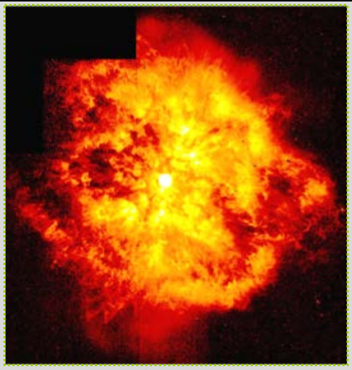
ASTR 1040: Stars & Galaxies



Winds from Massive Star

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Lecture 13 Tues 25 Feb 2020

zeus.colorado.edu/astr1040-toomre

Topics for Today + Thur

- Begin by first looking at stars near end of lives on "Main Sequence" as they exhaust hydrogen fuel in their cores
- Then look at how 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
- Return to post-MS life on Thur

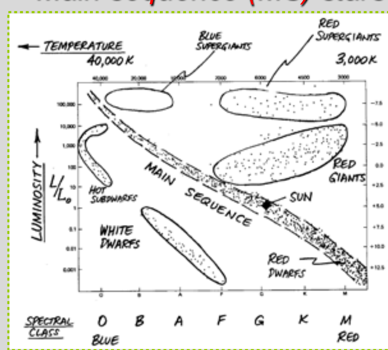
Things to do

- 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'

- Overview on Stellar Evolution passed out
- HW #5 returned graded, with answer sheet
- Observatory Night #4 tonight, by signup

Main sequence (MS) stars

REMINDER



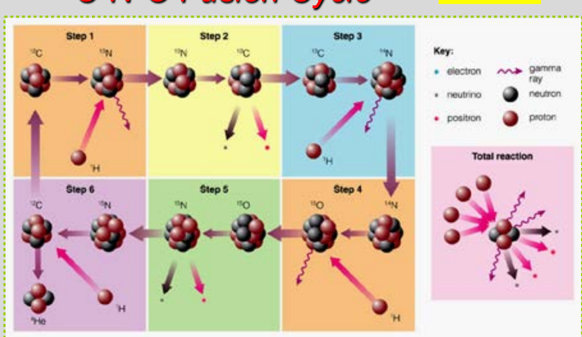
Burning hydrogen in their cores

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

More luminous (higher fusion rates)

C-N-O Fusion Cycle

REMINDER



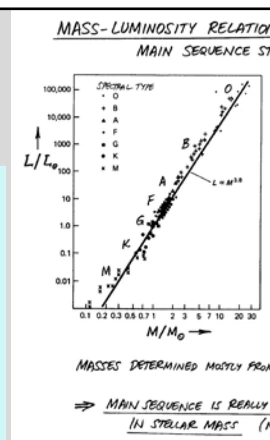
Can provide vast luminosity for massive stars on MS

"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)



REMINDER

$L \sim M^4$

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: **REMINDER**

ENERGY: $E_{TOTAL} \propto MASS \quad (\propto M)$ (∝ = PROPORTIONAL TO)

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

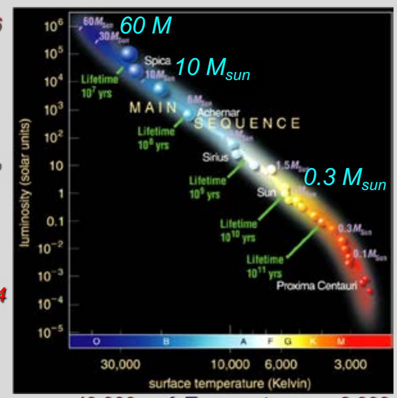
1. CONSIDER SUN ($1 M_\odot$) AS EXAMPLE:
   ~ 10% BY TOTAL MASS CAN CORE BURN 0.1
   0.7% MASS ⇒ ENERGY 0.007
2. TOTAL ENERGY SUPPLY: ($E = mc^2$)
   $E_{TOTAL} = 0.1 \times 0.007 \times \underbrace{M_\odot c^2}_{1.8 \times 10^{54} ergs}$
   $= 1.3 \times 10^{51}$ ergs
3. ENERGY LOST AT RATE: (LUMINOSITY)
   $L_\odot = 3.9 \times 10^{33}$ 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

