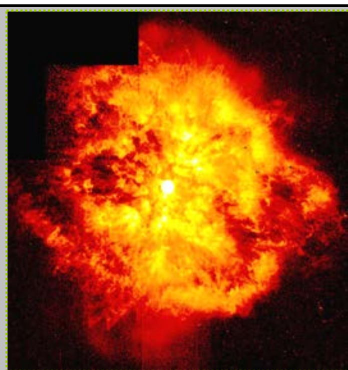
ASTR 1040: Stars & Galaxies



Winds from Massive Star

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Lecture 13 Tues 28 Feb 2017

zeus.colorado.edu/astr1040-toomre

Topics for Today

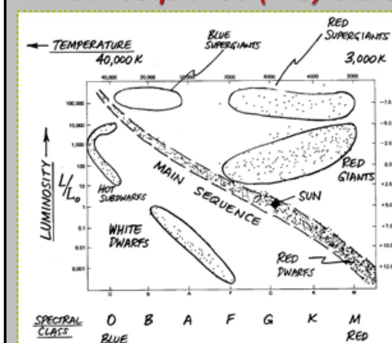
- Briefly look at life in stars AFTER they have exhausted the hydrogen fuel in their cores – return to this in Thur+ lecture
- But first look at how do stars get to the "Main Sequence" – with MS their longest phase
- Examine birth of stars in molecular clouds
- Find many more M and G stars are made than 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 Birth of Stars 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'
- Observatory # 4 tonight, but dubious since snow possible
- Class meets in Fiske Planetarium next Tues March 7 -- go there directly

Main sequence (MS) stars

REMINDER



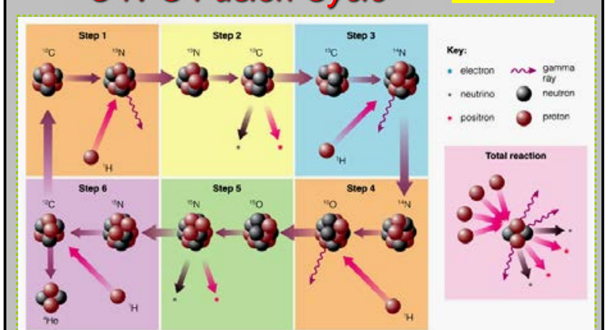
Burning hydrogen in their cores

Temperatures are hotter for more massive stars (crush of gravity)

More luminous (higher fusion rates)

C-N-O Fusion Cycle

REMINDER



Can provide vast luminosity for massive stars on MS

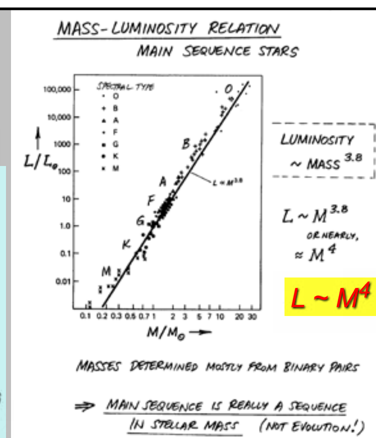
"Observed" MASS -- LUMINOSITY relation for main sequence

But why such a steep variation with mass ?

BIGGER CRUSH OF GRAVITY needs

→ HIGHER central PRESSURE (or temperature)

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



$L \sim M^4$

How long can stars burn H in their cores?

TIME TO BURN UP HYDROGEN IN CORE
... OR "LIFE ON MAIN SEQUENCE"

OTHER STARS COMPARED TO SUN:

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

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

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

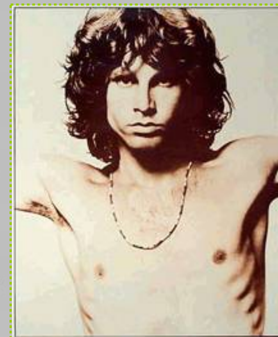
⇒ MASSIVE STARS HAVE SHORT LIVES!

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)

More massive star have (very) short lives

Short lives of massive stars on MS

- Rock-star analogy:



