


ASTR 1040: Stars & Galaxies



Etched Hourglass Nebula

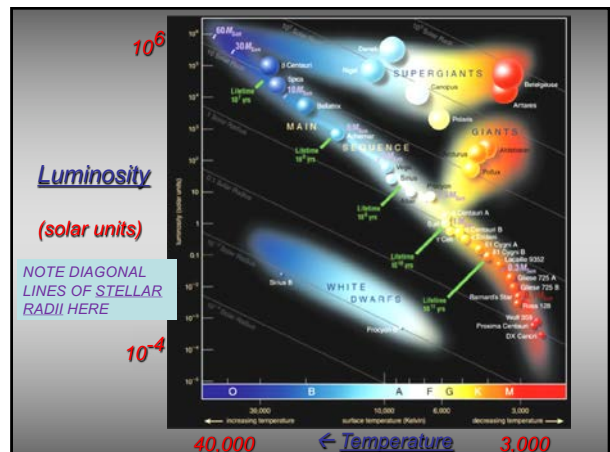
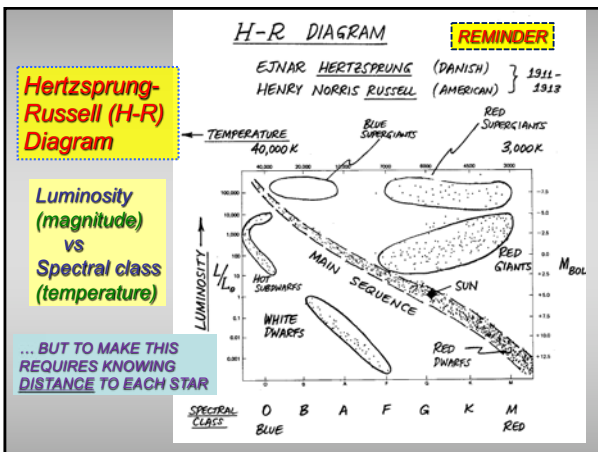
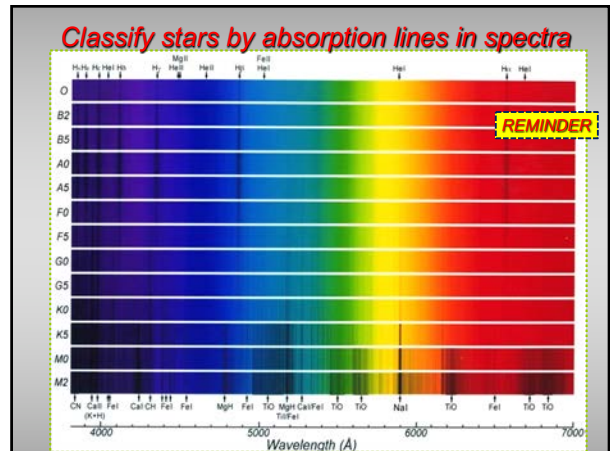
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Lecture 12 Thur 4 Oct 2018
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Stuff to do

- **Paper shuffle:** Homework #5 due, new HW #6 passed out. Graded MT-Exam 1 still available. The overall grade points on exam reduced to 106 from 110, with Q44 and Q45 not counted. Grade boundaries remain same.
- Re-read 15.3 Star Clusters with care, and review all of Chap 15 "Surveying the Stars"
- Read 16.1 "Stellar Nurseries" & 16.2 "Stages of Star Birth" for Tues lecture (getting to the Main Sequence)

Topics for Today

- Brief review of roadmap to the stars: Hertzsprung-Russell (H-R) diagram
- **Binary stars** allow us to measure **MASS**
- Why O and B stars are so luminous on MS?
- C-N-O cycle dominates fusion burning of H in massive stars, really pours out the energy
- Explains observed **MASS-LUMINOSITY** relation
- Estimate lifetime on the main sequence (MS)
- What **star clusters** can tell us



Further refinements:

DECIMAL SUBDIVISION

LUMINOSITY CLASSES

Sun is: G2 V

COLOR CLASS

STARS: REFINEMENTS IN CLASSIFYING THEM

REMINDER

SUBDIVISION OF SPECTRAL COLOR CLASSES:

```

    A --- G0
    |   |
    F   G1
    |   |
    G   G2
    |   |
    K   G3
    |   |
    |   G4
    |   |
    |   G5
    |   |
    |   G6
    |   |
    |   G7
    |   |
    |   G8
    |   |
    |   G9
  
```

LUMINOSITY CLASSES:

FOR THE SAME COLOR OF STAR (SPECTRAL CLASS), LARGER STARS HAVE NARROWER ABSORPTION LINES

WHY? PRESSURES AT SURFACE ARE GREATER, ATOMS ARE LESS DISTURBED BY COLLISIONS

EXAMPLE:

THIS LUMINOSITY (OR "TECHNICAL") CLASSIFICATION:

SUN: G2 V

COLOR CLASS

I SUPERCANTANTS
 II BRIGHT GIANTS
 III GIANTS
 IV SUBGIANTS
 V MAIN SEQUENCE (OR DWARF) FAINTLY

Why do visible spectra of hottest stars (O and B types) show few absorption lines?

