2018 Div. C (High School) Astronomy Help Session
Sunday, Feb. 17th, 2019
Stellar Evolution in normal and star burst galaxies
Scott Jackson Mt. Cuba Astronomical Observatory

• SO competition on March 2nd

• Resources
  – two computers or two 3 ring binder or one laptop plus one 3 ring binder
  – Programmable calculator
  – Connection to the internet is not allowed!
  – Help session before competition at Mt. Cuba Astronomical Observatory
1. **DESCRIPTION:** Teams will demonstrate an understanding of stellar evolution **in normal & starburst galaxies.**

**A TEAM OF UP TO:** 2  

**APPROXIMATE TIME:** 50 minutes

2. **EVENT PARAMETERS:**
   a. Each team may bring one of the following options containing information in any form and from any source:
      i. two three-ring binders;
      ii. a computer/tablet and a three-ring binder; or,
      iii. two computers/tablets, of any kind.
   b. If three ring binders are used they may be of any size and the information contained should be attached using the available rings. The information or pages may be removed during the event. Sheet protectors and laminated sheets are allowed.
   c. Each team may bring **two stand-alone calculators of any type** to use during the event. **If the participants are using a computer/tablet they may use a calculator app or other program on their device in place of a stand-alone calculator.**
   d. No Internet access is allowed during any part of this event. **Participants using computers/tablets as a resource should have all information stored so that it is available to them off-line.**

3. **THE COMPETITION:**
   Using information which may include Hertzsprung-Russell diagrams, spectra, light curves, motions, cosmological distance equations and relationships, stellar magnitudes and classification, multi-wavelength images (X-ray, UV, optical, IR, radio), charts graphs and **JS9 imaging analysis software,** teams will complete activities and answer questions related to:
   a. Stellar evolution, including stellar classification, spectral features and chemical composition, luminosity, blackbody radiation, color index and H-R diagram transitions, **star formation,** Cepheids, **RR Lyrae stars,** Type Ia & Type II supernovas, neutron stars, pulsars, stellar mass black holes, supermassive black holes, X-ray & gamma-ray binary systems, **ultraluminous X-ray sources** (ULXs), globular clusters, stellar populations, **normal & starburst galaxies; galactic structure and interactions, gravitational waves.**
   b. Use Kepler’s laws, rotation and circular motion to answer questions relating to the orbital motions of binary systems and galaxies; use parallax, spectroscopic parallax the distance modulus, **the period-luminosity relationship,** Hubble’s law and **the Tully-Fisher relationship** to calculate distances.
c. Identify and answer questions relating to the content areas outlined above for the following objects:

i. M51/NGC 5195
ii. IC 10
iii. SPT 0346-52
iv. M81/M82
v. ESO 137-001
vi. SN2014
vii. Phoenix Cluster
viii. NGC 4993
ix. 47 Tucanae/X9
x. Chandra deep field-south
xi. Cen A
xii. M100
xiii. Abell 400/NGC 1128/3C 75
xiv. Antennae Galaxies
xv. Sagittarius A*
Study aid -1

• Google each object,
  – Know what they look like in different parts of the spectrum. For example, the IR, optical, UV and Xray
  – Understand what each part of the spectrum means
  – Have a good qualitative feel for what the object is doing or has done within the astrophysical concepts that the student is being asked to know.
Study aid - 2

- **Know the algebra behind the physics**
  - *Just because you think you have the right “equation” to use does not mean you know how to use it!!!*
  - *Hint for math problems: Solve equations symbolically BEFORE you put in numbers. Things tend to cancel out including parameters you do not need to have values for.*
  - *Know how to use scientific notation.*
The test – 2 parts

• Part 1 – multiple choice and a couple fill in the blanks

• Part 2 – word problems for astrophysics there will be some algebra
  
  → Solve the equations symbolically first then put in numbers!!!!
  
  → Hint: most problems will not need a calculator if done this way
Stellar evolution
- stellar classification,
- spectral features and chemical composition,
- luminosity,
- blackbody radiation,
- color index
- H-R diagram transitions,

*star formation*,

Cepheids,

**RR Lyrae stars,**

**Type Ia** & Type II supernovas,

neutron stars, pulsars, stellar mass black holes,

**supermassive black holes,**

X-ray & gamma-ray binary systems,

**ultraluminous X-ray sources (ULXs), globular clusters, stellar populations, normal & starburst galaxies, galactic structure and interactions, gravitational waves.**

- Kepler’s laws to answer questions relating to the orbital motions of binary systems & galaxies;

Determine distances: parallax, spectroscopic parallax the distance modulus, **the period- luminosity relationship,** Hubble’s law and the **Tully-Fisher relationship**
Objects

Concepts / themes
1. Colliding galaxies can cause star birth – shock waves perturb gas clouds to coalesce into new stars
2. Supermassive black holes [SMBH] (millions of suns) can regulate the production of new stars – Active galactic centers SMBH can heat adjacent gas and make it too hot to coalesce into new star; quiescent black holes can allow gas to be cool and allow new star formation; BUT lack of material will stop star formation
3. Our own galactic center (Sagittarius A) is quiescent – our galaxy is not considered a star birth galaxy
4. Star formation is seen outside the nucleaus in spiral arms in ionized hydrogen regions (HII regions)
M51/NGC 5195  Dwarf galaxy interacting with whirlpool galaxy
IC 10  Dwarf irregular star birth galaxy
SPT 0346-52  Very distant galaxy merger causing star formation
M81/M82  Two galaxies merging. M82 showing star birth
ESO 137-001  Galaxy showing star birth is gas being stripped from it
SN2014  SN2014J Super novae in M82
Phoenix Cluster  Galaxy cluster with extreme star formation
NGC 4993  Gravity waves detected from neutron star merger in this galaxy
47 Tucanae/X9  Globular cluster with a white dwarf closely orbiting a black hole
Chandra deep field-south  high density of blackholes
Cen A  star birth galaxy w active galactic nucleas (supermassive black hole)
M100  Star birth galaxy
Abell 400/NGC 1128/3C 75  Galaxy cluster / galaxy in that cluster / supermassive black holes in orbit around each other.
Antennae Galaxies  galaxies colliding and producing star birth
Sagittarius A*  Supermassive black hole at the core of our galaxy
Whirlpool galaxy colliding with smaller galaxy NGC5195. X-ray found supermassive black hole in NGC5195 that has had outbursts in the last few million years.

