{dr}+\frac{GM\rho}{r^2}\right)4\pi r^3\,dr=0$$

→ Virial Theorem: $3(\gamma-1)U+W_g=0$

$$(C)\,\frac{\int\left(\frac{dP}{dr}+\frac{GM\rho}{r^2}\right)4\pi r^3\,dr}{\int 4\pi r^2\rho\,dr}$$

→ $3(\gamma-1)U+W_g=M\left\langle 3(\gamma-1)U\right\rangle+M\left\langle W_g\right\rangle=0$

Energy and the Virial Theorem

$$VT:\ 3(\gamma-1)U+W_g=0\rightarrow U=-\frac{1}{3(\gamma-1)}W_g$$

$$\rightarrow E=U+W_g=\frac{-W_g}{3(\gamma-1)}+W_g=\frac{(3\gamma-4)}{3(\gamma-1)}W_g$$

CASES

$$I.\ \gamma=\frac{5}{3}\rightarrow E=\frac{1}{2}W_g$$

Monotomic gas

$$II.\ \gamma=\frac{7}{5}\rightarrow E=\frac{1}{6}W_g$$

Diatomic molecular gas

$$III.\ \gamma=\frac{4}{3}\rightarrow E=0$$

Relativistic gas

II. Jeans Mass

$$\langle 3(\gamma - 1)U \rangle + \langle W_g \rangle = 0$$

Say we have an uniform ISM cloud with $T = 10$ K, and $n = 1{,}000\ \mathrm{cm}^{-3}$ (3.4×10^{-21} g), initially in equilibirum. Then,

- $<3(\gamma-1)U> = 3(\gamma-1)NkT = 3(\gamma-1)(M/2m_H)kT$
- $<W_g> = -0.6GM^2/R = -0.6GM^{5/3}(2m_H n)^{1/3}$

sum to 0, suggesting a critical mass, the *Jeans Mass*,

$$\boxed{M_J = 11 M_s \left(\frac{T}{10K}\right)^{3/2} \left(\frac{n}{10^3}\right)^{-1/2}}$$

The *Jeans Mass*,

$$M_J = 11 M_s \left(\frac{T}{10K} \right)^{3/2} \left(\frac{n}{10^3} \right)^{-1/2}$$

increases with temperature and decreases with density.

Do these properties seem reasonable to you?

The *Jeans Mass*,

$$M_J = 11 M_s \left(\frac{T}{10K}\right)^{3/2} \left(\frac{n}{10^3}\right)^{-1/2}$$

1. HI cloud, *$T = 50$ K, $n = 500$ cm^{-3}*, *$M_J = 1{,}500\ M_s$*
2. H2 cloud, *$T = 10$ K, $n = 8{,}000$ cm^{-3}*, *$M_J = 4\ M_s$*
3. For *$1\ M_S$, $n = 1.2\text{x}10^5$ cm^{-3}* if *$T = 10$ K*

The first clouds to become unstable have *$M_J >> 100\ M_S$*, the upper mass limit for Main Sequence stars. Low mass clouds become unstable at high density. Star formation is a top-down process and suggests

FRAGMENGTATION

Fragmentation

$$M_J = 11 M_s \left(\frac{T}{10K}\right)^{3/2} \left(\frac{n}{10^3}\right)^{-1/2}$$

1. HI cloud, *$T = 50$ K, $n = 500$ cm^{-3}*, $M_J = 1{,}500\ M_s$
2. H2 cloud, *$T = 10$ K, $n = 8{,}000$ cm^{-3}*, $M_J = 4\ M_s$
3. For $1\ M_s$, *$n = 1.2\times10^5$ cm^{-3}* if *$T = 10$ K*

$$\rho \frac{d^2 r}{dt^2} = -\frac{dP}{dr} - G\frac{M(r)}{r^2}\rho(r)$$

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho v) = 0$$

$$\rho \frac{d^2 r}{dt^2} = -\frac{dP}{dr} - G\frac{M(r)}{r^2}\rho(r) \qquad \frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho v\right) = 0$$

Homologous Collapse

$$\rho\frac{d^2r}{dt^2} = -\nabla P(r) - G\frac{M(r)}{r^2}\rho(r) \approx -G\frac{M(r)}{r^2}\rho(r)$$

$$\rightarrow \frac{d^2r}{dt^2} \approx -G\frac{M(r)}{r^2}$$

$$v(r) = \frac{dr}{dt} \rightarrow\rightarrow \frac{d^2r}{dt^2} = \frac{dv(r)}{dt} = \frac{dr}{dt}\frac{dv(r)}{dr} = v(r)\frac{dv(r)}{dr}$$

$$\rightarrow \frac{d^2r}{dt^2} = \boxed{\frac{1}{2}\frac{dv(r)^2}{dr} \approx -G\frac{M(r)}{r^2}}$$

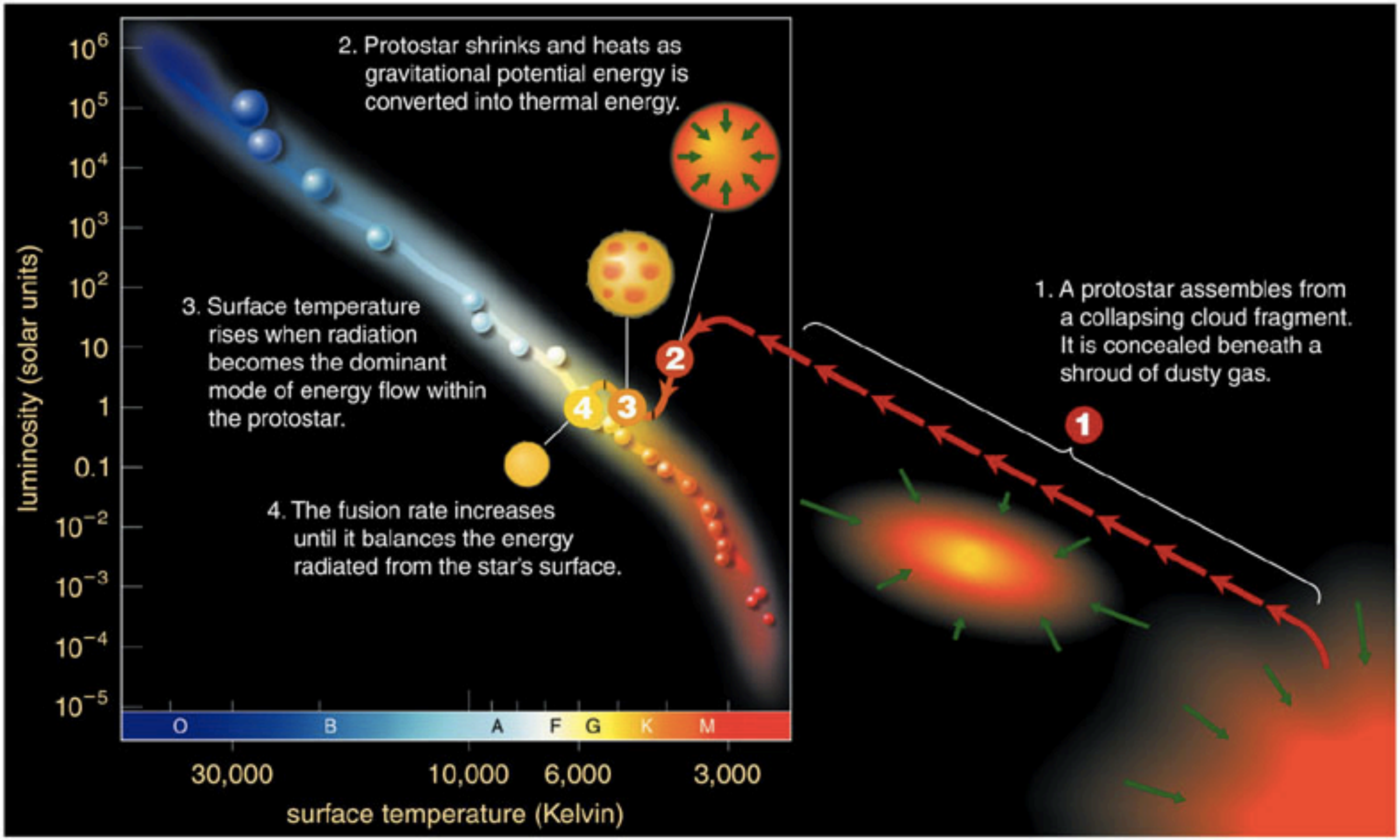
$$\frac{1}{2}\frac{dv(r)^2}{dr} \approx -G\frac{M(r)}{r^2} \rightarrow \frac{v(r)^2}{2}\Big|_0^v = GM\left(\frac{1}{r}\right)_R^r \approx \frac{GM}{r}$$