E.

- A. Many elements have been used up in these stars
- B. These stars are old and were formed before there were many elements in the galaxy
- C. Many atoms in these stars are ionized – have lost electrons – so cannot absorb
- D. Much of their absorption is in the ultraviolet
- E. C and D

Estimating the size of a star – its RADIUS

Stefan-Boltzmann

But how to measure MASS: ... binary stars

MEASUREMENTS OF STARS:

REMINDER

TEMPERATURE (from spectral lines)

BRIGHTNESS } ⇒ LUMINOSITY

DISTANCE } (NEARBY STARS < 100 PC)

RECALL STEFAN-BOLTZMANN LAW:

$$L = 4\pi R^2 \times \sigma \times T^4$$

↑ LUMINOSITY (MEASURED) ↑ STAR'S RADIUS (UNKNOWN) CONSTANT ↑ TEMPERATURE (MEASURED)

⇒ LUMINOSITY & TEMP ⇒ RADIUS

BUT HOW TO GET THE MASS?

(TRICKIER: USE BINARIES)

"Proper motions"

wiggly motions (parallax) and binaries ...

STELLAR MOTIONS IN SKY... WITH RESPECT TO "FIXED STARS"

PROPER MOTION CAUSED BY:

- ACTUAL MOTION OF STARS RELATIVE TO SUN
- MOTION OF SUN AROUND OUR GALAXY

BIG DIPPER IS CHANGING

WIGGLY LOOPS IN PATHS OF NEARBY STARS = PARALLAX:

- DUE TO EARTH MOTION AROUND SUN
- ONE LOOP PER YEAR
- SIZE OF LOOP ~ 1/DISTANCE

10⁶ YEARS AGO, TODAY, 10⁶ YEARS IN FUTURE

BINARY STARS

BINARY STARS

4 varieties:

Visual Astrometric Spectroscopic Eclipsing

Use to measure stellar masses

BINARY STARS MORE THAN 1/2 OF ALL STARS!

EVIDENCE OF ORBITAL MOTION (... HOW WE DETECT THEM):

- VISUAL BINARY** TRACK PROPER MOTIONS OF BOTH STARS
- ASTROMETRIC BINARY** WIGGLY MOTION OF ONE STAR REVEALS UNSEEN COMPANION
- SPECTROSCOPIC BINARY** ABSORPTION LINES OF ONE OR BOTH STARS SHOW PERIODIC DOPPLER SHIFTS
- ECLIPSING BINARY**
 - ONE STAR BLOCKS OR ENHANCES LIGHT FROM OTHER
 - REVEALS PROPERTIES FROM PERIODIC LIGHT CURVE

Eclipsing binaries

one star gets in front or behind other

ECLIPSING BINARY STAR SYSTEMS

STARS IN CLOSE ORBITS CAN BLOCK OR ENHANCE LIGHT

SHAPE OF PERIODIC LIGHT CURVE CAN BE USED TO DEDUCE ORBITS AND NATURE OF COMPANIONS

TWO STARS ABOUT SAME SIZE: PARTIAL ECLIPSES

SIZE OF UNOCCULTED STAR: TOTAL AND ANNULAR ECLIPSES

AS ABOVE, BUT WITH DIFFERENTIAL DISTANCE OF STARS

WHAT YOU SEE AS OBSERVER IS SENSITIVE TO TILT OF ORBIT PLANE RELATIVE TO YOU!

Eclipsing: Variations in brightness with time

We see light from both A and B. We see light from all of B, some of A. We see light from both A and B. We see light only from A.

apparent brightness

time

Very useful (can even infer stellar radii), but RARE ... viewing angle has to be right on edge!