Ionized hydrogen regions ("HII" regions in pink) formed from gas from black hole outburst slamming into hydrogen gas – forming new stars.

Other HII star forming regions in M51 proper caused by gas slamming together in the spiral arms.

http://chandra.harvard.edu/photo/2016/ngc5195/
Ultra Luminous Xray Source (ULX) in M51 (circled)
Xrays purple
Optical (red, green, blue)

Neutron star sucking material
Strong magnetic field allows more matter to fall into the neutron hole and causes the matter to glow in Xrays.

Matter infall rate appears to be greater than Eddington limit = X-ray light pushing material away from the star

M51 proper caused by gas slamming together in the spiral arms.

http://chandra.harvard.edu/photo/2018/m51/
IC 10

Dwarf, irregular galaxy star burst galaxy with HII regions in its core

Huge envelope of hydrogen gas envelopes IC10 – reservoir for material to make new stars.

Hydrogen regions mapped on top of visual image (next slide)

http://www2.lowell.edu/users/massey/lgsurv ey/IC10_BVHa.jpg

http://adsbit.harvard.edu//full/1990PASP..102...26H/0000026.000.html
Dwarf, irregular galaxy
star burst galaxy with HII regions in its core

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http://adsbit.harvard.edu/full/1990PASP..102...26H/0000026.000.html
Galaxy 12.7 Billion lys away from earth (about a 1 billion years after the big bang)

Strong IR emissions either from explosion or star birth

No X-ray emissions = no black hole

Possible merger of two galaxies causing rapid star formation

X-ray = blue (Chandra)
Short IR = green (Hubble)
Longer IR = red (Spitzer)
Longer yet IR = magenta (ALAM radio)
Galaxy collision
Starburst & HII regions in M82 (right)

https://apod.nasa.gov/apod/ap130925.html
Galaxy collision
Starburst & HII regions in M82

M81 / M82 and NGC3077
Galaxy traveling through a galaxy cluster at 4.5 million miles/hr (!)
Interstellar gas is stripped away from “ram pressure stripping”
Stars not affected since they are held together by gravity

Composite Xrays – Bue (Chandra)
Other colors visible (Hubble)
Young, massive stars are formed in the strips of gas. Hot Stars are seen as blue and ultraviolet light.

The galaxy is being drained of star-forming hydrogen, and will not be able to make stars in the future.

http://chandra.harvard.edu/photo/2014/eso137/
SN2014 (J) in M82

Supernova occur ~ one in 10 years (rapidly) in M82

Type 1a

Closest recent type 1a supernovae

Apparent magnitude = 10.5

11.5 ± 0.8 million light-years (3.5 ± 0.3 megaparsecs)

Phoenix Cluster

Xray Blue (Chandra)
Optical, Red green
UV
Large cluster of galaxies
Extreme star formation
One of the greatest producer of Xrays among galaxy clusters

X-ray cavities were carved out of the surrounding gas by powerful jets of high-energy particles emanating from near a supermassive black hole in the central galaxy of the cluster

http://chandra.harvard.edu/photo/2015/phoenix/
Black hole may be switching between accretion disk (x-rays) or jet (radio waves).

Rapid cooling may have occurred in between these outbursts, triggering star formation in clumps and filaments throughout the central galaxy at a rate of about 610 solar masses per year.

http://chandra.harvard.edu/photo/2015/phoenix/phoenix_optical_radio.jpg
the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo Interferometer both detected gravitational waves from the collision of two neutron stars within this galaxy. The event also resulted in a flare of light, called a kilonova, which is visible to the upper left of the galactic center in this image from the NASA/ESA Hubble Space Telescope.

https://www.spacetelescope.org/images/heic1717c/
Gravity waves

https://www.ligo.caltech.edu/page/what-is-interferometer
Net mass loss in black hole mergers

- When black holes merge they give off a tremendous amount of energy as a result of producing gravity waves.
- The energy from producing these energy waves comes from conversion of the mass of the black hole to energy
  - $E=mc^2$
- The amount of mass lost observed by Ligo is ~3 solar masses

[Link to the article](https://physicstoday.scitation.org/doi/full/10.1063/PT.3.1294)
White dwarf close to a black hole in a globular cluster

Globular star clusters very dense star density – very old clusters

Orbital period = 25 minutes

Distance between = 2.5 distance between earth and our moon.

Red = lowest-energy X-rays are
Green = the medium X-rays the
Blue = highest-energy X-rays.

Highest concentration of black
holes ever observed

Measured rates of star
formation rate density (SFRD)
and black hole accretion rate
density (BHAD) as a function
of distance (Z) or time from
present.

Next slide

http://chandra.harvard.edu/photo/2017/cdfs/
Star formation rate (SFR) density versus the distance (time) away from us. $Z$ is redshift.

If $Z=2$, $t = 2.7$ billion years after the big bang.

Black Hole accretion rate density.

Cen A  a star birth galaxy with active galactic nucleus (AGN)

Jet from supermassive black hole (55 million suns) at the galaxy center – material being sucked in through an accretion disk and blown out the poles of the black hole.

