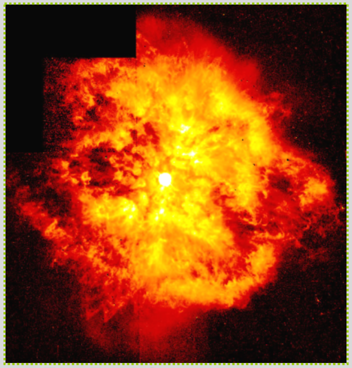
ASTR 1040: Stars & Galaxies



Winds from Massive Star

Prof. Juri Toomre TAs: Peri Johnson, Ryan Horton

Lecture 13 Tues 27 Feb 2018

zeus.colorado.edu/astr1040-toomre

Topics for Today

- Briefly look at life in stars AFTER they have exhausted the hydrogen fuel in their cores – return to this in Thur+ lecture
- But next look at how do stars get to the "Main Sequence" – with MS their longest phase
- Examine <u>birth of stars</u> in molecular clouds
- Find many more M and G stars are made than massive O and B stars

Things to do

- Read Chap 16 `Star Birth' in detail – it is a bit complex, so devote some time
- We will revisit <u>Birth of Stars</u> several times
- Overview read Chap17 'Star Stuff', and 17.2 'Life as Low-Mass Star' for Thur lecture
- Then read 17.3 'Life as High-Mass Star'
- Class meets in Fiske Planetarium next Tues March 6 -- go there directly
- HW #5 returned graded, with answer sheet

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LA Info Session

Thursday, March 1
5-6 PM
University Memorial Center, Room 235

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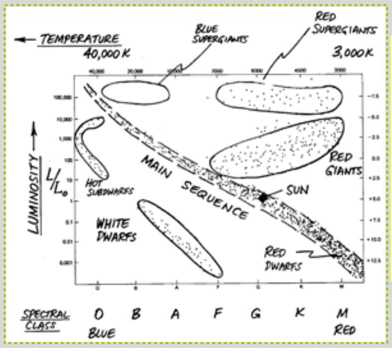
Main sequence (MS) stars

REMINDER



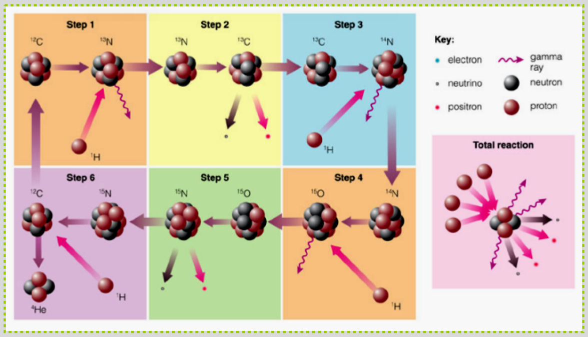
<u>Burning hydrogen in their cores</u>

<u>Temperatures are hotter</u> for more massive stars (crush of gravity)

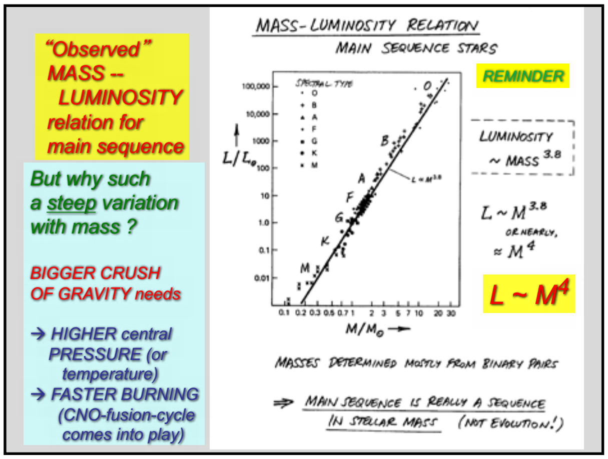
<u>More luminous</u> (higher fusion rates)

C-N-O Fusion Cycle

REMINDER



Can provide <u>vast luminosity</u> for massive stars on MS



"Observed" MASS -- LUMINOSITY relation for main sequence

But why such a <u>steep</u> variation with mass ?