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

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

Estimating LIFE on MS

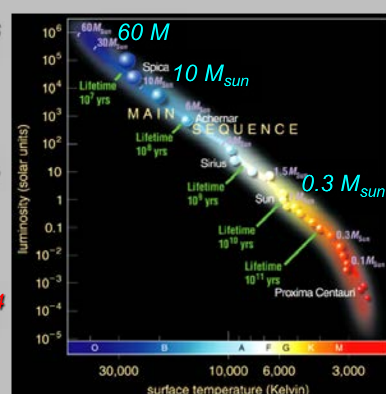
Four steps in our estimate

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: $(E = mc^2)$
   $E_{TOTAL} = 0.1 \times 0.007 \times \underbrace{M_\odot c^2}_{1.8 \times 10^{54} \text{ ergs}}$
   $= 1.3 \times 10^{51}$ ergs
3. ENERGY LOST AT RATE: (LUMINOSITY)
   $L_\odot = 3.9 \times 10^{33}$ ergs/sec
4. LIFETIME ON MAIN SEQUENCE:
   LUMINOSITY × LIFETIME = TOTAL ENERGY OUTPUT
   $L_\odot \times t_{LIFE} = E_{TOTAL}$
   OR $t_{LIFE} \sim \frac{E_{TOTAL}}{L_\odot} = 3 \times 10^{17}$ 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, higher MASS, shorter LIFE

How MS stars do it

THEORY OF MAIN SEQUENCE STARS

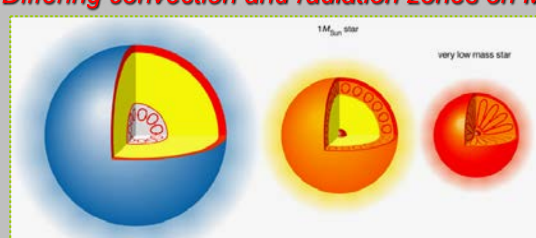
SAME 3 PRINCIPLES AS SUN!

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 $4H \Rightarrow {}^4He$ IN CORE

"DEFINITION" OF MAIN SEQUENCE STAR!

Differing convection and radiation zones on MS

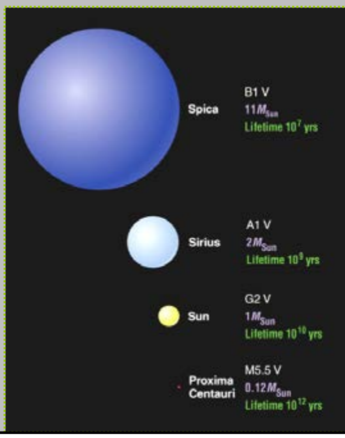


High mass: convective core, deep radiative envelope

Solar mass: radiative interior, convective envelope

Low mass: very deep convective envelope

Deeper convection may yield fiercer magnetic dynamos

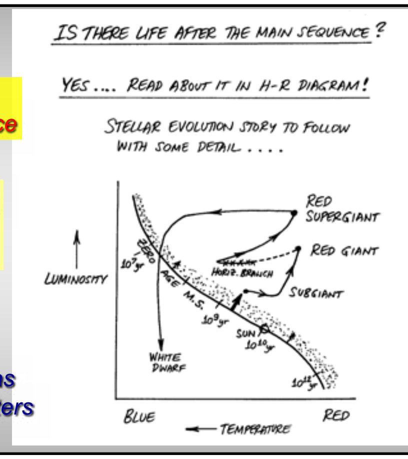


Sizes of stars
main sequence

Life AFTER
main sequence

Stars evolve off MS, not along it !

Now let us test such ideas with star clusters



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

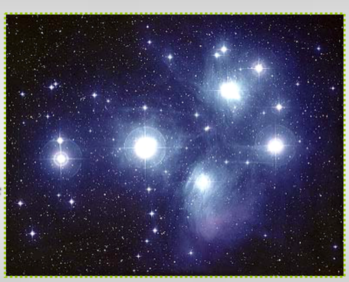
Open cluster
young, thousands of stars

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

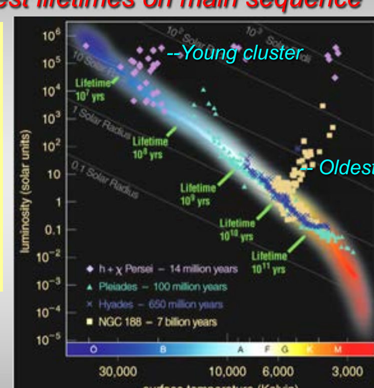
Clusters can test lifetimes on main sequence

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

All formed at about same time

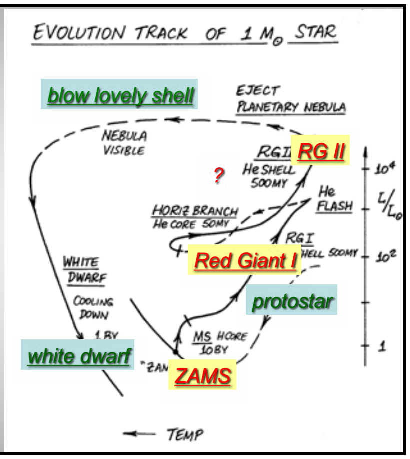
Range of different mass stars !