10^6

L / L_o

10^{-4}



40,000 ← Temperature 3,000

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

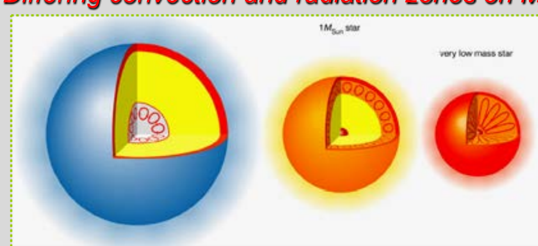
SAME 3 PRINCIPLES AS SUN!

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

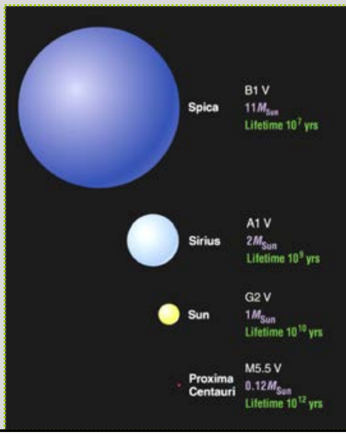
"DEFINITION" OF MAIN SEQUENCE STAR!

Differing convection and radiation zones on MS



High mass:	Solar mass:	Low mass:
convective core, deep radiative envelope	radiative interior, convective envelope	very deep convective envelope

Deeper convection may yield fiercer magnetic dynamos

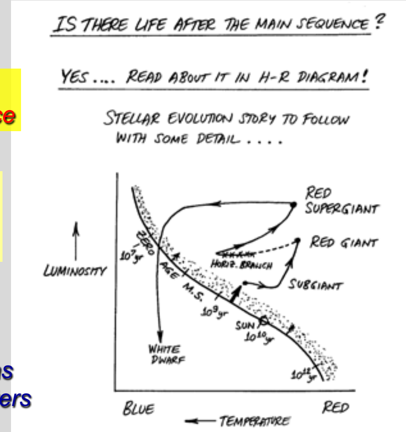


Sizes of stars main sequence

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

SUBARU

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

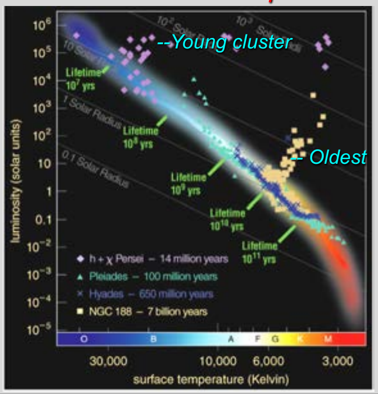
Clusters can test lifetimes on main sequence

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

All formed at about same time

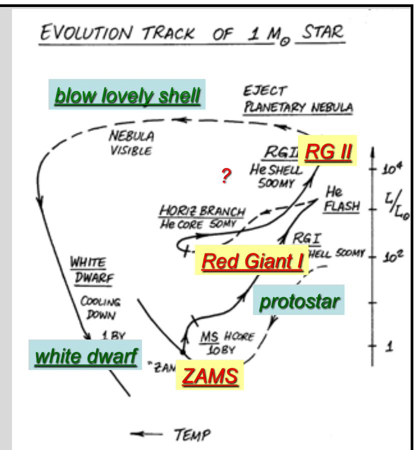
Range of different mass stars !