Caused by a collision with a smaller galaxy

https://en.wikipedia.org/wiki/Centaurus_A#/media/File:ESO_Centaurus_A_LABOCA.jpg
M100 - a star burst galaxy

Xrays – gold (Chandra)
Visible – yellow-white, blue
(Very Large Telescope)
IR – red (Spitzer)

Birth of a black hole SN1979c

http://chandra.harvard.edu/photo/2010/sn1979c/
M100 - a star burst galaxy

Previous image with Hα emmissions demarking HII regions and star birth regions in M100

Great amount of star birth in both the spiral arms and in the core of the galaxy.

Abell 400 galaxy cluster
NGC 1128 galaxy in this cluster
3C 75 supermassive black holes orbiting each other in this galaxy

Two white dots are the blackholes
When they merge, will created detectable gravity waves
dumbbell structure of this galaxy is likely caused by two galaxies merging

http://chandra.harvard.edu/photo/2006/a400/
Two galaxies in the process of colliding. Causing tremendous amount of new stars to form. Burst in supernovae as most massive stars have died.

Xray – blue (Chandra)

Visible – gold, brown (Hubble)

IR- red (Spitzer)

http://chandra.harvard.edu/photo/2010/antennae/
Antennae Galaxies

HII regions

Sagittarius A* -- supermassive black hole at the core of our galaxy mass = 4 million suns

Core of our Milky Way galaxy

Many stellar mass (5-30 suns) black holes orbiting the core.

Black holes circled in red with other possible black hole candidates circled in white

http://chandra.harvard.edu/photo/2018/sgra_swarm/
Sagittarius A* -- supermassive black hole at the core of our galaxy mass= 4 million suns

Core of our Milky Way galaxy
“Normal” stars orbiting Sag A* → used to pinpoint its mass and to confirm general relativity

http://chandra.harvard.edu/photo/2018/sgra_swarm/
Star populations

Population I – Hot young stars in the spiral arms/disk of galaxies – seeded with metals from dying earlier generation of stars == 2% of all stars

Population II – Found in globular clusters and galactic nucleus – Older, less luminous, and cooler than Pop I. Less metal content

Population III – Hypothetical first generation of stars formed with NO metals at all. First generation of stars right after the big bang. Could be VERY massive >100x suns. We have never observed these!!!
Hydrogen regions

- **HI** neutral atomic hydrogen – no electron transitions, no emission lines from ionized hydrogen but a 21 cm emission from spin parity transition

- **HII regions** – ionized hydrogen. Signature for star formation – hot new stars ionizing neutral hydrogen, short lived.

- Predecessor to HII regions are giant molecular clouds (GMC) of hydrogen. These collapse to form hot new stars that make molecular H and ionize the hydrogen making HII regions.

- HII regions generally seen in spiral (arms) and in irregular galaxies – not seen in elliptical galaxies since they are believed to be older and products of galaxy mergers.

- HII regions detected from emission lines of hydrogen:
  - Hα and Hβ are common lines (emission lines in the Balmer series – in visible region)
  - Lyman series (ultraviolet) can also be used
HII regions
Generally star forming regions in the galaxy where hot new stars have ionize hydrogen causing it to “glow”.

Luminous Blue Variables (LBV), Red supergiants (RSG) and Wolf-Rayet stars (WR). Evolved from Main Sequence OB stars [O type stars or early B type stars]. Very massive stars that are formed in groups call OB associations. Lots of UV radiation emitted.
Brightness of Stars

- Brightness measured as luminosity or magnitude
  - Luminosity is the total energy output of a star
    - Depends on size and surface temperature
    - Usually measure relative to our sun, e.g., 4 times our sun.
  - A star’s magnitude is the logarithm of its luminosity
  - Apparent magnitude (m) [what we see] – is determined by four factors
    - Its temperature or color (wattage of a light bulb)
    - Its size
    - How far away it is
    - If it is obscured by dust (extinction)
  - Absolute magnitude (M)
    - Magnitude of a star when viewed from a fixed distance
    - Most abs magnitudes will be a negative number (bright)
Brightness of a star: A star’s magnitude

- Magnitude is more often used to describe an object's brightness.
- The *higher* the magnitude the *dimmer* the object.
  - The apparent magnitude of our sun is -26.7
  - The apparent magnitude of a full moon is -12.6
  - The apparent magnitude of the Sirius is ~ -1
  - Dimmest star you see (in Wilmington) ~+3.5
  - Dimmest star you see in a dark sky location ~+5.5
- The absolute magnitude is the magnitude of the star/object if it was placed a fixed distance away (10 parsecs -- later).
- The absolute magnitude of our sun is ~ +4.8
Spectral class of stars

- **O**
- **B** – SPBs – **Slowly Pulsating B** type stars
  - WR: **Wolf Rayet** stars
  - DBV: **Dwarf B** variables
  - DAV: **Dwarf A** variables
- **A**
- **F**
- **G** Our sun – G2, M=4.8
- **K**
- **M** - red SR: **SemiRegular**
- **L** Red Dwarfs (failed stars)
- **T** Brown Dwarfs (failed stars)
Categorizing stars by their spectra

1. Spectra can tell you the stars approximate temperature (blackbody radiation)

2. Absorption (dark) lines in a star’s spectra give a fingerprint of elements that are seen in that spectral class of stars

BUT emission spectra (bright lines against a dark background) are given off by nebulae – glowing gas clouds
Spectral class of stars

- He+ lines
- H Balmer lines (B, A & F stars)
- Ca+ lines (F & G stars)
- Fe and neural metals K & M stars
- TiO2 lines
### Spectral classification & Temperature of main sequence stars