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



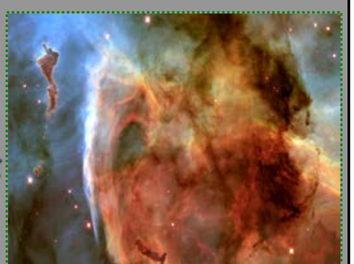
But how did stars GET to the main sequence?

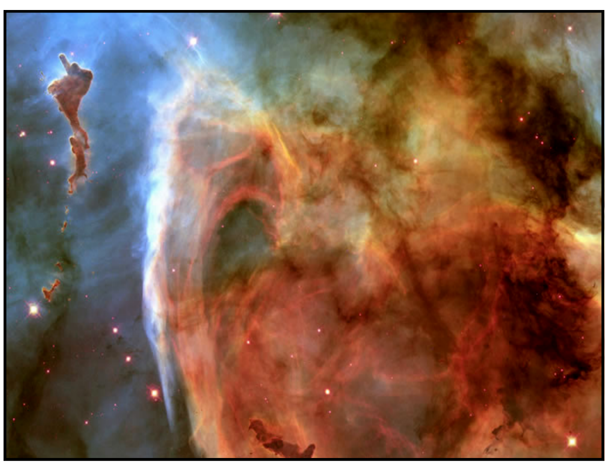
… STAR BIRTH

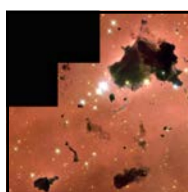
STAR BIRTH within big cold clouds

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

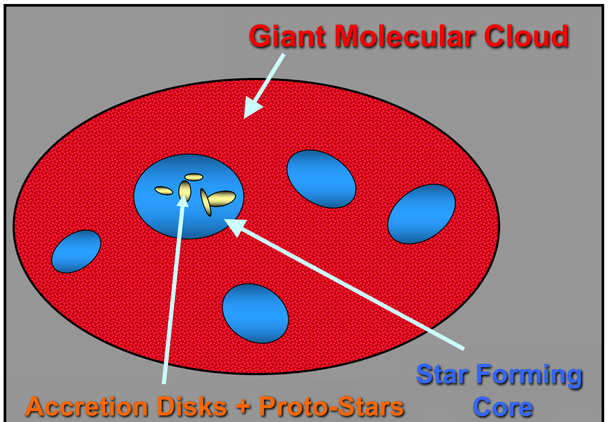
- First collapse from very large, cold cloud – cold enough to contain molecules (molecular clouds)
- The cloud fragments into star-sized masses
- Temperature increases in each fragment as it continues to collapse

Dusty, dark molecular cloud regions

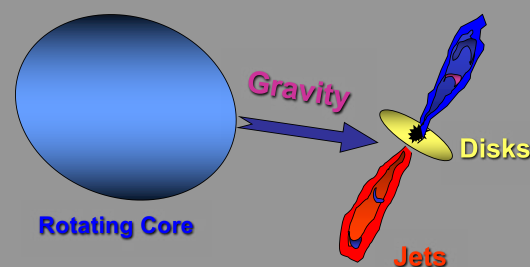
Black Cloud B58 ESO

Star birth in Scorpius AAT

Stellar nurseries start as cold places



Gravity, Spin, Magnetic Fields

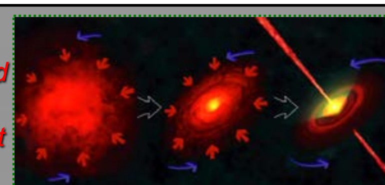


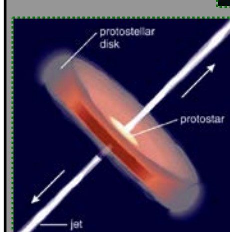
Collapse from large, cold cloud

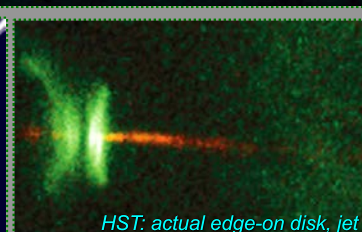
Conservation of angular momentum: material spins faster

Disks and Jets form around protostar

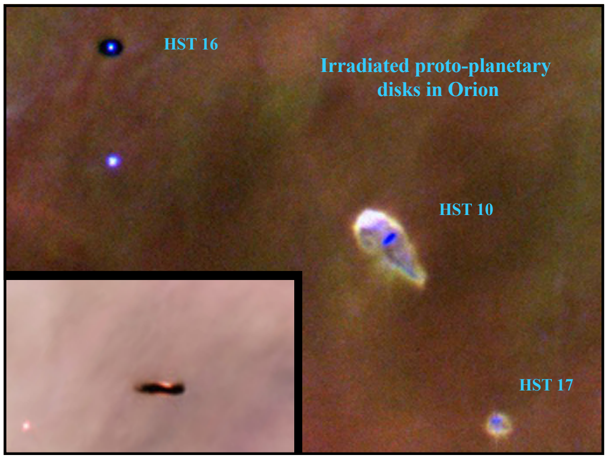
Collapsing cloud spins up, forms star, disk and jet