$$\rightarrow v(r) = -\sqrt{\frac{2GM}{r}} \rightarrow \frac{dr}{dt} = -\sqrt{\frac{2GM}{r}}$$

$$\rightarrow r^{3/2}\Big|_R^r = -\sqrt{\frac{9GM}{2}}t$$

$$\rightarrow r^{3/2}\Big|_R^r = -\sqrt{\frac{9GM}{2}}t \rightarrow \boxed{r = \left(R^{3/2} - \sqrt{\frac{9GM}{2}}t\right)^{2/3}}$$

Schematic for Star Formation



2. Protostar shrinks and heats as gravitational potential energy is converted into thermal energy.

3. Surface temperature rises when radiation becomes the dominant mode of energy flow within the protostar.

4. The fusion rate increases until it balances the energy radiated from the star's surface.

1. A protostar assembles from a collapsing cloud fragment. It is concealed beneath a shroud of dusty gas.

Can We Make Sense of the General Tracks?

1. The initial phase is a pressureless collapse, the collapsing cloud is optically thin to infrared radiation (IR)
2. The pressureless collapse halts when the cloud becomes optically thick to IR
3. Slow contraction ensues:
    - Hayashi track
    - slow contraction to hydrogen ignition, Zero Age Main Sequence

Estimate Timescales

1. Homologous, pressure-free collapse:

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho_o}} = 5.3\times10^7\left(\frac{n_H}{1\ cm^{-3}}\right)^{-1/2} y$$

2. Slow contraction phases: ?

Slow Contraction Phases

Assume contraction is slow enlugh to use a quasi-static approximation. Start with energy equation

$$E = U + W$$

Rewrite using Virial Theorem

$$3(\gamma - 1)U + W = 0 \rightarrow E = \frac{3\gamma - 4}{\gamma - 1} W_g$$

Slow contraction phases

Use γ=5/3, assume uniform sphere, and take time derivative of energy equation

$$E=\frac{1}{2}W_g \rightarrow \dot{E}=\frac{1}{2}\dot{W}_g=-\frac{3}{10}\frac{GM^2}{R^2}\dot{R}=L$$

For Hayashi track, use constant T_{eff} so that $L = 4\pi\sigma R^2\sigma T_{eff}^4$ so that

$$L=-\frac{3}{10}\frac{GM^2}{R^2}\dot{R} \rightarrow 4\pi\sigma R^2 T_{eff}^4=-\frac{3}{10}\frac{GM^2}{R^2}\dot{R}$$

$$\rightarrow -\frac{\dot{R}}{R^4} = \frac{40\pi\sigma T_{eff}^4}{3GM^2} \rightarrow \left(\frac{1}{3R^3}\right)_{R_o}^{R} = \frac{40\pi\sigma T_{eff}^4}{3GM^2}\tau_H$$

$$\rightarrow \boxed{\tau_H \approx \left(\frac{3GM^2}{120\pi\sigma T_{eff}^4 R^3}\right)\left(1-\frac{R^3}{R_o^3}\right)}$$

For slow radiative track, assume constant *L*

$$L = -\frac{3}{10}\frac{GM^2}{R^2}\dot{R}$$

$$\rightarrow -\frac{\dot{R}}{R^2} = \frac{10L}{3GM^2} = -\left(\frac{1}{R}\right)\Bigg|_{R_o}^{R} = \frac{10L}{3GM^2}\tau_{rad}$$

$$\rightarrow \boxed{\tau_{rad} = \left(\frac{3GM^2}{10LR}\right)\left(1 - \frac{R}{R_o}\right)}$$

SUN: ISM, n=10^3 cm^{-3}, Hayashi, T_{eff}=4000 K,R=0.5[10^8-10^7], radiative, L=0.4-0.7,R=1.4-0.8

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho_o}} = 1.7\times10^6\left(\frac{n_H}{1000\ \ cm^{-3}}\right)^{-1/2} y$$

$$\tau_H = \left(\frac{3GM^2}{120\pi\sigma T_{eff}^4 R^3}\right)\left(1-\frac{R^3}{R_o^3}\right) = \left(\frac{2GM^2}{5L_s R}\right)\left(1-\frac{R^3}{R_o^3}\right)$$

$$\tau_{rad} = \left(\frac{3GM^2}{10(0.7)L_s R}\right)\left(1-\frac{R}{R_o}\right)$$