<table>
<thead>
<tr>
<th>Star Spectral Class</th>
<th>Proportion of Stars</th>
<th>Surface Temperature (° F)</th>
<th>Star Mass (Sun = 1.0)</th>
<th>Star Luminosity (Sun = 1.0)</th>
<th>Lifespan (Billions of Years)</th>
<th>Example Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>1% A0 - A9</td>
<td>20,000</td>
<td>2.8</td>
<td>60</td>
<td>0.5</td>
<td>Vega</td>
</tr>
<tr>
<td>A1</td>
<td>---</td>
<td>18,400</td>
<td>2.35</td>
<td>22</td>
<td>1.0</td>
<td>Sirius</td>
</tr>
<tr>
<td>A5</td>
<td>---</td>
<td>15,000</td>
<td>2.2</td>
<td>20</td>
<td>1.0</td>
<td>---</td>
</tr>
<tr>
<td>F0</td>
<td>3% F0 - F9</td>
<td>13,000</td>
<td>1.7</td>
<td>6</td>
<td>2.0</td>
<td>---</td>
</tr>
<tr>
<td>F5</td>
<td>---</td>
<td>12,000</td>
<td>1.25</td>
<td>3</td>
<td>4.0</td>
<td>Procyon A</td>
</tr>
<tr>
<td>G0</td>
<td>9% G0 - G9</td>
<td>11,000</td>
<td>1.06</td>
<td>1.3</td>
<td>10</td>
<td>---</td>
</tr>
<tr>
<td>G2</td>
<td>---</td>
<td>10,600</td>
<td>1.00</td>
<td>1.0</td>
<td>12</td>
<td>Sun</td>
</tr>
<tr>
<td>G5</td>
<td>---</td>
<td>10,000</td>
<td>0.92</td>
<td>0.8</td>
<td>15</td>
<td>Alpha Centauri A</td>
</tr>
<tr>
<td>K0</td>
<td>14% K0 - K9</td>
<td>9,000</td>
<td>0.80</td>
<td>0.4</td>
<td>20</td>
<td>Alpha Centauri B</td>
</tr>
<tr>
<td>K2</td>
<td>---</td>
<td>8,700</td>
<td>0.76</td>
<td>0.3</td>
<td>24</td>
<td>Epsilon Eridani</td>
</tr>
<tr>
<td>K5</td>
<td>---</td>
<td>8,000</td>
<td>0.69</td>
<td>0.1</td>
<td>30</td>
<td>61 Cygni A</td>
</tr>
<tr>
<td>M0</td>
<td>73% M0 - M9</td>
<td>7,000</td>
<td>0.48</td>
<td>0.02</td>
<td>75</td>
<td>---</td>
</tr>
<tr>
<td>M5</td>
<td>---</td>
<td>5,000</td>
<td>0.20</td>
<td>0.001</td>
<td>200</td>
<td>Proxima Centauri (Alpha Centauri C)</td>
</tr>
<tr>
<td>Class</td>
<td>Effective temperature</td>
<td>Conventional color description</td>
<td>Actual apparent color</td>
<td>Main-sequence mass (solar masses)</td>
<td>Main-sequence radius (solar radii)</td>
<td>Main-sequence luminosity (bolometric)</td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------</td>
<td>--------------------------------</td>
<td>-----------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>O</td>
<td>≥ 30,000 K</td>
<td>blue</td>
<td>blue</td>
<td>≥ 16 $M_\odot$</td>
<td>≥ 6.6 $R_\odot$</td>
<td>≥ 30,000 $L_\odot$</td>
</tr>
<tr>
<td>B</td>
<td>10,000–30,000 K</td>
<td>blue white</td>
<td>deep blue white</td>
<td>2.1–16 $M_\odot$</td>
<td>1.8–6.6 $R_\odot$</td>
<td>25–30,000 $L_\odot$</td>
</tr>
<tr>
<td>A</td>
<td>7,500–10,000 K</td>
<td>white</td>
<td>blue white</td>
<td>1.4–2.1 $M_\odot$</td>
<td>1.4–1.8 $R_\odot$</td>
<td>5–25 $L_\odot$</td>
</tr>
<tr>
<td>F</td>
<td>6,000–7,500 K</td>
<td>yellow white</td>
<td>white</td>
<td>1.04–1.4 $M_\odot$</td>
<td>1.15–1.4 $R_\odot$</td>
<td>1.5–5 $L_\odot$</td>
</tr>
<tr>
<td>G</td>
<td>5,200–6,000 K</td>
<td>yellow</td>
<td>yellowish white</td>
<td>0.8–1.04 $M_\odot$</td>
<td>0.96–1.15 $R_\odot$</td>
<td>0.6–1.5 $L_\odot$</td>
</tr>
<tr>
<td>K</td>
<td>3,700–5,200 K</td>
<td>orange</td>
<td>pale yellow orange</td>
<td>0.45–0.8 $M_\odot$</td>
<td>0.7–0.96 $R_\odot$</td>
<td>0.08–0.6 $L_\odot$</td>
</tr>
<tr>
<td>M</td>
<td>2,400–3,700 K</td>
<td>red</td>
<td>light orange red</td>
<td>0.08–0.45 $M_\odot$</td>
<td>≤ 0.7 $R_\odot$</td>
<td>≤ 0.08 $L_\odot$</td>
</tr>
</tbody>
</table>
### Spectral Class and Temperature