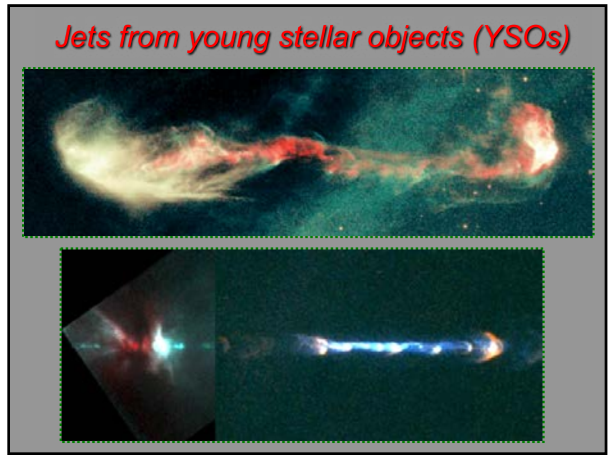


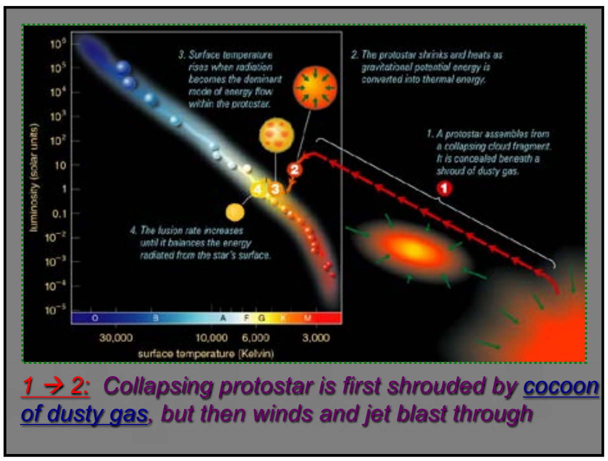




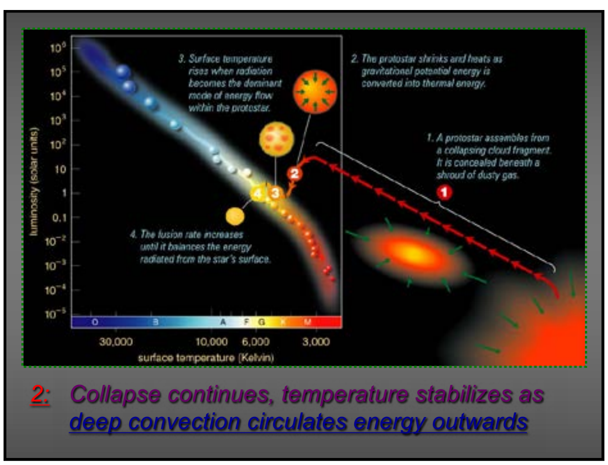
HST: actual edge-on disk, jet


HST 16
Irradiated proto-planetary disks in Orion
HST 10
HST 17


Jets from young stellar objects (YSOs)


luminosity (solar units)
surface temperature (Kelvin)
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
IR lets us look into the dark clouds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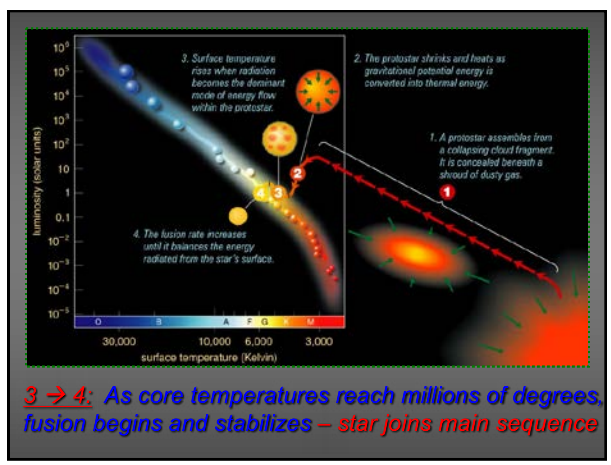
2: Collapse continues, temperature stabilizes as deep convection circulates energy outwards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4. The fusion rate increases until it balances the energy radiated from the star's surface.
3 → 4: As core temperatures reach millions of degrees, fusion begins and stabilizes – star joins main sequence