Measuring the Stars

- How big are stars?
- How far away?
- How luminous? How hot?
- How old & how much longer to live?
- Chemical composition?
- How are they moving?
- Are they isolated or in clusters?
The Sun

The Sun is a star: a shining ball of gas powered by nuclear fusion.

Mass of Sun \( = 2 \times 10^{33} \text{ g} = 330,000 \, M_{\text{Earth}} \)
\( = 1 \, M_{\text{Sun}} \)

Radius of Sun \( = 7 \times 10^5 \text{ km} = 109 \, R_{\text{Earth}} \)
\( = 1 \, R_{\text{Sun}} \)

Luminosity of Sun \( = 4 \times 10^{33} \text{ erg/s} = 1 \, L_{\text{Sun}} \)
(amount of energy put out each second in form of radiation, \( = 10^{25} \) 40W light bulbs)
• Temperature at surface = 5800 K => yellow (Wien’s Law)

• Temperature at center = 15,000,000 K

• Average density = 1.4 g/cm$^3$

• Density at center = 160 g/cm$^3$

• Composition:
  - 74% of mass is H
  - 25% He
  - 1% the rest

Rotation period = 27 days at equator
  31 days at poles
The Interior Structure of the Sun
(not to scale)
The (Visible) Solar Spectrum

Spectrum of the Sun shows:

1) The Black-body radiation

2) Absorption lines (atoms/ions absorbing photons at specific wavelengths).

10,000's of lines from 67 elements, in various excited or ionized states.

Again, this radiation comes from photosphere, the visible surface of the Sun. Elements weren’t made in Sun, but in previous stellar generations.
Stellar Spectra
Spectra of stars differ mainly due to atmospheric temperature (composition differences also important).

“hot” star

“cool” star
How Far Away are the Stars?

Earth-baseline parallax - useful in Solar System

Earth-orbit parallax - useful for nearest stars
New distance unit: the parsec (pc).

Using Earth-orbit parallax, if a star has a parallactic angle of 1", it is 1 pc away.

If the angle is 0.5", the distance is 2 pc.

Distance (pc) = \frac{1}{\text{Parallactic angle (arcsec)}}

Closest star to Sun is Proxima Centauri. Parallactic angle is 0.7", so distance is 1.3 pc.

1 pc = 3.3 light years
   = 3.1 \times 10^{18} \text{ cm}
   = 206,000 \text{ AU}

1 \text{ kiloparsec (kpc)} = 1000 \text{ pc}
1 \text{ Megaparsec (Mpc)} = 10^6 \text{ pc}
Earth-orbit parallax using ground-based telescopes good for stars within 30 pc (1000 or so). Tiny volume of Milky Way galaxy. Other methods later.

Our nearest stellar neighbors
Stars can be single, double (binary), or multiple.

**Apparent** binaries are happenstance alignments.
True binaries orbit each other.

**Visual** binaries can be resolved into two stars in a telescope. **Spectroscopic** binaries are stars that orbit so closely, from Earth’s vantage point, that it requires a Doppler shift measurement to determine that there is more than a single star present.
Who named the stars?

-- Most bright stars have Arabic names
-- A few are from Latin or other languages
-- Some stars had other names in ancient cultures; for example “Sirius” = “Sothis” (Egypt)

-- Modern star designations (used by professional astronomers) usually use a catalog name and number, e.g.:

HD9078
(“Henry Draper” catalog)

HIP90738
(“Hipparcos” catalog)

Alhazen (965 - c. 1040 AD)
σ Ori - HIP 26549 A

Magnitude: **4.00** (B-V: -0.03)
Absolute Magnitude: -3.73
RA/DE (J2000): 5h38m44.8s/-2° 36'00.2"
RA/DE (of date): 5h39m18s/-2°35'40"
Hour angle/DE: 0h20m53s/-2°35'40"
Az/Alt: +188°29'08"/+51°58'09"
Spectral Type: O9.5V...
Distance: 1148.44 Light Years
Parallax: 0.00284"
Star exhibit *proper motion*: movement across the sky relative to other stars. Caused by real, non-uniform motion of stars in the Galaxy.

Most stars have very little proper motion.

Large proper motion tends to be due to closeness to the Solar System, but there are also variations in stars’ speed as they move through the Galaxy.
How Luminous are Stars?

Remember, luminosity of the Sun is

\[ L_{\text{Sun}} = 4 \times 10^{33} \text{ erg/s} = 4 \times 10^{26} \text{ Watts} \]

Luminosity also called “absolute brightness”.