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Temperature (Kelvin)</th>
<th>Spectral Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>28,000 - 50,000</td>
<td>Ionized helium</td>
</tr>
<tr>
<td>B</td>
<td>10,000 - 28,000</td>
<td>Helium, some hydrogen</td>
</tr>
<tr>
<td>A</td>
<td>7500 - 10,000</td>
<td>Strong hydrogen, some ionized metals</td>
</tr>
<tr>
<td>F</td>
<td>6000 - 7500</td>
<td>Hydrogen, ionized calcium (labeled H and K on spectra) and iron</td>
</tr>
<tr>
<td>G</td>
<td>5000 - 6000</td>
<td>Neutral and ionized metals, especially calcium; strong G band</td>
</tr>
<tr>
<td>K</td>
<td>3500 - 5000</td>
<td>Neutral metals, sodium</td>
</tr>
<tr>
<td>M</td>
<td>2500 - 3500</td>
<td>Strong titanium oxide, very strong sodium</td>
</tr>
</tbody>
</table>

### Spectral Lines and Wavelengths (Angstroms)

<table>
<thead>
<tr>
<th>Spectral Lines</th>
<th>Wavelengths (Angstroms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_\alpha$, $H_\beta$, $H_\gamma$</td>
<td>6600, 4800, 4350</td>
</tr>
<tr>
<td>Ionized Calcium H and K Lines</td>
<td>3800 - 4000</td>
</tr>
<tr>
<td>Titanium Oxide</td>
<td>lots of lines from 4900 - 5200, 5400 - 5700, 6200 - 6300, 6700 - 6900</td>
</tr>
<tr>
<td>G Band</td>
<td>4250</td>
</tr>
<tr>
<td>Sodium</td>
<td>5800</td>
</tr>
<tr>
<td>Helium (neutral)</td>
<td>4200</td>
</tr>
<tr>
<td>Helium (ionized)</td>
<td>4400</td>
</tr>
</tbody>
</table>
Hertzsprung-Russell Diagram

Y axis is always brightness or relative luminosity
X axis is always temperature, color or spectral class
Each dot is a star
A is the location of our sun on the main sequence
B are red giant stars that are fusing helium in their core
C are red supergiants with Helium and Hydrogen burning in shells and carbon in its core
D are white dwarfs (super hot carbon stars)

Instability gaps on an H-R diagram for the pulsating class of variable stars

→ Period of pulses scale with absolute brightness of the star

“Period-luminosity relationship”

Green = RR Lyrae variables
Red = Red Giant Branch
Yellow = horizontal branch
Blue = asymptotic giant branch

Unstable stars that work like Cepheid variables = standard candles
Found mostly in globular clusters (M5 shown here) and used to determine distances to clusters
Dim – not used beyond our local group of galaxies
Accretion disks
• Circumstellar disks
• Many accretion disks seen in binary star systems when one
  star has filled its “Roche” limit and is having material
  “sucked” away from it to a companion star

M82 X-2
Birth of a solar mass star
The birth of a 1 solar mass star going onto the main sequence.

Before point 4, contraction of interstellar gas cloud. The cloud heats up as it contracts, causing its luminosity to increase -- we don’t see it because the protostar is hidden in dust.

From point 4 to 6, -- The cloud contracts more and its luminosity drops.

Point 6, hydrogen starts to fuse to helium in the stars core. The heat generated from fusion balances gravity. The star’s surface heats up slightly.  

*This is the location of T Tauri stars*

Point 7. The star has reached a long lived equilibrium where the heat from fusing hydrogen to helium balances gravity. The star resides on the **main sequence** for most of its life (~10 billion years for a 1 solar mass star).
Death of main sequence stars
Low mass star like our sun stops at carbon formation in its core...
And fluffs off its outer layers to make a planetary nebulae and a white dwarf star.
But a high mass star, like those in the early universe had enough mass to fuse nuclear material all the way to iron. However, once iron accumulates in its core no net energy generation can be done by fusion of iron, gravity takes over and core collapse occurs and.....
Electrons are pushed into protons making neutrons and a flood of neutrinos....

It goes boom!!!!... A supernovae!!! (this is the Crab Nebulae) ... 

Which make lots of heavy elements needed to make terrestrial (earth like) planets. This is NOT a type 1a supernovae.

*It is a type II supernovae.*
.. And it spreads heavy elements throughout space to be picked up by a new generation of stars,.....
.. The shock wave either from the supernovae or from the initial star formation stage can initiate new star formation,.....
Before they ultimately die, high mass stars go through a red supergiant stage. During this time they may have very strong “solar wind” and shed a lot of its mass. –

The strong solar wind may also make the star appear larger (and hence brighter) than normal –
The wavelength at maximum radiation changes with temperature

\[ \lambda_{\text{max}} = 550 \text{ nm} \rightarrow 5300 \text{ K} \]

temperature for our sun.

“G” type star (subclass “2”) or G2

\[ \lambda_{\text{max}} \times \text{Temperature} = \text{constant} \]

\[ = 2.9 \times 10^6 \text{ nm}\cdot{^\circ}\text{K} \]

Or \[ = 2.9 \times 10^7 \text{ Å}\cdot{^\circ}\text{K} = 2.9 \times 10^3 \mu\text{m}\cdot{^\circ}\text{K} \]

Nm[=] nanometers for wavelength

Or A [=] Angstrom units for wavelength

Or \( \mu\text{m} [=] \) microns units for wavelength

\(^\circ\text{K} [=] \) degrees Kelvin
Another way to look at black body radiation

Plot $\log \lambda$ (x axis) vs log of spectral intensity at that $\lambda$
Example calculation for a star’s temperature

So the shorter the wavelength the hotter or colder the star???