Timeline for Star Formation

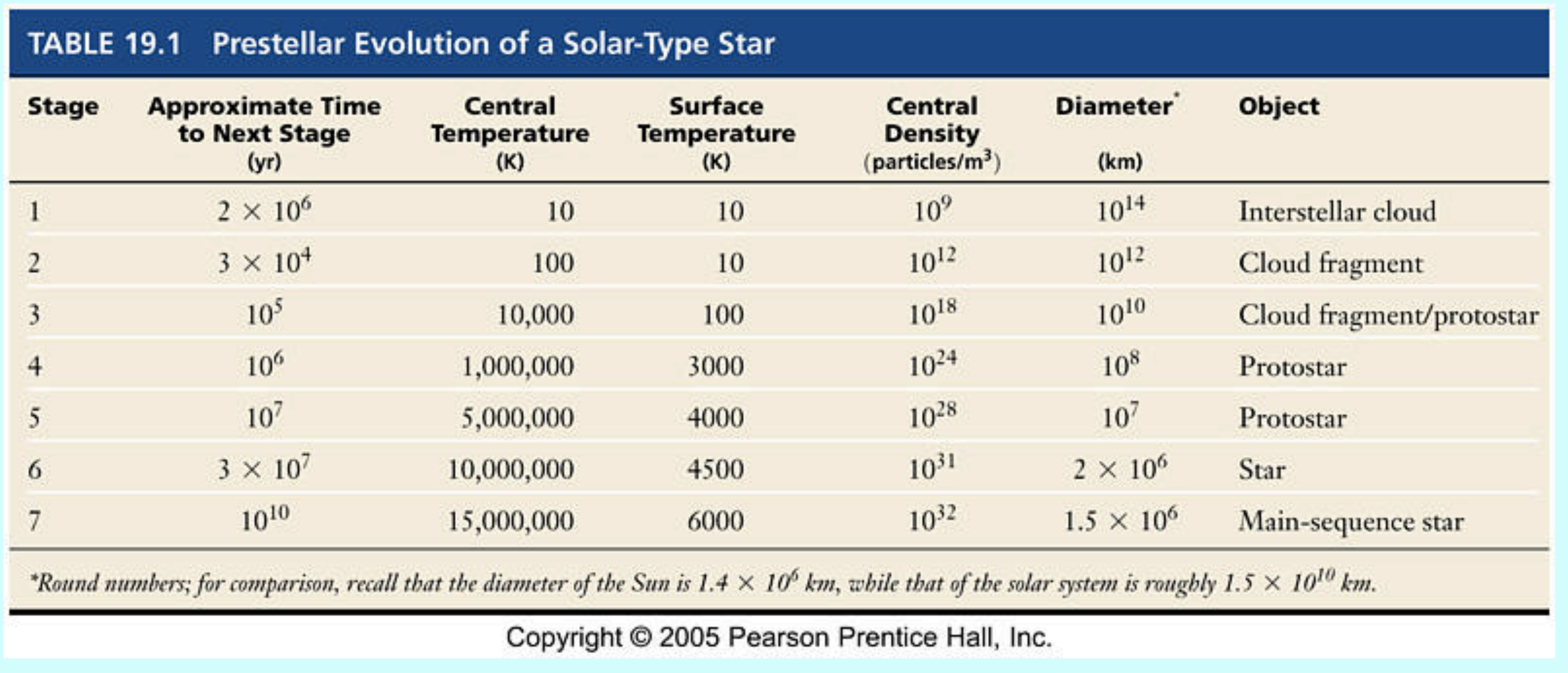
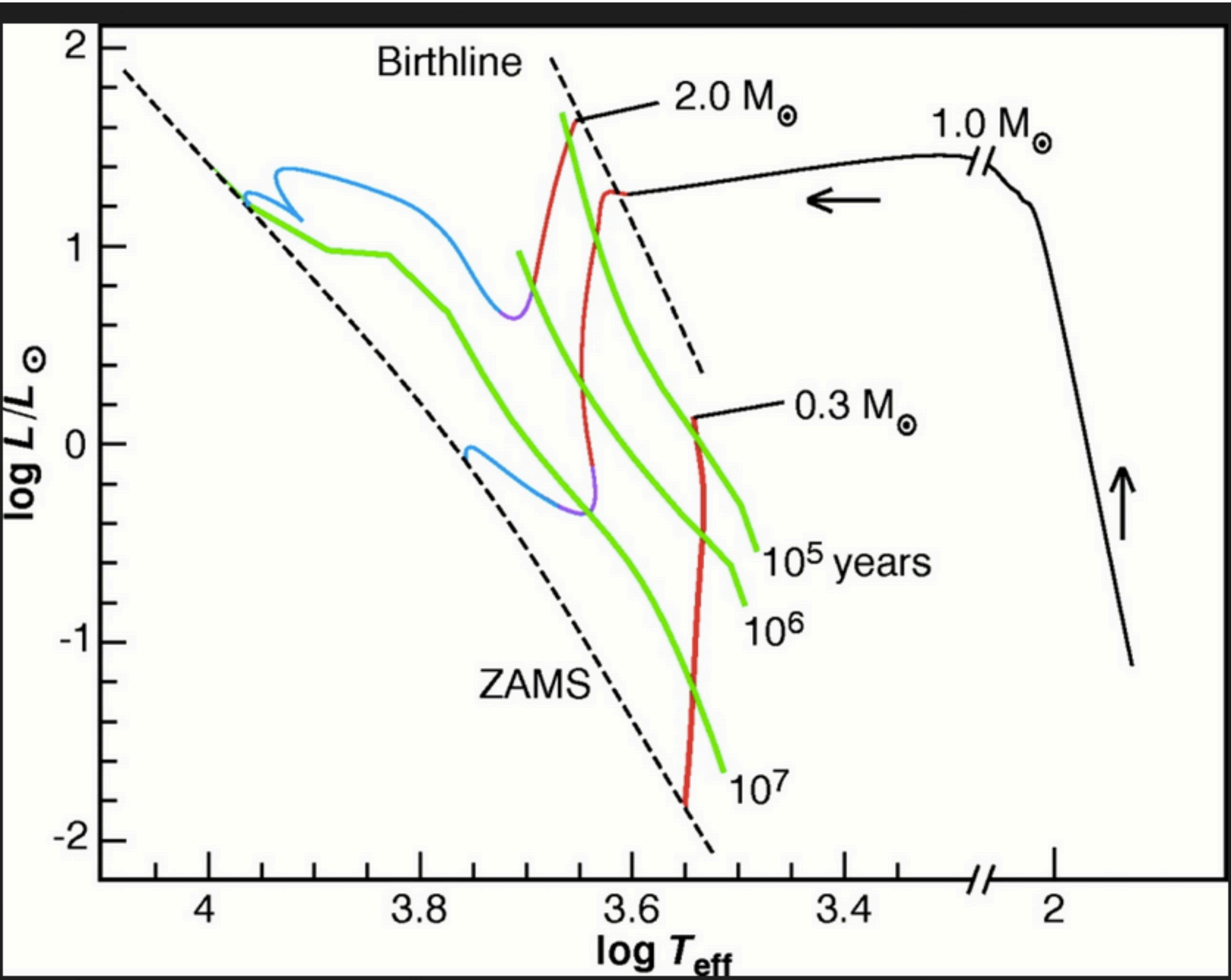
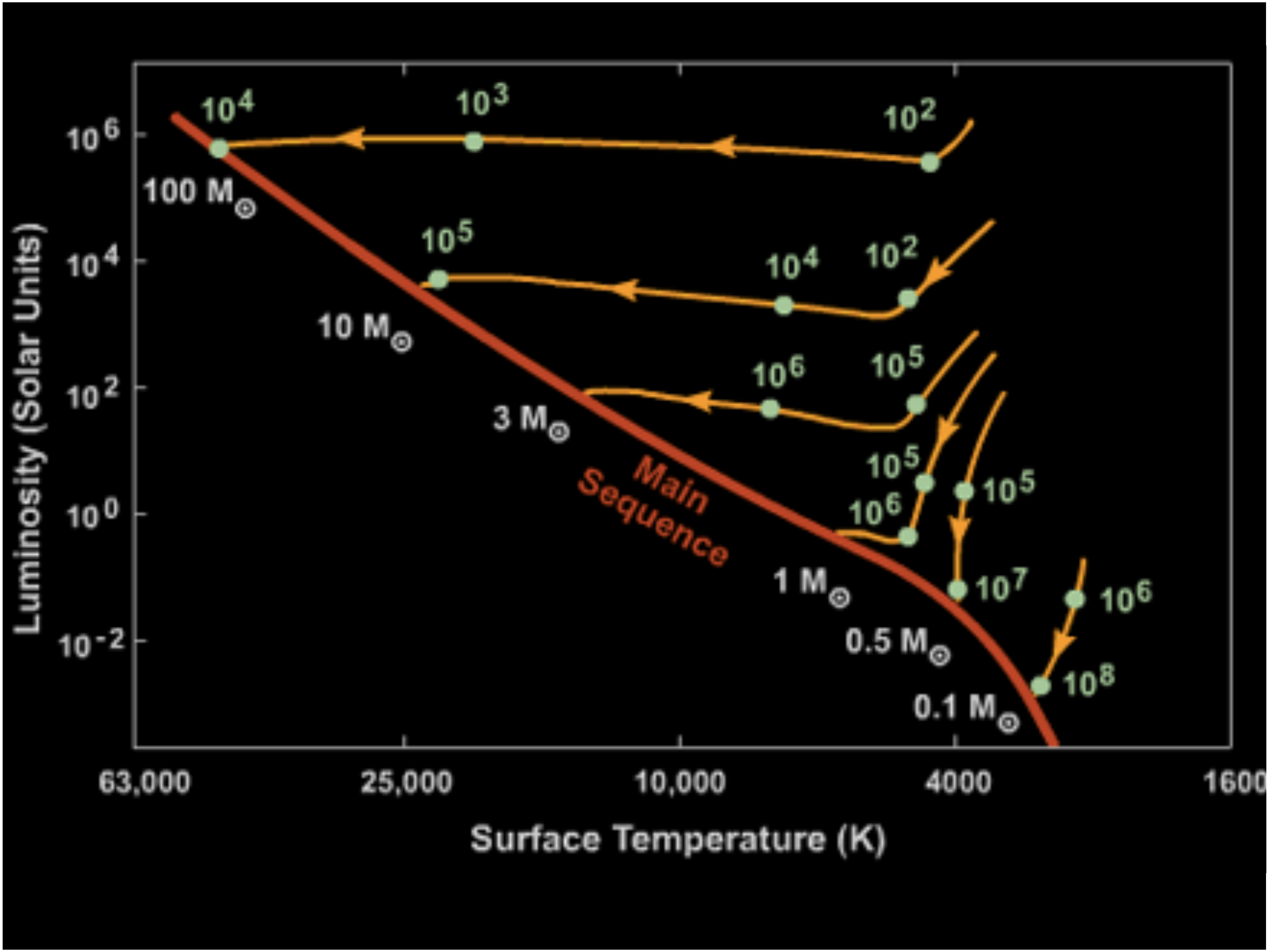