BIGGER CRUSH OF GRAVITY needs

→ HIGHER central PRESSURE (or temperature)

→ FASTER BURNING (CNO-fusion-cycle comes into play)

MASS-LUMINOSITY RELATION

MAIN SEQUENCE STARS

REMINDER

LUMINOSITY ~ MASS $^{3.8}$

$L \sim M^{3.8}$

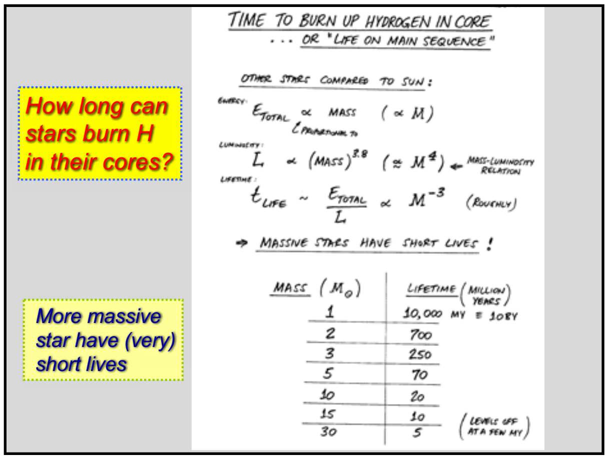
OR NEARLY,

$\approx M^4$

$L \sim M^4$

MASSES DETERMINED MOSTLY FROM BINARY PAIRS

⇒ MAIN SEQUENCE IS REALLY A SEQUENCE IN STELLAR MASS (NOT EVOLUTION!)



How long can stars burn H in their cores?

More massive star have (very) short lives

TIME TO BURN UP HYDROGEN IN CORE

. . . OR "LIFE ON MAIN SEQUENCE"

OTHER STARS COMPARED TO SUN:

ENERGY: $E_{TOTAL} \propto$ MASS $(\propto M)$

$\propto$ PROPORTIONAL TO

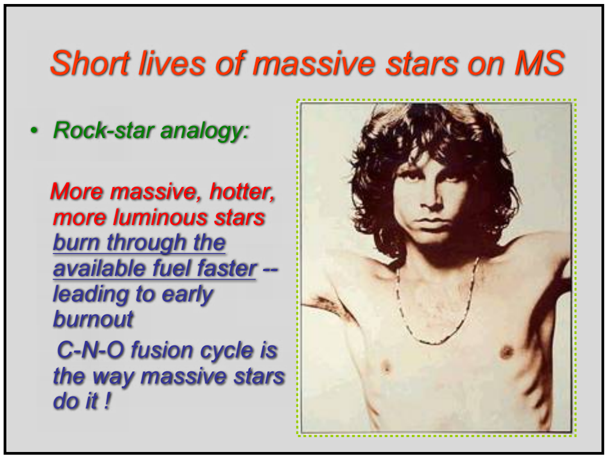
LUMINOSITY: $L \propto (\text{MASS})^{3.8} \quad (\approx M^4)$ ← MASS-LUMINOSITY RELATION

LIFETIME: $t_{LIFE} \sim \frac{E_{TOTAL}}{L} \propto M^{-3}$ (ROUGHLY)

→ MASSIVE STARS HAVE SHORT LIVES !

MASS $(M_\odot)$	LIFETIME (MILLION YEARS)
1	10,000 MY ≡ 10 BY
2	700
3	250
5	70
10	20
15	10
30	5

(LEVELS OFF AT A FEW MY)

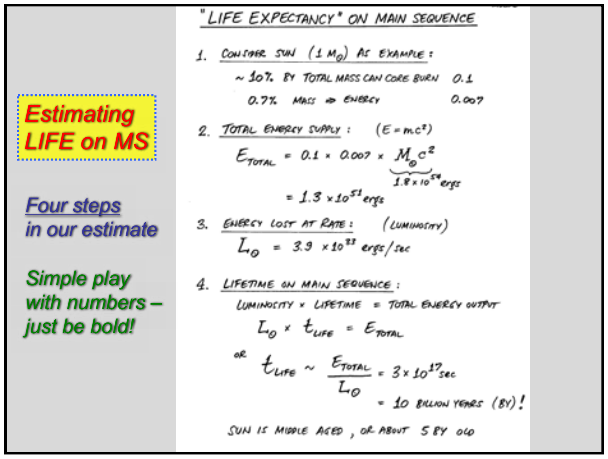


Short lives of massive stars on MS

- Rock-star analogy:

More massive, hotter, more luminous stars <u>burn through the available fuel faster</u> -- leading to early burnout

C-N-O fusion cycle is the way massive stars do it !