Spectroscopic Binary System

DETECT AS PERIODIC DOPPLER SHIFTS IN SPECTRA

ORBITS (TOP VIEW) SUCCESSIVE INSTANTS

DOPPLER VELOCITY (POSSIBLY DETECTABLE FROM LINE SHIFTS IN SPECTRA)

RECEDE

APPROACH

TIME

TWO SPECTRA FROM κ AURIGAE "DOUBLE LINE BINARY"

DOUBLE-LINE 1,3

SINGLE 2,4

TWO SPECTRA FROM α CENTAURUS "SINGLE LINE BINARY"

1

2

3

Spectroscopic binaries

Most common of all

Do not see stars individually – but see shifting absorption lines

Sometimes TWO sets

Spectroscopic Binary

Star B spectrum at time 1: approaching, therefore blueshifted

to Earth

Star B spectrum at time 2: receding, therefore redshifted

1 approaching us

2 receding from us

Harder to interpret, since do not know viewing angle

MIZAR the "DEAMON" – four stars, actually

Mizar is a visual binary ...

Alcor

Mizar

Mizar B

Mizar A

... and spectroscopy shows that each of the visual "stars" is itself binary.

Recall from Chap 3 :

KEPLER devised 3 laws for planetary (or stellar) motions

In 1687, NEWTON explained them as balance of gravity and centrifugal force

GRAVITY (INVERSE SQ LAW), ELLIPTICAL ORBITS AND ANGULAR MOMENTUM (INVERSE)

- ARISTOTLE, COPERNICUS (1543), TYCHO BRAHE (~160)
- "PERFECT OBJECTS" MOVE ON CIRCLES (OR CIRCULAR ORBITES)
- KEPLER (1609, 1618) : LAWS OF PLANETARY MOTIONS

ELLIPTIC (CIRCLE HAS 2 FOCI EQUIDISTANT)

MAJOR AXIS

MINOR AXIS

FOCUS

FOCUS

1st LAW: PLANETS ORBIT SUN ON ELLIPSES, SUN AT ONE FOCUS (COMBINED MASS)

2nd LAW: ALL PLANETS MOVE AT CONSTANT SPEED, SWEEPING EQUAL AREA IN EQUAL TIME

3rd LAW: $(\text{ORBITAL PERIOD})^2 \propto (\text{AVERAGE DISTANCE})^3$ (AU)

NEWTON (1687):

GRAVITY FORCE: $F = G \frac{M_1 M_2}{d^2}$

DOUBLE STARS: WEIGHING THEM

BINARIES HELP DETERMINE STELLAR MASS & RADIUS

MEASURE: PERIOD (ONLY)

ORBITAL SPEED (SPECTROSCOPIC BINARIES)

SEPARATION (VISUAL BINARIES)

RECALL KEPLER'S THIRD LAW:

$$(M_1 + M_2) \cdot P^2 = a^3$$

MASS, SOLAR UNITS (UNKNOWN)

PERIOD, YEARS (MEASURED)

SEPARATION, A.U. (EARTH-SUN DIST) (MEASURED)

\Rightarrow PERIOD & SEPARATION \Rightarrow MASS

ECLIPSING BINARIES:

ORBITAL SPEED & ECLIPSE DURATION

\Rightarrow RADIUS

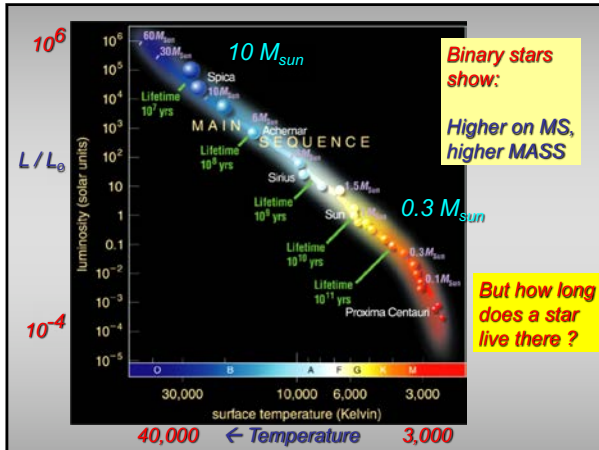
(INDEPENDENT MEASURE)

So why all the fuss with BINARIES?

Can really "weigh" a star !

STELLAR MASSES can be inferred from watching orbits

(via law of gravity – Kepler and Newton)

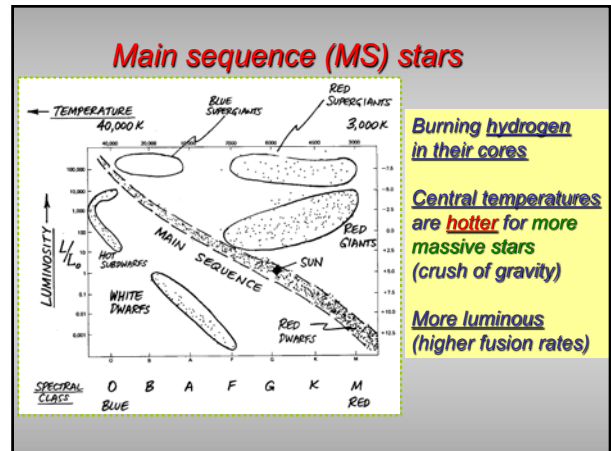


Brightness / Distance **B.** Clicker Q

- Leonardo and Guinevere are two stars that have the same apparent brightness. Leonardo has a larger parallax angle than Guinevere. Which star is more luminous?
- **A.** Leonardo
- **B.** Guinevere
- **C.** Cannot determine from data given