TABLE 19.1 Prestellar Evolution of a Solar-Type Star

Stage	Approximate Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (particles/m^3)	Diameter* (km)	Object
1	2×10^6	10	10	10^9	10^{14}	Interstellar cloud
2	3×10^4	100	10	10^{12}	10^{12}	Cloud fragment
3	10^5	10,000	100	10^{18}	10^{10}	Cloud fragment/protostar
4	10^6	1,000,000	3000	10^{24}	10^8	Protostar
5	10^7	5,000,000	4000	10^{28}	10^7	Protostar
6	3×10^7	10,000,000	4500	10^{31}	2×10^6	Star
7	10^{10}	15,000,000	6000	10^{32}	1.5×10^6	Main-sequence star

**Round numbers; for comparison, recall that the diameter of the Sun is 1.4×10^6 km, while that of the solar system is roughly 1.5×10^{10} km.*


2
1
0
-1
-2
log $L/L_\odot$
4
3.8
3.6
3.4
2
log $T_{\rm eff}$
Birthline
2.0 $M_\odot$
1.0 $M_\odot$
0.3 $M_\odot$
10^5 years
10^6
10^7
ZAMS


Luminosity (Solar Units)
10^6
10^4
10^2
10^0
10^{-2}
Surface Temperature (K)
63,000
25,000
10,000
4000
1600
Main Sequence
100 $M_\odot$
10 $M_\odot$
3 $M_\odot$
1 $M_\odot$
0.5 $M_\odot$
0.1 $M_\odot$
10^4
10^3
10^2
10^5
10^4
10^2
10^6
10^5
10^5
10^6
10^5
10^7
10^6
10^8