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



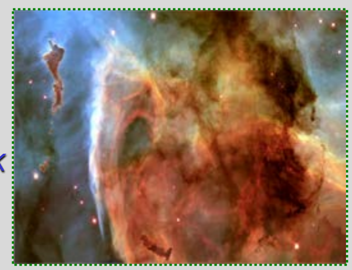
But how did stars GET to the main sequence?

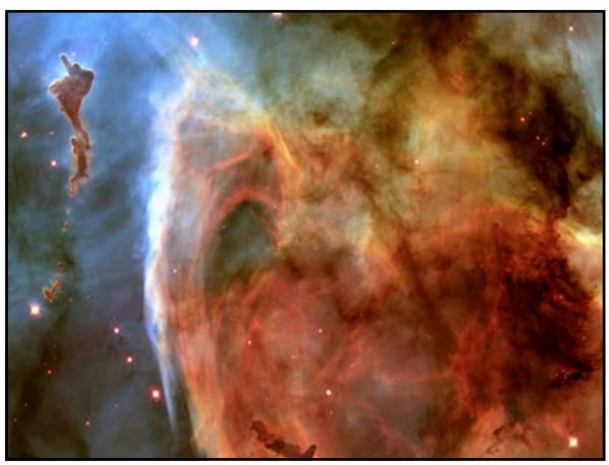
… STAR BIRTH

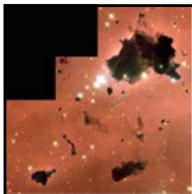
STAR BIRTH within big cold clouds

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

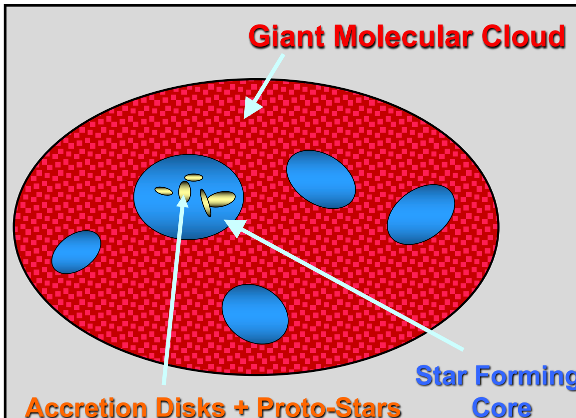
- First collapse from very large, cold cloud – cold enough to contain molecules (molecular clouds)
- The cloud fragments into star-sized masses
- Temperature increases in each fragment as it continues to collapse