Estimating LIFE on MS

<u>Four steps</u> in our estimate

Simple play with numbers – just be bold!

"LIFE EXPECTANCY" ON MAIN SEQUENCE

1. CONSIDER SUN $(1\,M_\odot)$ AS EXAMPLE:

~ 10% BY TOTAL MASS CAN CORE BURN 0.1

0.7% MASS ⇒ ENERGY 0.007

2. TOTAL ENERGY SUPPLY: $(E = mc^2)$

$$E_{TOTAL} = 0.1 \times 0.007 \times \underbrace{M_\odot c^2}_{1.8 \times 10^{54}\,\text{ergs}}$$

$$= 1.3 \times 10^{51}\,\text{ergs}$$

3. ENERGY LOST AT RATE: (LUMINOSITY)

$$L_\odot = 3.9 \times 10^{33}\,\text{ergs/sec}$$

4. LIFETIME ON MAIN SEQUENCE:

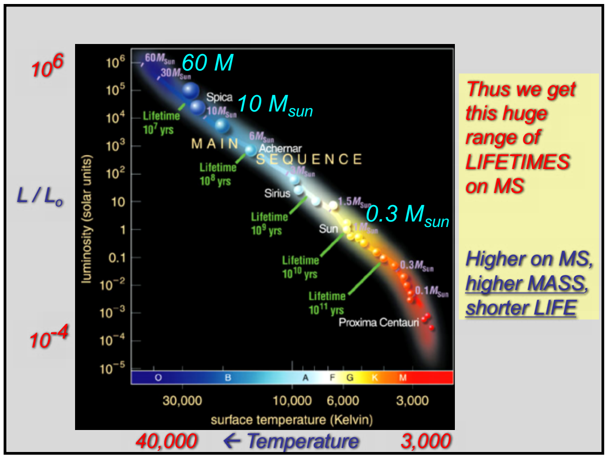
LUMINOSITY × LIFETIME = TOTAL ENERGY OUTPUT

$$L_\odot \times t_{LIFE} = E_{TOTAL}$$

OR $$t_{LIFE} \sim \frac{E_{TOTAL}}{L_\odot} = 3 \times 10^{17}\,\text{sec}$$

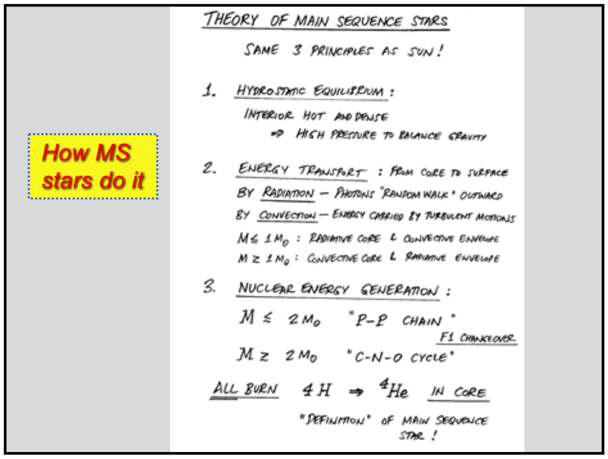
= 10 BILLION YEARS (BY)!

SUN IS MIDDLE AGED, OR ABOUT 5 BY OLD



Thus we get this huge range of LIFETIMES on MS

Higher on MS, <u>higher MASS, shorter LIFE</u>



How MS stars do it

THEORY OF MAIN SEQUENCE STARS

SAME 3 PRINCIPLES AS SUN!