Multiple Star Systems

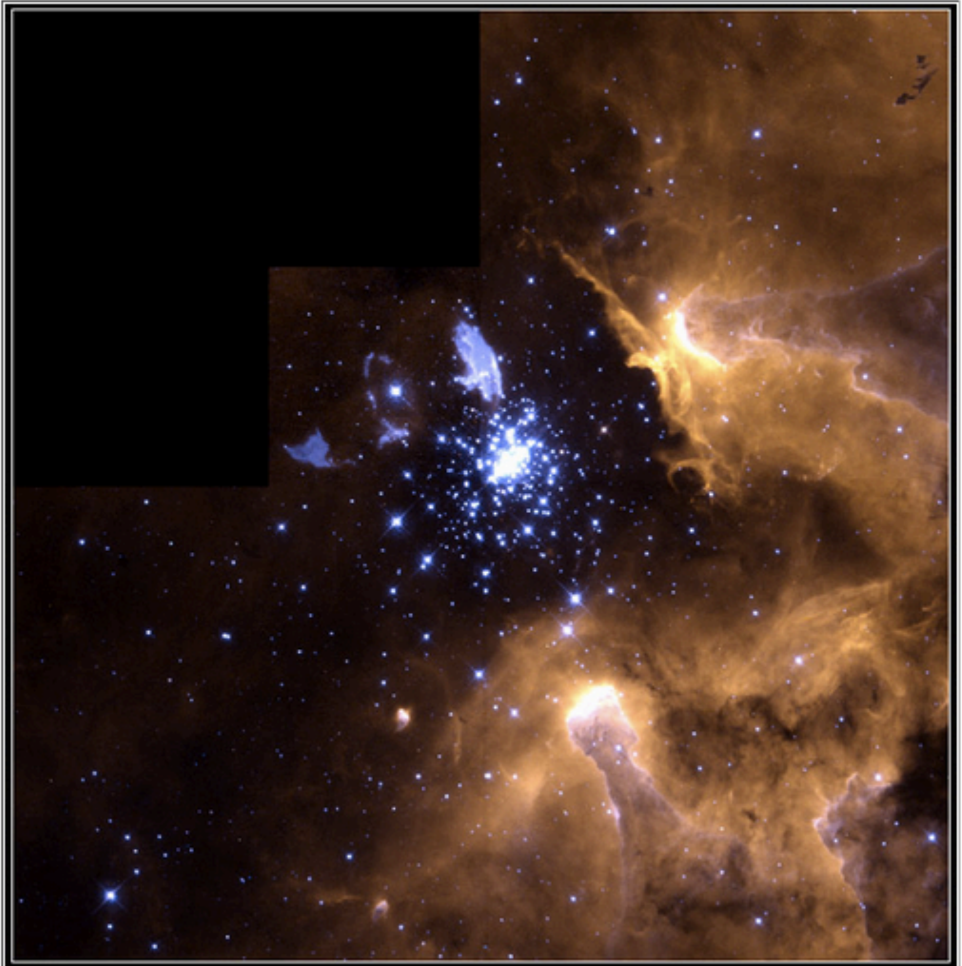
The preceding discussion concerned the formation of single stars. However, more than half (and perhaps up to 85 %) of all stars are in mulitple (double star, triple star, quadruple star, ...) star systems. In addition, over 1,000 extra-Solar planetary systems are known. Thus an important point to try and understand is how do we form multiple star systems and planetary systems.

Do binary star systems form by captures of random stars or do the stars in the systems form at the same time from the same cloud?

- P(orbital) > 100 years, M_1/M_2 is roughly the same as for indiviual stars observed in the Galaxy ===> stars probably form as individual stars, either because the binary system is so large that they form essentially as individual stars or because they formed in different regions and simply were captured into the binary system.

- P(orbital) < 100 years, years, $M_1/M_2 \sim 1$ ➔ stars in short orbital period binary star systems (and in the extreme, planetary systems) probably form as units.

The theory of how individual stars form is in fairly good shape. The details of how binary stars form is much less secure.



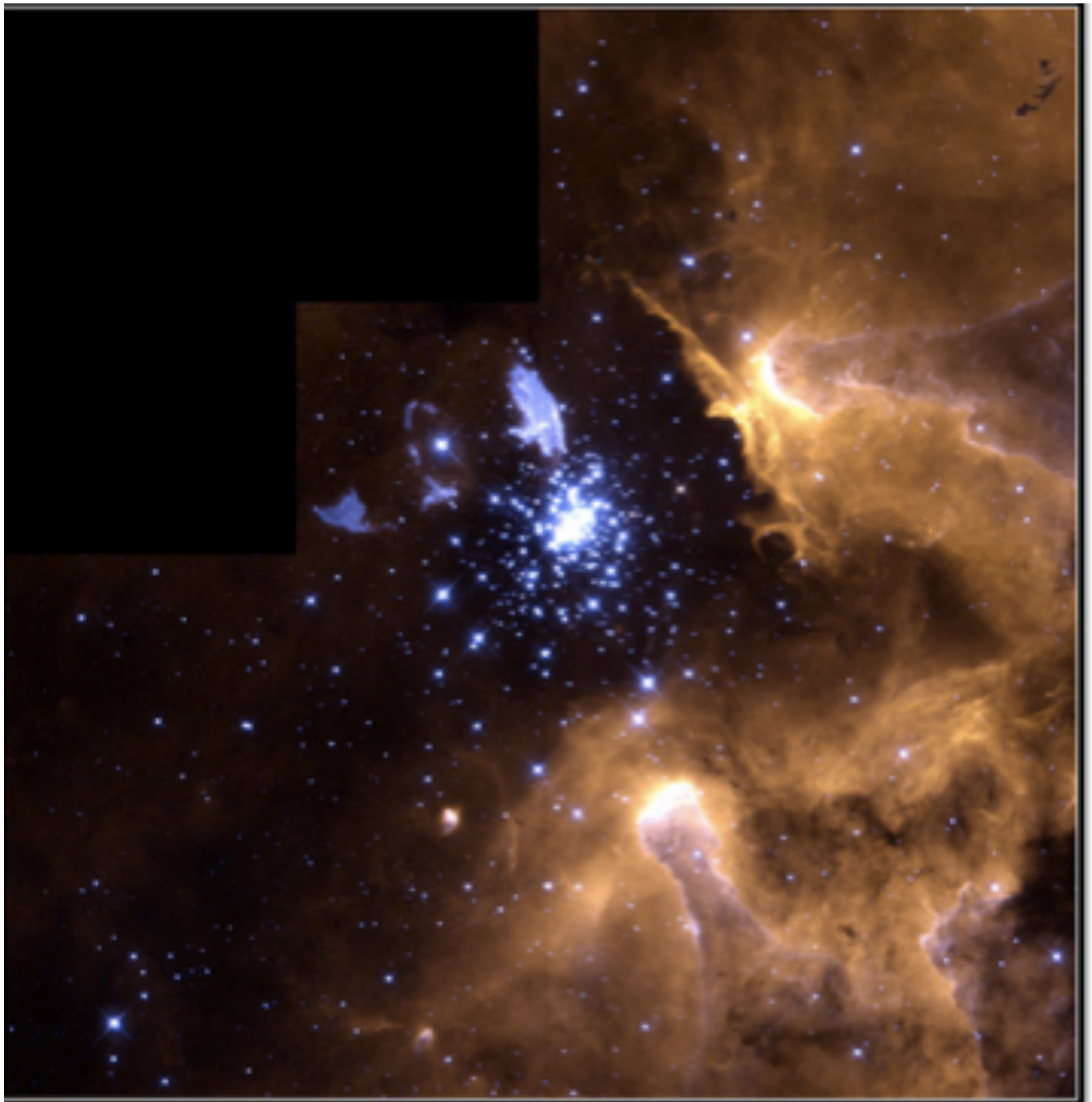
NGC 3603 **HST** • WFPC2

PRC99-20 • STScI OPO • June 1, 1999

Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA

HUBBLE SNAPSHOT CAPTURES LIFE CYCLE OF STARS

In this stunning picture of the giant galactic nebula NGC 3603, the crisp resolution of NASA's Hubble Space Telescope captures various stages of the life cycle of stars in one single view and highlights how astronomers study the evolution of objects whose lifetimes are much longer than human lifetimes (and, in fact, humanity's lifetime).