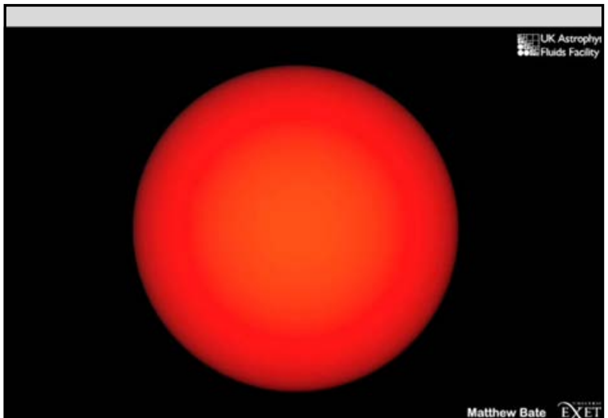
Dusty, dark molecular cloud regions

Black Cloud B58 ESO

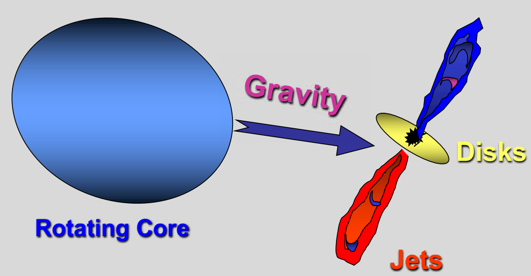
Star birth in Scorpius AAT

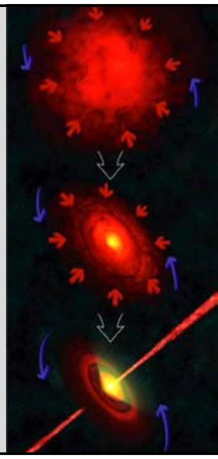
Stellar nurseries start as cold places





Gravity, Spin, Magnetic Fields



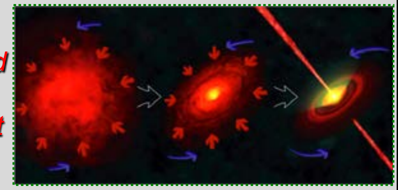


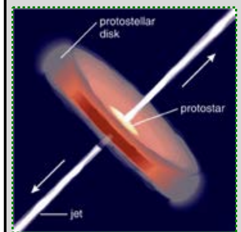
Collapse from large, cold cloud

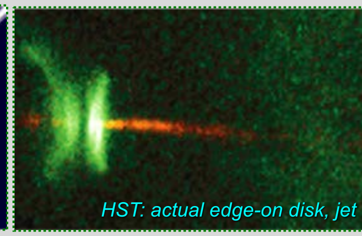
Conservation of angular momentum: material spins faster