1. HYDROSTATIC EQUILIBRIUM:

INTERIOR HOT AND DENSE

⇒ HIGH PRESSURE TO BALANCE GRAVITY

2. ENERGY TRANSPORT: FROM CORE TO SURFACE

BY RADIATION – PHOTONS "RANDOM WALK" OUTWARD

BY CONVECTION – ENERGY CARRIED BY TURBULENT MOTIONS

$M \lesssim 1 M_\odot$: RADIATIVE CORE & CONVECTIVE ENVELOPE

$M \gtrsim 1 M_\odot$: CONVECTIVE CORE & RADIATIVE ENVELOPE

3. NUCLEAR ENERGY GENERATION:

$M \lesssim 2 M_\odot$ "P-P CHAIN"

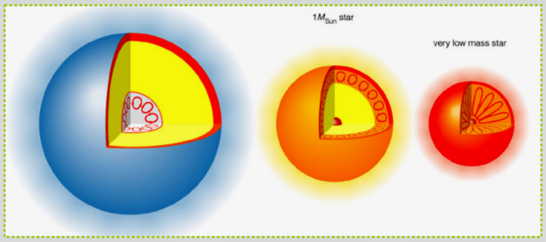
F1 CHANGEOVER

$M \gtrsim 2 M_\odot$ "C-N-O CYCLE"

ALL BURN $4\,H \Rightarrow {}^4He$ IN CORE

"DEFINITION" OF MAIN SEQUENCE STAR!

Differing convection and radiation zones on MS

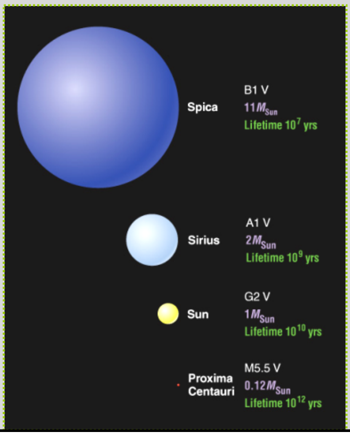


High mass: convective core, deep radiative envelope

Solar mass: radiative interior, convective envelope

Low mass: very deep convective envelope

Deeper convection may yield fiercer magnetic dynamos



Sizes of stars main sequence

Life AFTER main sequence

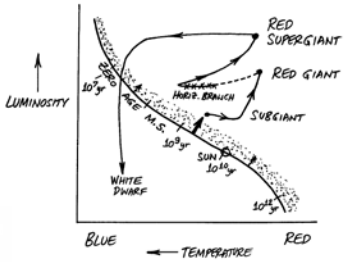
Stars evolve off MS, not along it !

Now let us test such ideas with star clusters

IS THERE LIFE AFTER THE MAIN SEQUENCE?

YES .... READ ABOUT IT IN H-R DIAGRAM!

STELLAR EVOLUTION STORY TO FOLLOW WITH SOME DETAIL ....

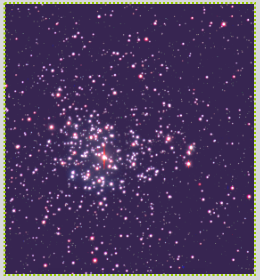


STAR CLUSTERS – two varieties

both are groups of star that have evolved together -- great for testing ideas about evolution of stars

Globular cluster

old, millions of stars



Open cluster

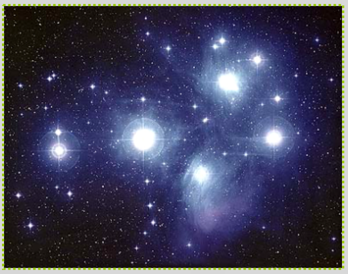
young, thousands of stars

Globular clusters -- much older, bigger

- generally *much older* -- up to 13 BILLION years
- made up of *millions of stars*, very densely packed

Open star cluster: Pleiades

- "Open cluster" only about 100 MY old – involves *several thousand stars*
- Unlike Sun's age of 4.6 BY



Bright B-type stars, O stars now missing

Oh to describe a star ! B.