\( \lambda_{\text{max}} \sim 0.9 \, \mu\text{m} \)

What is the star’s temperature?

\[ T \sim 2.9 \times 10^3 \, \mu\text{m-K} / 0.9 \, \mu\text{m} \]

= 3200 K (M type star)

If \( \lambda_{\text{max}} \sim 10 \, \mu\text{m} \)

What is the star’s temperature?

\[ T \sim 2.9 \times 10^3 \, \mu\text{m-K} / 10 \, \mu\text{m} \]

= 290 K (black dwarf)

\( \lambda_{\text{max}} \times \text{Temperature} = \text{constant} \)

= 2.9 \times 10^6 \, \text{nm-} ^{\circ} \text{K} \\
Or = 2.9 \times 10^7 \, \text{A-} ^{\circ} \text{K} = 2.9 \times 10^3 \, \mu\text{m-K} \\
Nm[=] \text{nanometers for wavelength} \\
Or A[=] \text{Angstrom units} \\
Or \mu\text{m}[=] \text{microns units} \\
^{\circ} \text{K}[=] \text{degrees Kelvin}
• What is the “temperature” of an object emitting x-rays or gamma rays?

\[ \lambda \cdot \text{temperature} = 2.9 \times 10^6 \text{ nm}\cdot{^\circ\text{K}} \]

If \( \lambda \) is 1 nm (soft x-rays) then Temperature = 2.9 million degrees(!)

What is \( \lambda_{\text{max}} \) for an “O” type star? \( T \approx 40,000 \text{ K} \) \( \Rightarrow \lambda_{\text{max}} \approx 72 \text{ nm} \) \( \Rightarrow \)

it shines in the ultraviolet light!!! We can still “see” it in visible light because part of its light is there.

What is \( \lambda_{\text{max}} \) for Betelgeuse? \( T \approx 3400\text{K} \) \( \Rightarrow \)

\[ \lambda_{\text{max}} \approx 850 \text{ nm or 0.85 } \mu\text{m} \]
Neutron stars

• When higher mass stars “die” gravity takes over and the core of the star collapses. At > 4 suns, Electron degeneracy pressure is overcome and electrons are pushed into the protons to form neutrons (and a flood of neutrinos – that give rise to a supernovae).

• Initial angular momentum will be distributed between the supernovae remnant and the resulting neutron “star”.

• The angular momentum of the neutron star can cause it to spin very quickly – creating a pulsar.

• Strong magnetic fields can focus a beam of radiation like a light house

• Pulsars can have an accretion disk (from the blown off remnant of the star) that generates x-rays as matter is accelerated to near the speed of light as it falls into the neutron star.
Mass of the main sequence star is reduced as it evolves and dies.

Material is shed either during the formation of a planetary nebula (white dwarf) or during a supernovae.

The supernovae in this diagram are meant to be Type II and not Type Ia.
Kepler’s laws – gold standard for “weighing” stars

1. Orbits are ellipses with sun at one focus
2. Equal areas swept out in equal time
3. Harmonic law: Square of the period (P) is proportional to the cube of the semimajor axis (a). — Gold standard for determining masses in the universe – exoplanets and binary stars.

Kepler’s law

\[ P^2 = a^3 / (m_1 + m_2) \]

P = orbital period (years)
a = Distance between the two bodies (expressed in astronomical units [AU] – distance from earth to sun)
1 AU = 107.5 sun diameters or 215 sun’s radius
m_1, m_2 = mass of the two bodies orbiting each other (solar masses)
Measuring Distances…

Brightness of stars…
Brightness of Stars

• Brightness measured as luminosity or magnitude
  – Luminosity is the total energy output of a star
    • Depends on size and surface temperature
    • Usually measure relative to our sun, e.g., 4 times our sun.
  – A star’s magnitude is the logarithm of its luminosity
  – Apparent magnitude (m) [what we see] – is determined by four factors
    • Its temperature or color (wattage of a light bulb)
    • Its size
    • How far away it is
    • If it is obscured by dust (extinction)
  – Absolute magnitude (M)
    • Magnitude of a star when viewed from a fixed distance
    • Most abs magnitudes will be a negative number (bright)
Brightness of a star: A star’s magnitude

• Magnitude is more often used to describe an object's brightness.
• The *higher* the magnitude the *dimmer* the object.
  – The apparent magnitude of our sun is ~ -26.7
  – The apparent magnitude of a full moon is ~ -12.6
  – The apparent magnitude of the Sirius is ~ -1
  – Dimmest star you see (in Wilmington) ~ +3.5
  – Dimmest star you see in a dark sky location ~ +5.5
• The absolute magnitude is the magnitude of the star / object if it was placed a fixed distance away (10 parsecs -- later).
• The absolute magnitude of our sun is ~ +4.8
Cosmological Distances

- solar system ($10^{-4}$ ly)
- nearby stars ($10^2$ ly)
- Milky Way ($10^5$ ly)
- nearby galaxies ($10^7$ ly)
- galaxy clusters ($10^{10}$ ly)

Variables

- white dwarf supernovae
- Cepheids
- RR Lyrae
- Tully–Fisher relation
- distant standards

Hubble's law: $d = \frac{v}{H_0}$
Distances

- **Astronomical unit.** Average distance between the earth and our sun. \((\text{AU} = 1.496 \times 10^{11} \text{ meters} \text{ or } 97 \text{ million miles} \text{ or about } 8.3 \text{ light minutes})\) This is a small unit of measure.
  - Used for interplanetary measures and for distances between stars in binary star systems (Kepler’s Laws)

- **Light years.** The distance light travels in a year
  - \(\text{LY} = 9.46 \times 10^{15} \text{ meters}, 6.33 \times 10^4 \text{ AU}\)

- **Parsec [pc].** The distance to an object that has a parallax of 1 arc second (next slide) \(\rightarrow\) preferred unit by astronomers
  - \(\text{pc} = 3.26 \text{ LY} = 2.06 \times 10^5 \text{ AU} = 3.086 \times 10^{16} \text{ meters}\)