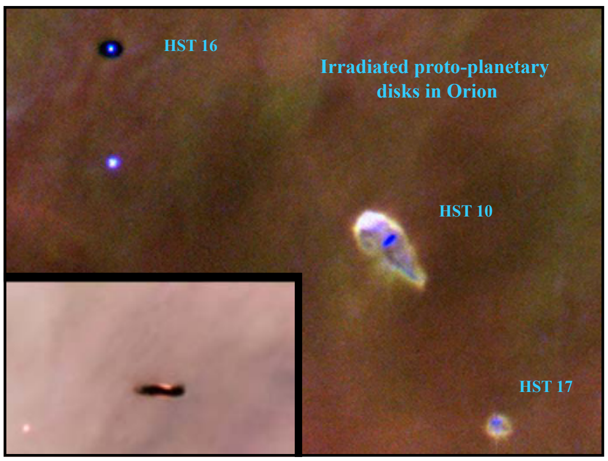
Disks and Jets form around protostar

Collapsing cloud spins up, forms star, disk and jet

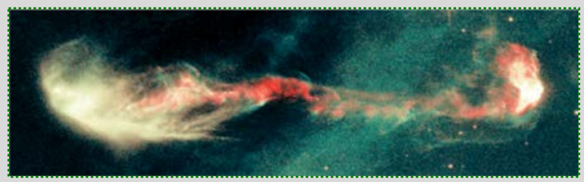


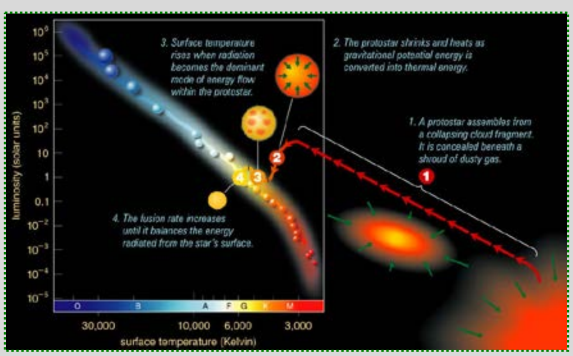




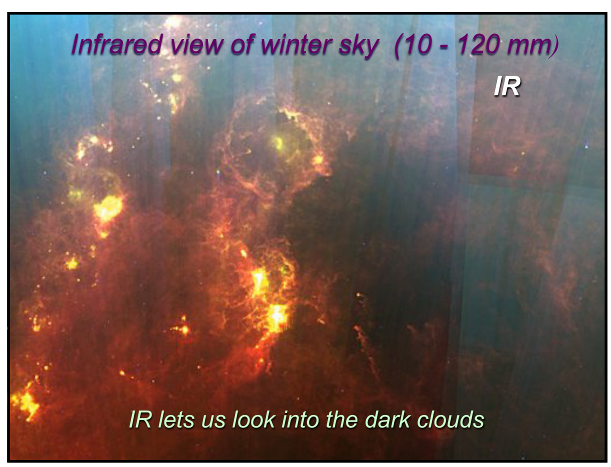


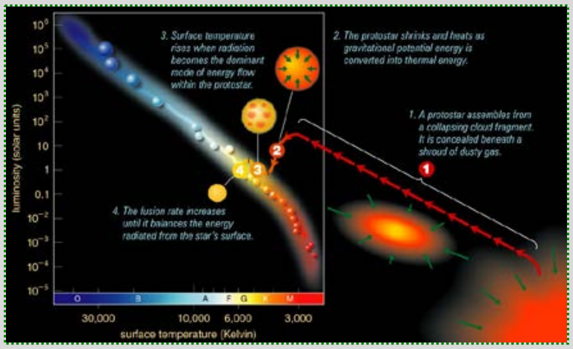
Jets from young stellar objects (YSOs)



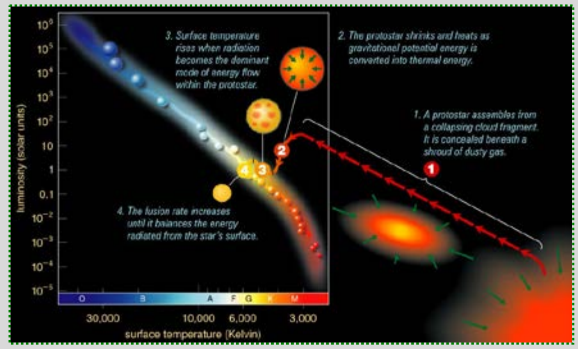


1 → 2: Collapsing protostar is first shrouded by cocoon of dusty gas, but then winds and jet blast through





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

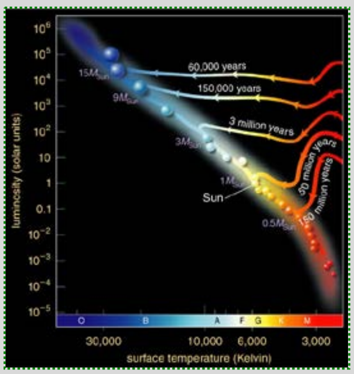


3 → 4: As core temperatures reach millions of degrees, fusion begins and stabilizes – star joins main sequence

Protostars of different masses follow different life tracks toward MS

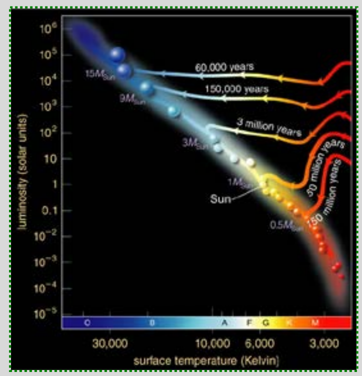
More massive stars go more quickly, and nearly horizontally across H-R diagram

Life now begins on "zero-age main sequence" (ZAMS)

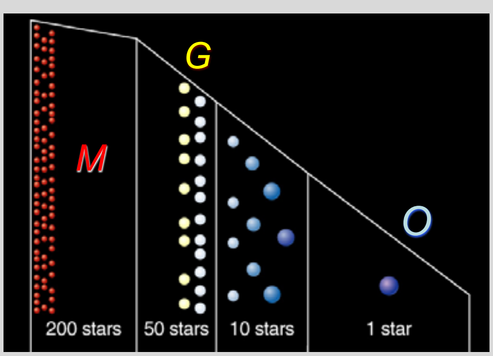


Starbirth and color

For every massive O-star that is born, there are ~200 low-mass M-stars also born !



What kinds of stars are made?



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

Protostar has joined the MS: "ZAMS"