- Which is a red supergiant ?
- A. Spectral type G2, luminosity class V
- B. Spectral type M2, luminosity class I
- C. Spectral type O9, luminosity class I
- D. Spectral type M1, luminosity class V

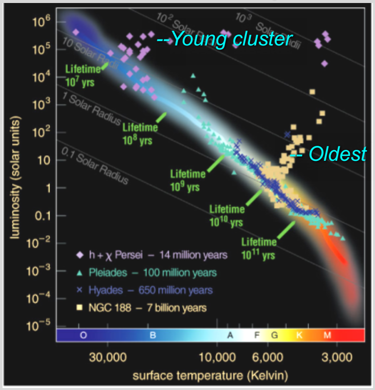
Clusters can test lifetimes on main sequence

Great advantages:
All stars at about same distance (apparent brightness tracks luminosity)

All formed at about same time

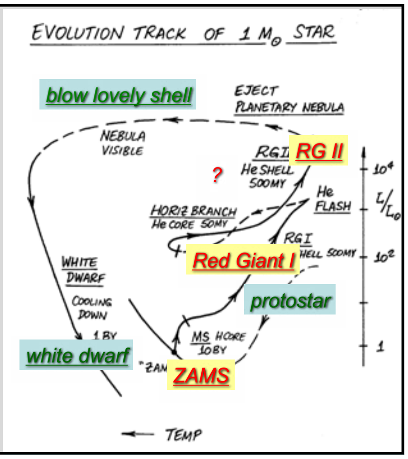
Range of different mass stars !

Stars "peel off" MS as core H exhausted
→ red giants



Life track in H-R diagram of solar-mass star

Many meanders, but MS phase longest, red giant phase(s) shorter, finally white dwarf left to cool slowly

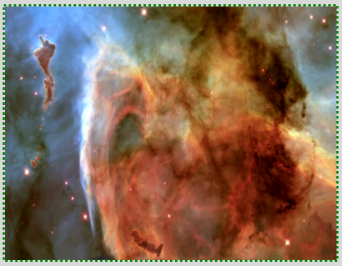


But how did stars GET to the main sequence?

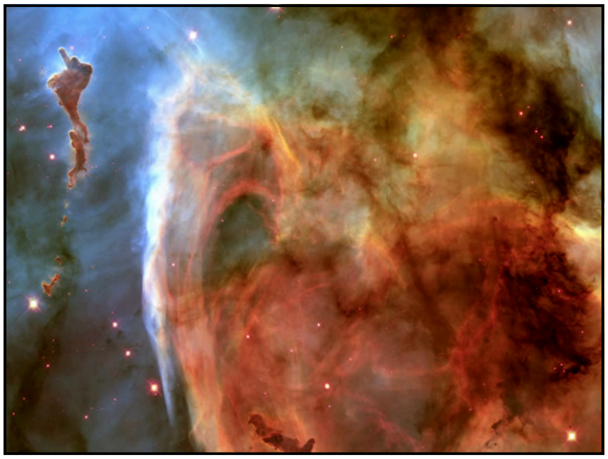
… STAR BIRTH

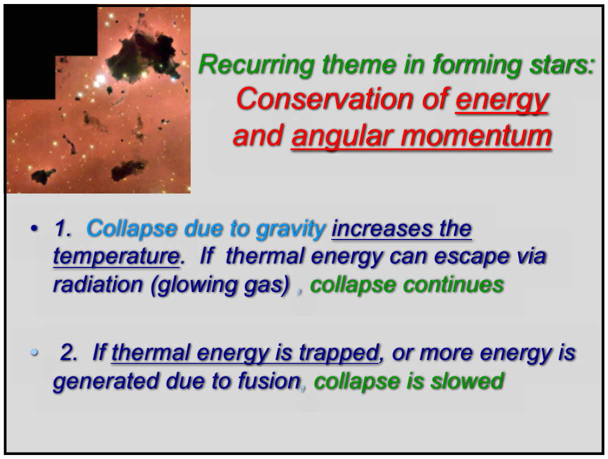
STAR BIRTH within big cold clouds

Start with clouds of cold, interstellar gas



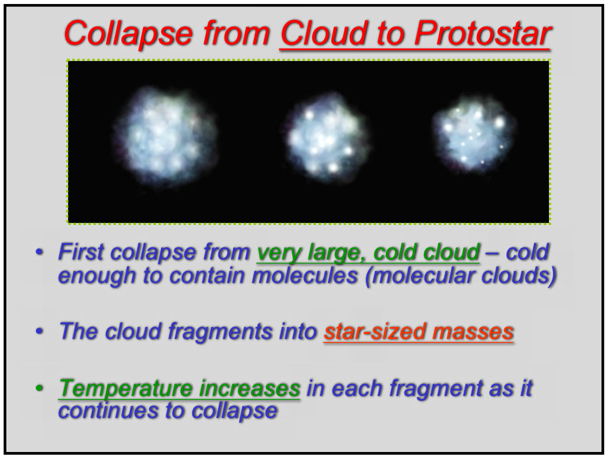
- Molecular clouds -- cold enough to form molecules T=10-30K
- Often dusty
- Collapses under its own gravity