How bright a star **appears** to us is the “apparent brightness”, which depends on its luminosity and distance from us:

\[ \text{apparent brightness} \propto \frac{\text{luminosity}}{(\text{distance})^2} \]

So we can determine luminosity if apparent brightness and distance are measured:

\[ \text{luminosity} \propto \text{apparent brightness} \times (\text{distance})^2 \]

Please read about magnitude scale.
## Natural Sources of Illumination
(at the Earth’s surface)

*Note: at $\lambda = 550$ nm*

<table>
<thead>
<tr>
<th>Source</th>
<th>conditions</th>
<th>magnitude $m_v$</th>
<th>Spectral Irradiance $W / m^2$-micron</th>
<th>Spectral Radiance $W / m^2$-micron-sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td></td>
<td>-26.74</td>
<td>1800</td>
<td>2.65 x $10^7$</td>
</tr>
<tr>
<td>Skylight</td>
<td>Daytime</td>
<td>-24.55</td>
<td>239</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Night, full moon</td>
<td>-8.28</td>
<td>7.5 x $10^{-5}$</td>
<td>1.19 x $10^{-5}$</td>
</tr>
<tr>
<td>Moon</td>
<td>Full</td>
<td>-12.73</td>
<td>4.5 x $10^{-3}$</td>
<td>69.9</td>
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<tr>
<td></td>
<td>1st quarter</td>
<td>-10.10</td>
<td>4.0 x $10^{-4}$</td>
<td>12.5</td>
</tr>
<tr>
<td>Starlight</td>
<td>Galactic equator</td>
<td></td>
<td></td>
<td>4.43 x $10^{-6}$</td>
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<tr>
<td></td>
<td>Mean</td>
<td>-6.66</td>
<td>1.67 x $10^{-5}$</td>
<td>1.33 x $10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Galactic pole</td>
<td></td>
<td></td>
<td>4.05 x $10^{-7}$</td>
</tr>
<tr>
<td>Mean Earthlight</td>
<td>Sun only</td>
<td></td>
<td></td>
<td>218</td>
</tr>
<tr>
<td><em>lit by source</em></td>
<td>Full Moon only</td>
<td></td>
<td></td>
<td>5.44 x $10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>Mean starlight</td>
<td></td>
<td></td>
<td>6.14 x $10^{-7}$</td>
</tr>
<tr>
<td>Brightest star</td>
<td>(Sirius = $\alpha$ CMa)</td>
<td>-1.46</td>
<td>1.39 x $10^{-7}$</td>
<td>1.9 x $10^{8}$</td>
</tr>
</tbody>
</table>
Stellar Magnitudes (1)

We measure the apparent brightness of stars using a (logarithmic) scale, the magnitude scale. A difference of 5 magnitudes = 100 x in brightness.

→ SMALLER MAGNITUDE = BRIGHTER STAR

Astronomers also refer to a star’s absolute magnitude, which is related to its luminosity.

The visible stars have magnitudes less than about 6.

Larger magnitude = dimmer star.
Smaller magnitude = brighter star.

Brightest star : Sirius, magnitude (V) = -1.5
(Type = A1V) [will discuss stellar types soon]
Stellar Magnitudes (II)

Stellar magnitudes are measured in various color bands.

V = visual
B = blue

These bands are formed at the telescope by using colored filters that pass only light of certain wavelengths.

Magnitudes in B and V are used to form a star’s color index, a rough estimate of its temperature (blueness).

\[
\text{color index} = B - V
\]
Stellar Magnitudes (III)

• **Apparent** magnitude = magnitude we observe by eye, or measure at the telescope, here on Earth

  = dependent on luminosity, and proportional to \(1/\text{distance}^2\)  
  [why?? …]

  Denoted by lower-case letters, e.g., \(m_V\) or \(m_B\)

• **Absolute** magnitude = apparent magnitude the star would have if placed at a standard distance (10 pc) from the Earth

  = dependent on **luminosity only**

  Denoted by upper-case letters, e.g., \(M_V\) or \(M_B\)
Variable Stars (brightness varies periodically) have Different Causes

**Intrinsic variables**

Luminosity changes periodically, usually associated with changes in size (pulsation), and color (spectrum)

Periods: hours to weeks, typically

**Eclipsing binaries** -- example

Binary star seen nearly (not completely) edge-on
Shows changes in the total light due to the Partial eclipse of one star by another.
How Hot are Stars at the Surface?

Stars have roughly black-body spectra. Color depends on surface temperature. A quantitative measure of “color”, and thus temperature, can be made by observing star through various color filters. See text for how this is done.

Betelgeuse
T=3000 K

Rigel
T=20,000 K
Blackbody Radiation

*Emitted by hot, self-luminous objects*

Wavelength of peak emission: Wien’s displacement law

\[ \lambda_{\text{peak}} T_{\text{eff}} = 2898 \text{ [micron} - K] \]

Shape of curve: Planck’s radiation law
Classification of Stars Through Spectroscopy

Pattern of absorption lines depends on temperature (mainly) and chemical composition.