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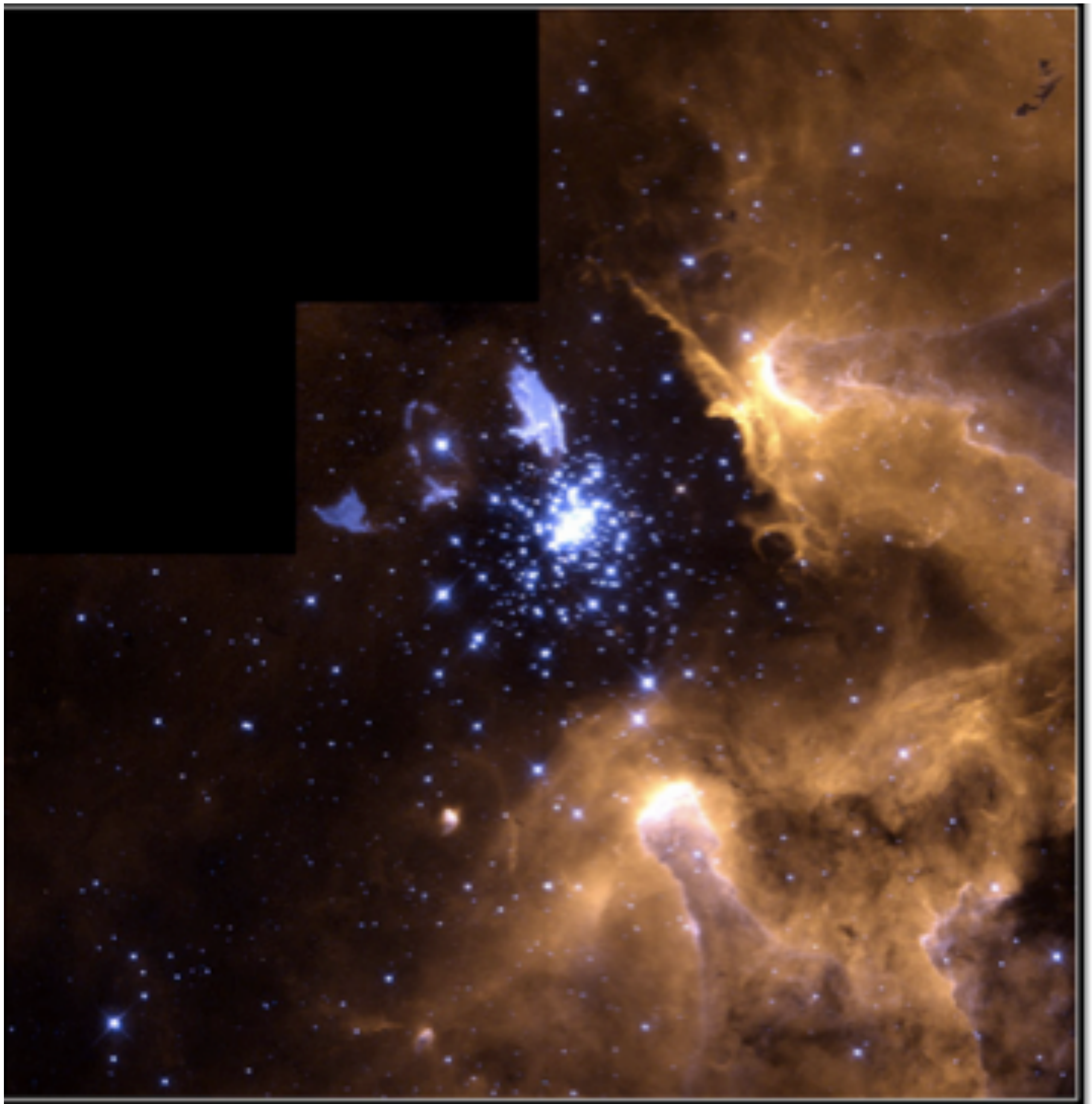