Brightness vs Distance

- Leonardo has a larger parallax angle -- thus he is closer to us
- They both have the same APPARENT brightness, but Leo is closer
- **B.** Guinevere must be more luminous



Lifetimes on Main Sequence (MS)

- Stars spend 90% of their lives on MS
- **Lifetime on MS** = amount of time star burns hydrogen (gradually) in its core
- For Sun, this is about 10 billion years
- For more massive stars (OBAF), lifetime is (much) shorter
- For less massive stars (KM), lifetime is longer
- But how do we get these numbers?

Look at broad sample, to figure out any lifespan

- Stars take millions to billions of years to go through their life stages - we rarely see a single star change
- Observing many different stars lets us figure out the sequence of a single star's life

P-P Chain & C-N-O Cycle

Both fusion processes occur in parallel, but C-N-O makes far more energy at higher temperatures

Stars hotter than F1, C-N-O wins

THERMONUCLEAR FUSION: HYDROGEN BURNING

PROTON-PROTON CHAIN

C-N-O CYCLE

C-N-O CYCLE DOMINATES ENERGY PRODUCTION AT HIGHER TEMPERATURES:

$$\begin{aligned}
 &^{12}\text{C}_6 + ^1\text{H}_1 \rightarrow ^{13}\text{N}_7 + \gamma \\
 &^{13}\text{N}_7 \rightarrow ^{13}\text{C}_6 + e^+ + \nu \\
 &^{13}\text{C}_6 + ^1\text{H}_1 \rightarrow ^{14}\text{N}_7 + \gamma \\
 &^{14}\text{N}_7 + ^1\text{H}_1 \rightarrow ^{15}\text{O}_8 + \gamma \\
 &^{15}\text{O}_8 \rightarrow ^{15}\text{N}_7 + e^+ + \nu \\
 &^{15}\text{N}_7 + ^1\text{H}_1 \rightarrow ^{12}\text{C}_6 + ^4\text{He}_2
 \end{aligned}$$

4 HYDROGEN + CARBON
HELIUM + ENERGY + CARBON TO RECYCLE!

C-N-O Fusion Cycle

Can provide vast luminosity for massive stars on MS

C-N-O Cycle (another view)

Main Sequence:

range of stellar properties

L range is biggest!

THE MAIN SEQUENCE:

STARS BURNING HYDROGEN IN CORE

RANGE OF PROPERTIES

(RED GIANTS, WHITE DWARFS NOT MAIN SEQUENCE STARS: SHOW DIFFERENT EXTREMES OF P, L, ...)

SUN IS "INTERMEDIATE" MAIN SEQ. STAR

MASS: 0.01 → 100 M_☉

TEMPERATURE: ~ 2,000 → 100,000 K (SURFACE)

RADIUS: 0.01 → 100 R_☉

LUMINOSITY: 0.001 → 100,000 L_☉

LUMINOSITY ~ (MASS)^{3.8}

RADIUS ~ (MASS)^{0.75} (ROUGHLY)

"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)

MASS-LUMINOSITY RELATION MAIN SEQUENCE STARS

LUMINOSITY ~ MASS^{3.8}

L ~ M^{3.8} OR NEARLY, ~ M⁴

L ~ M⁴

MASSSES DETERMINED MOSTLY FROM BINARY PAIRS

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

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

OTHER STARS COMPARED TO SUN:

ENERGY E_{TOTAL} ∝ MASS (∝ M)

LUMINOSITY L ∝ (MASS)^{3.8} (∝ M⁴) ← MASS-LUMINOSITY RELATION

LIFETIME t_{LIFE} ~ E_{TOTAL} / L ∝ M⁻³ (ROUGHLY)

⇒ MASSIVE STARS HAVE SHORT LIVES!

| MASS (M _☉) | LIFETIME (MILLION YEARS) |
|------------------------|---------------------------|
| 1 | 10,000 MY ≈ 100BY |
| 2 | 700 |
| 3 | 250 |
| 5 | 70 |
| 10 | 20 |
| 15 | 10 |
| 30 | 5 (LOWER OFF AT A FEW MY) |

How long can stars burn H in their cores?

More massive star have (very) short lives