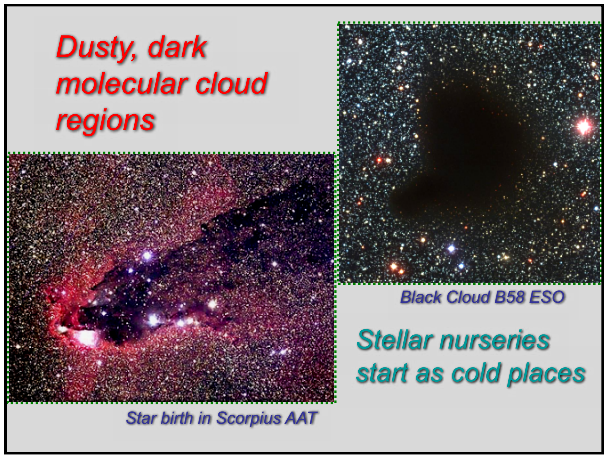
Recurring theme in forming stars:
Conservation of energy and angular momentum

- *1. Collapse due to gravity increases the temperature. If thermal energy can escape via radiation (glowing gas), collapse continues*
- *2. If thermal energy is trapped, or more energy is generated due to fusion, collapse is slowed*



Collapse from Cloud to Protostar

- *First collapse from very large, cold cloud – cold enough to contain molecules (molecular clouds)*
- *The cloud fragments into star-sized masses*
- *Temperature increases in each fragment as it continues to collapse*