- **Kiloparsecs (Kpc) \(\rightarrow\) 1000 parsecs \((10^3 \text{ parsecs})\)
- **Megaparsecs (Mpc) \(\rightarrow\) 1 million parsecs \((10^6 \text{ parsecs})\)
• Geometric parallax ➔ Gold standard for distances
  – 1 Parsec = $3.09 \times 10^{16}$ meters

• parsec - (pc): distance at which an object would have a parallax of one arc second. Equals approximately 3.26 light years or about 206,265 astronomical units

Star appears to move with season
Cosmological Distances

- **Milky Way (10^5 ly)**
  - Variables
    - Cepheids
    - RR Lyrae

- **nearby galaxies (10^7 ly)**
  - white dwarf supernovae
  - Tully–Fisher relation
  - distant standards

- **galaxy clusters (10^{10} ly)**

- **solar system (10^{-4} ly)**
  - radar ranging
  - Venus, Sun

- **nearby stars (10^2 ly)**
  - parallax

**Hubble’s law:**
\[ d = \frac{v}{H_0} \]
Spectroscopic Parallax

1. Measure the spectrum of a star. Lines in the spectra will indicate if it is a main sequence star. The star needs to be bright enough to provide a measurable spectrum, which is about 10,000 parsecs.

2. Using the star spectra or using the UVB index, make certain that it is on the main sequence, deduce its spectral type (O, B, A, F, G, K, M, L).

3. From the spectral type deduce its absolute magnitude \([M]\) (H-R diagram or table).

4. Measure the apparent magnitude \((m)\). Knowing the apparent magnitude \((m)\) and absolute magnitude \((M)\) of the star, one can calculate the distance modulus \((m-M)\) and the actual distance in parsecs – next slide.

Good for stars that are \(<~ 10,000\) parsecs from us (or 32,600 light years) – most of the stars in our galaxy.
Distance modulus is

m-M if there is no interstellar dust (or extinction)

If there is interstellar dust then distance modulus is

((m-E)-M) where E is the extinction magnitude

M=m-E+5-5log_{10}D

Or,  \[ D = 10^{\frac{(m-M-E+5)}{5}} \]

D [ly]=3.26 * D [pc]

m = apparent magnitude
M = absolute magnitude
E = Extinction magnitude (due to interstellar dust)
D is distance in parsecs

Although parsecs was originally used from geometric parallax, it is the common unit of distance no matter how distance is measured.

The larger the distance modulus the further away the object is.

Little m is usually >+10

Capital M is usually small – many times negative,

E can be as much a 1 or 2 (magnitudes of extinction due to dust in our or the distant host galaxy of the object)
\[ L = 2.512^{(4.8-M)} \]

\[ M = 4.8 - 2.5 \times \log_{10} L \]

Relationships between distance modulus, luminosity, distances in parsecs and absolute magnitude

\( m = \) apparent magnitude
\( M = \) absolute magnitude

\( m-M \) is called the distance modulus (wo extinction)

It will be \( m-E-M \) with the extinction magnitude, \( E \)

\( L = \) luminosity relative to our sun (at a fixed distance of 10 parsecs or 32.6 light years), our sun = 1.0 luminosity

\( K \) is 32.6 for light years or 10 for parsecs

\( D \) is distance in light years or parsecs

Astronomical unit [AU] = average earth- sun distance

1 AU = 1.496 x 10^8 km

Diameter of our sun = 1.391 x 10^6 km

1AU = 107.5 sun diameters

Msun = 4.8 (absolute magnitude or our sun)
Instability gaps on an H-R diagram for the pulsating class of variable stars

→ Period of pulses scale with absolute brightness of the star

“Period-luminosity relationship”

RR Lyrae variables

Unstable stars that work like Cepheid variables = standard candles

Found mostly in globular clusters (M5 shown here) and used to determine distances to clusters

Dim – not used beyond our local group of galaxies
Period-Luminosity Relationship equation for type 1 Cepheid

\[ M_v = -2.81 \log(P) - (1.43 \pm 0.1) \]

For Type I, Type II Cepheids and RR Lyrae

Cepheids named after the first star discovered in the constellation Cepheus (up north)

Note this is luminosity – these stars are much brighter than our sun.


\[ M = -2.81 \log(P) - 1.43 \]

P is period in days
Light curve for Delta Cephei

- Saw tooth curve for Type 1 Cepheid variable
RR Lyrae and Cepheid stars as standard candles

- Find the period.
- This gives the luminosity or its absolute magnitude
- Measure the apparent magnitude.
- Determine the distance from the apparent and absolute magnitude (distance modulus) (and an estimate of the extinction [E])

The same applies to RR Lyrae variable stars. Once you know that a star is an RR Lyrae variable (eg. from the shape of its light curve), then you know its luminosity

\[ M = -2.81 \times \log(P) - 1.43 \]

Type 1 Cepheid. P is period in days
A type Ia supernova occurs in binary stellar system (two stars orbiting one another) in which one of the stars is a white dwarf. The other star can be anything from a giant star to another white dwarf. OR it can be a merger of two white dwarfs.

Material is drawn off the other star (filling its “Roche” limit) onto the white dwarf until the white dwarf reaches the Chandrasekhar limit. Then electron degeneracy pressure is unable to prevent catastrophic collapse. If a white dwarf gradually accretes mass from a binary companion, its core will reach the ignition temperature for carbon fusion as it approaches the limit. If the white dwarf merges with another white dwarf, it will momentarily exceed the limit and begin to collapse, again raising its temperature past the nuclear fusion ignition point. Within a few seconds of initiation of nuclear fusion, a runaway reaction will occur and thus causing the supernovae.