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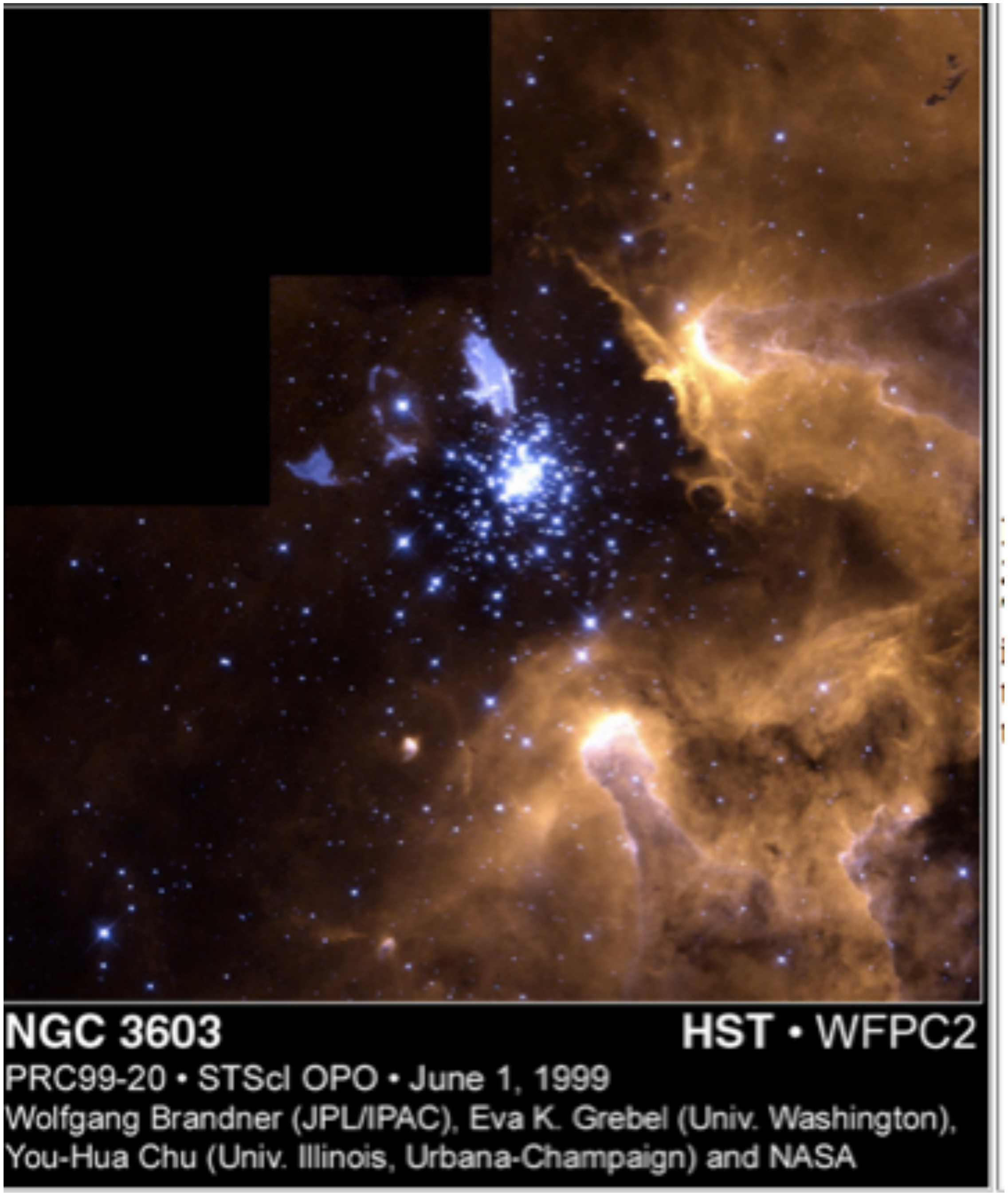
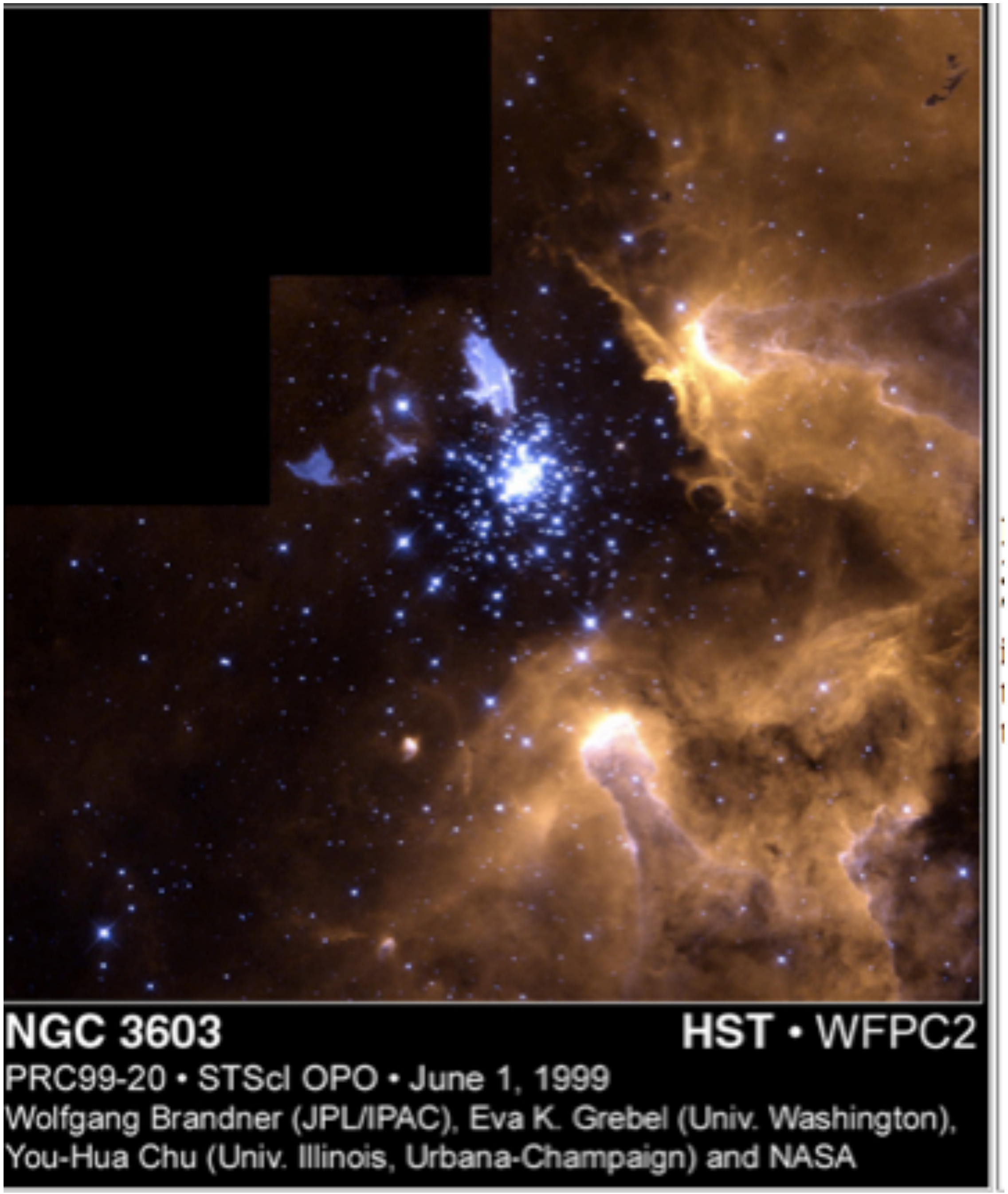
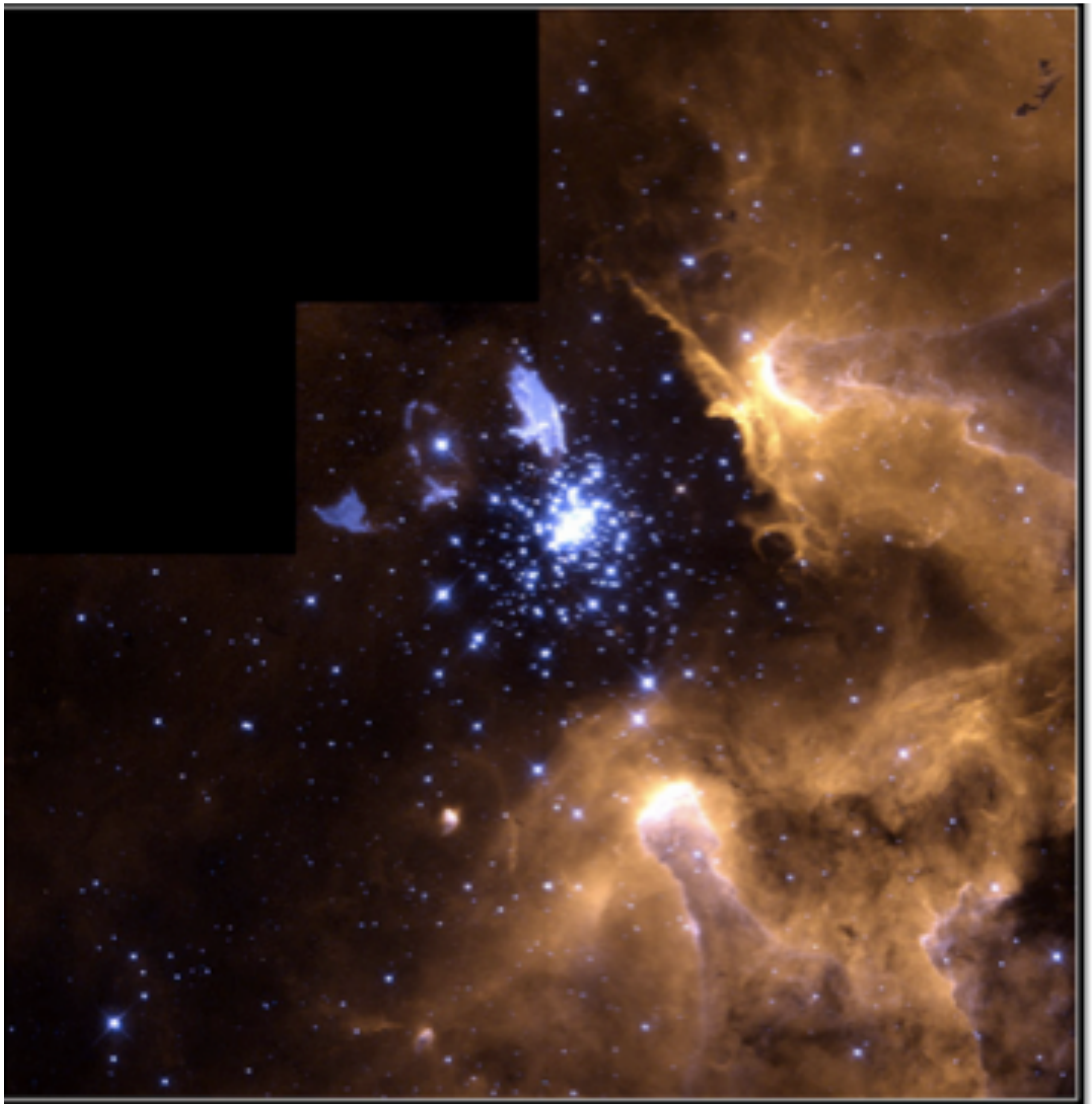
To the upper right of center is the evolved blue supergiant called Sher 25. The star has a unique circumstellar ring of glowing gas that is a galactic twin to the famous ring around the supernova 1987A. The grayish-bluish color of the ring and the bipolar outflows (blobs to the upper right and lower left of the star) indicates the presence of processed (chemically enriched) material