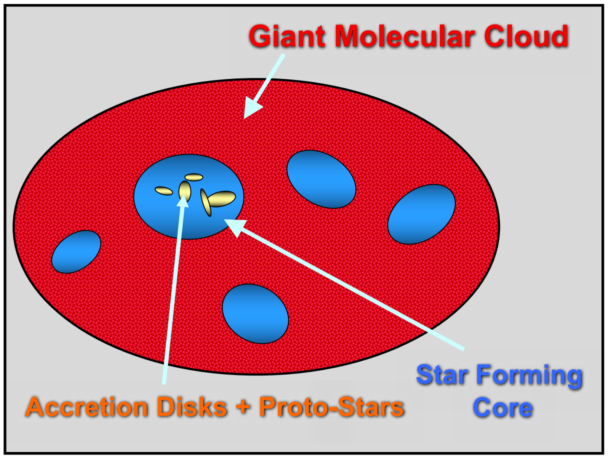


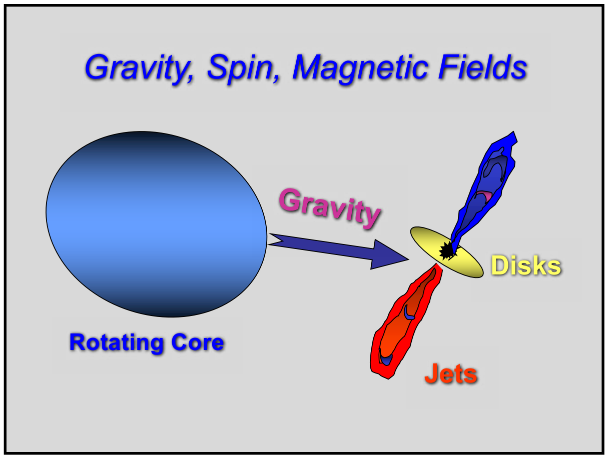
Dusty, dark molecular cloud regions

Black Cloud B58 ESO

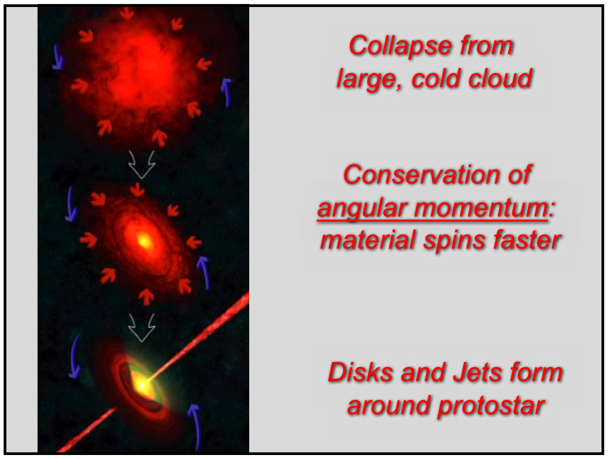
Star birth in Scorpius AAT

Stellar nurseries start as cold places





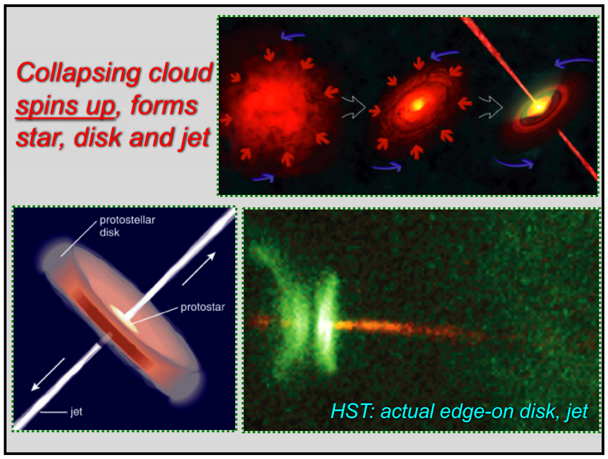
Gravity, Spin, Magnetic Fields



Collapse from large, cold cloud

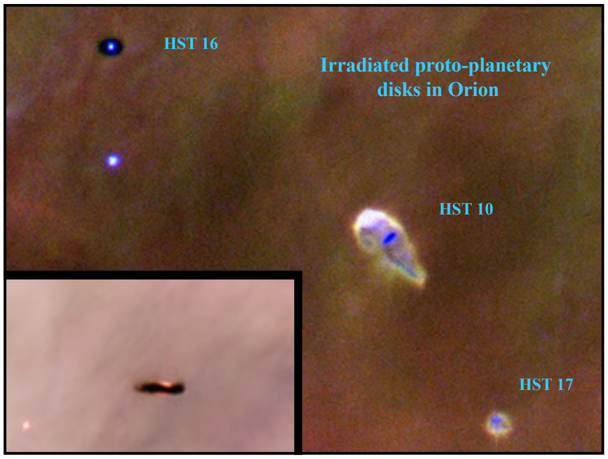
Conservation of angular momentum: material spins faster

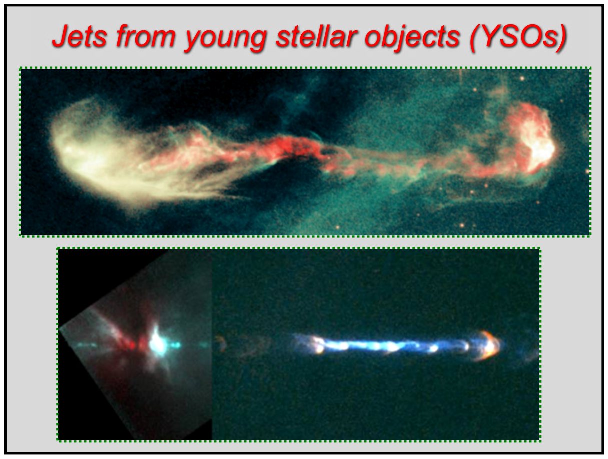
Disks and Jets form around protostar



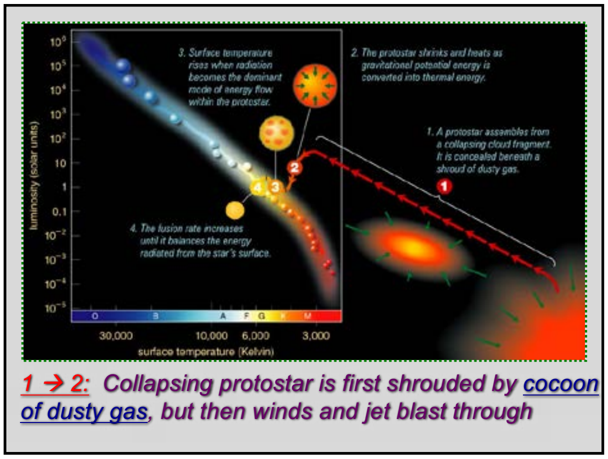
Collapsing cloud spins up, forms star, disk and jet