Bottom line: Type 1a SN produce a consistent peak in absolute luminosity because of the uniform mass of white dwarfs that explode via the accretion mechanism. Absolute magnitude is M ~ -19.5 (negative)
**Type Ia supernovae** is where a white dwarf collapses because it has pulled too much material from a nearby companion star onto itself. Because the type 1a “blows up” at the same mass limit (see earlier discussion) (Chandrasekhar limit ~1.4x mass of our sun) they have about the same absolute magnitude at its peak brightness → Standard candle
Using Type Ia supernovae as a standard candle

• Because a type Ia “explodes” at the Chandrasekhar limit, all type Ia SN are about the same brightness
  – Type 1a have an absolute magnitude of about M~ -19.2 (that is a negative sign)
• Observed in distant galaxies.
• Observe a supernovae as it occurs,
• Construct its light curve
• From the light curve determine if it is a type 1a and estimate its maximum apparent magnitude (m)
• \textit{Distance modulus is then (m+19.2) for Type Ia supernovae (m is apparent magnitude) assuming no extinction due to dust (which may be bad assumption)}
Cosmological Distances

- solar system (10^-4 ly)
- nearby stars (10^2 ly)
- Milky Way (10^7 ly)
- nearby galaxies (10^7 ly)
- galaxy clusters (10^{10} ly)

Variables
- white dwarf supernovae
- Cepheids
- RR Lyrae
- Spectroscopic Parallax
- Tully–Fisher relation
- distant standards

Hubble's law: d = \frac{v}{H_0}
Tully-Fisher relation

As a galaxy rotates, it is observed that the 21cm emission line for HI is widened – the width is a measure of the rotational velocity of a galaxy.

https://pages.uoregon.edu/imamura/323/lecture-3/tf.html
Tully-Fisher relation

Galaxy mass or absolute magnitude is correlated to the galaxy's rotational velocity.

The more massive the galaxy, the higher the velocity of stars around it.

$$M = -8.75 \times \log_{10}(V) - 0.8125$$

Where

- $M$ = absolute magnitude
- $V$ = rotational velocity (km/sec, inferred from doppler line broadening)

Calibrated using Cepheid variables.

Use $M$ in distance Modulus to determine distance.
Cosmological Distances

- Solar system (10^-4 ly)
  - Radar ranging
  - Venus
  - Sun

- Nearby stars (10^2 ly)
  - Parallax

- Milky Way (10^5 ly)
  - Spectroscopic Parallax
  - Relative apparent brightness
  - Surface temperature (K)

- Nearby galaxies (10^7 ly)
  - Variables
    - Cepheids
    - RR Lyrae
    - Tully–Fisher relation
    - Distant standards
  - White dwarf supernovae

- Galaxy clusters (10^10 ly)

Hubble's law: \( d = \frac{v}{H_0} \)
Red shifting a star’s spectrum

Wavelength of light (nanometers, nm)

$1 \text{ nm} = 1 \times 10^{-9} \text{ meters}$

Increasing red shift
Hubble’s law (measurement to very distant galaxies)
Fundamental parameter \( \rightarrow \) measure of the expansion of our universe

Hubble’s Law: \( d = \frac{V_r}{H_0} \) or for small distances \( d = \frac{zc}{H_0} \) \( (z < 0.5) \)

- \( d \) = distance in megaparsecs (millions of parsecs)
- \( V_r \) = recessional velocity (km/sec)
- Measure using red shift of the light spectrum of a galaxy
- \( H_0 \) = Hubble’s constant, \( \sim 75 \) km/sec / megaparsecs

- \( C \) = the speed of light \( (3 \times 10^5 \text{ km/sec}) \)

**Problem:** if wavelength of the observed light is 440 nm and the wavelength of the emitted light is 400 nm

What is \( Z \)?
What is recessional velocity?
What is the distance using Hubble’s law? In mpc? In light years?
Converting red shift (z) to time (t) distances (billion ly)

Given the red shift (Z)

\[ z = \frac{\text{wavelength of the observed light}}{\text{wavelength of the emitted light}} - 1 \]

What is the time, \( t \), since the start of the universe?

\[ t = \frac{27.2}{1+(1+z)^2} \]

where \( t \) is in billions of years since the big bang

How far away is the object?

\[ \text{Distance(bly)} = \frac{27.2}{2} - t \text{ in billion of light years} \]

So if an a distant object has a \( z = 3.5 \), then \( t = 1.28 \) billion years after the big bang. Distance = 13.3 billion light years...
Answer to problem

\[ z = \frac{440}{400} - 1 = 1.1 - 1 = 0.1 \]

\[ V_r = 0.1 \times 3 \times 10^5 \text{ (km/sec)} = 3 \times 10^4 \text{ (km/sec)} \]

What is the distance using Hubble’s law?
\[ D = \frac{3 \times 10^4 \text{ km/sec}}{75 \text{ km/sec/mpc [kilometers/second/megaparces]}} \]
\[ = \frac{3}{7.5} \times 10^3 \text{ megaparces (mpc)} = 0.4 \times 10^3 \text{ mpc} = 400 \text{ mpc} \]
\[ = 3.26 \text{ light year / pc} \times 10^6 \text{ pc/mpc} \times 400 \text{ mpc} = 1304 \times 10^6 \text{ light years} \]
\[ \text{or} = 1.3 \times 10^9 \text{ ly} \]
An star’s is named using its constellation and letter of multiple letter designation. So…

**RY Sagittarii** is in the constellation Sagittarius (summer sky) and counting up using the alphabet (a, b, c, d, e… z, AA, AB,… ) it is star RY in this constellation.

A class of stars (like the Cepheid variables or **RR Lyrae** variables) are named after the first star discovered in that class of stars. So the first Cepheid variable was discovered in the constellation of Cepheus. The **RR Lyrae** variables are named after the RR Lyrae (in the constellation of Lyra [string instrument]). The T Tauri stars were named after T Tauri (a star in Taurus).