Near the center of the view is a so-called starburst cluster dominated by young, hot Wolf-Rayet stars and early O-type stars . A torrent of ionizing radiation and fast stellar winds from these massive stars has blown a large cavity around the cluster.



The most spectacular evidence for the interaction of ionizing radiation with cold molecular-hydrogen cloud material are the giant gaseous pillars to the right and lower left of the cluster. These pillars are sculptured by the same physical processes as the famous pillars Hubble photographed in the M16 Eagle Nebula.



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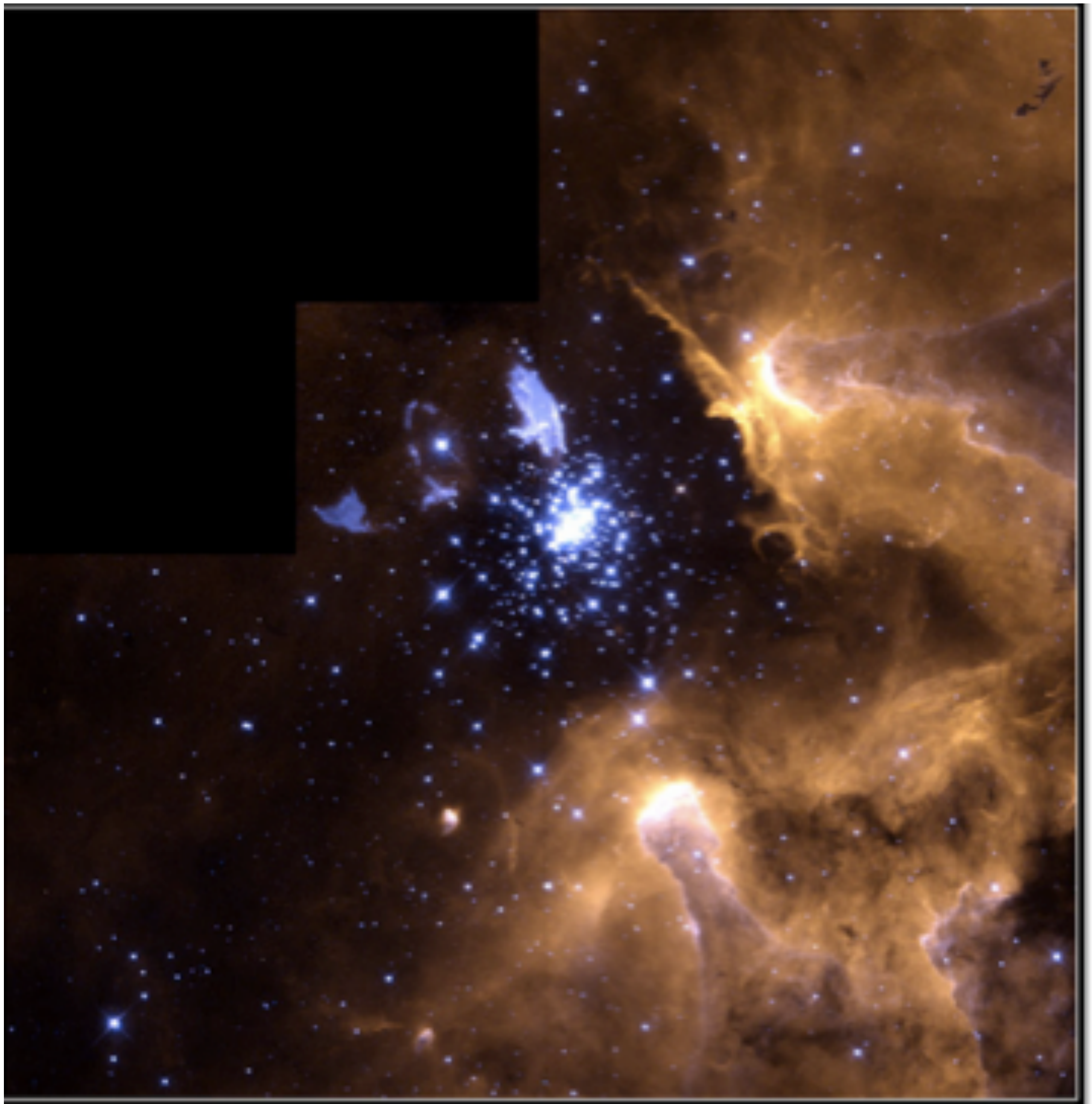
Dark clouds at the upper right are so-called Bok globules , which are probably in an earlier stage of star formation.

To the lower left of the cluster are two compact, tadpole-shaped emission nebulae. Similar structures were found by Hubble in Orion, and have been interpreted as gas and dust evaporation from possibly protoplanetary disks (proplyds). The "proplyds" in NGC 3603 are 5 to 10 times larger in size and correspondingly also more massive



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This single view nicely illustrates the entire stellar life cycle of stars, starting with the Bok globules and giant gaseous pillars, followed by circumstellar disks, and progressing to evolved massive stars in the young starburst cluster. The blue supergiant with its ring and bipolar outflow marks the end of the life cycle.