HST: actual edge-on disk, jet





Jets from young stellar objects (YSOs)



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

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

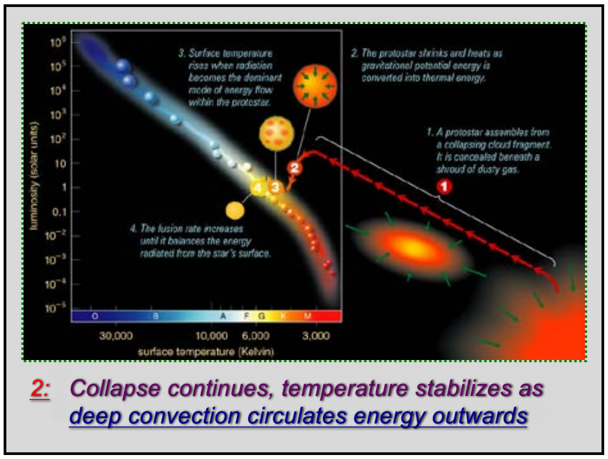
1. A protostar assembles from a collapsing cloud fragment. It is concealed beneath a shroud of dusty gas.

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

1 → 2: *Collapsing protostar is first shrouded by cocoon of dusty gas, but then winds and jet blast through*

Infrared view of winter sky (10 - 120 mm)

IR lets us look into the dark clouds



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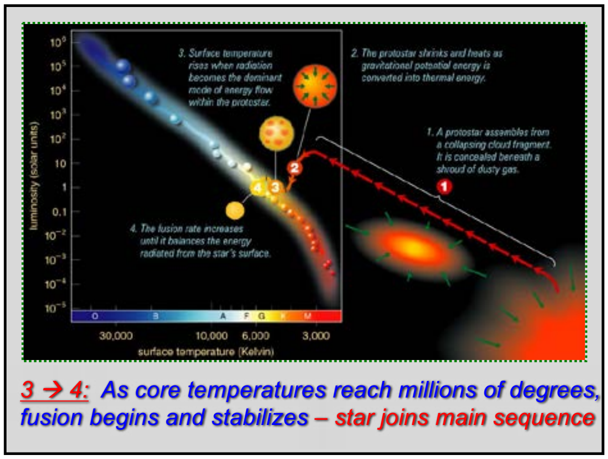
2: Collapse continues, temperature stabilizes as deep convection circulates energy outwards



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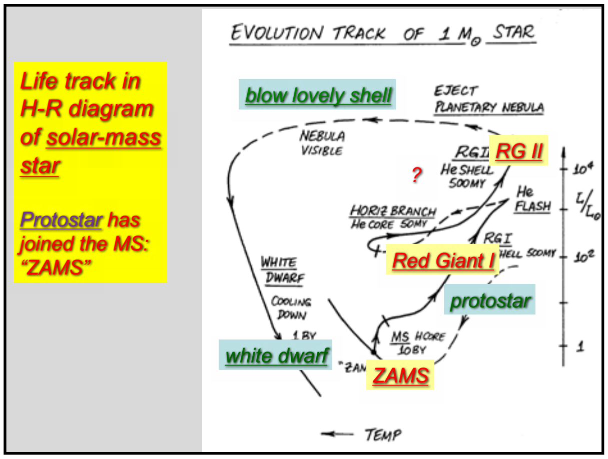
3 → 4: As core temperatures reach millions of degrees, fusion begins and stabilizes – star joins main sequence



Life track in H-R diagram of solar-mass star

Protostar has joined the MS: "ZAMS"

EVOLUTION TRACK OF 1 $M_\odot$ STAR