Spectra give most accurate info on these as well as:

• pressure in atmosphere
• velocity towards or from us
Strange lettering scheme is a historical accident.

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>Surface Temperature</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>30,000 K</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>20,000 K</td>
<td>Rigel</td>
</tr>
<tr>
<td>A</td>
<td>10,000 K</td>
<td>Vega, Sirius</td>
</tr>
<tr>
<td>F</td>
<td>7000 K</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>6000 K</td>
<td>Sun</td>
</tr>
<tr>
<td>K</td>
<td>4000 K</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>3000 K</td>
<td>Betelgeuse</td>
</tr>
</tbody>
</table>

Further subdivision: BO - B9, GO - G9, etc. GO hotter than G9. Sun is a $G_2$. 
Stellar Sizes

Almost all stars too distant to measure their radii directly. Need indirect method. For blackbodies, remember:

\[
\text{Luminosity } \propto (\text{temperature})^4 \times (4\pi R^2)
\]

Determine luminosity from apparent brightness and distance, determine temperature from spectrum (black-body curve or spectral lines), then find radius.
The Wide Range of Stellar Sizes
How Massive are Stars?

1. **Binary Stars.** Orbit properties (period, separation) depend on masses of two stars.

2. **Theory of stellar structure and evolution.** Tells how spectrum and color of star depend on mass.
A star’s position in the H-R diagram depends on its mass and evolutionary state.
H-R Diagram of Nearby Stars

H-R Diagram of Well-known Stars

Note lines of constant radius!
How does a star's Luminosity depend on its Mass?

$L \propto M^3$

(Main Sequence stars only!)
How Long do Stars Live (as Main Sequence Stars)?

Main Sequence stars fuse H to He in core. Lifetime depends on mass of H available and rate of fusion. Mass of H in core depends on mass of star. Fusion rate is related to luminosity (fusion reactions make the radiation energy).

So,

\[
\text{lifetime} \propto \frac{\text{mass of core}}{\text{fusion rate}} \propto \frac{\text{mass of star}}{\text{luminosity}}
\]

Because luminosity \(\propto (\text{mass})^3\),

\[
\text{lifetime} \propto \frac{\text{mass}}{(\text{mass})^3} \quad \text{or} \quad \frac{1}{(\text{mass})^2}
\]

So if the Sun's lifetime is 10 billion years, a 30 \(M_{\odot}\) star's lifetime is only 10 million years. Such massive stars live only "briefly".
Star Clusters

Two kinds:

1) Open Clusters
   - Example: The Pleiades
   - 10's to 100's of stars
   - Few pc across
   - Loose grouping of stars
   - Tend to be young (10's to 100's of millions of years, not billions, but there are exceptions)
2) **Globular Clusters**

- few \( \times 10^5 \) or \( 10^6 \) stars
- size about 50 pc
- very tightly packed, roughly spherical shape
- billions of years old

Clusters are crucial for stellar evolution studies because:

1) All stars in a cluster formed about same time (so about same age)
2) All stars are at about the same distance
3) All stars have same chemical composition
The Interstellar Medium (ISM)
Gas and Dust Between the Stars

Why study it?

Stars form out of it.

Stars end their lives by returning gas to it.

The ISM has:

- a wide range of structures
- a wide range of densities \( (10^{-3} \text{ - } 10^7 \text{ atoms / cm}^3) \)
- a wide range of temperatures \( (10 \text{ K} \text{ - } 10^7 \text{ K}) \)
Compare density of ISM with Sun or planets:

Sun and Planets:

1-5 g / cm$^3$

ISM average:

1 atom / cm$^3$

Mass of one H atom is $10^{-24}$ g!

So ISM is about $10^{24}$ times as tenuous as a star or planet!
ISM consists of gas (mostly H, He) and dust. 98% of mass is in gas, but dust, only 2%, is also observable.

**Effects of dust on light:**

1) "Extinction"
   Blocks out light

2) "Reddening"
   Blocks out short wavelength light better than long wavelength light => objects appear redder.
Longer wavelength radiation is not so easily absorbed by dust!

Grain sizes typically $10^{-5}$ cm. Composed mainly of silicates, graphite and iron.
Some characteristics of ISM components

- **GAS**:

  HI, HI, H2 -- collectively about 70%
  He -- about 28%
  C, N, O, Ne, Na, Mg, Al, Si, S … (remainder)

  Typical particle density 1/cm$^3$
  (mass density $\sim 10^{-21}$ kg/m$^3$)

  Studied: by absorption lines in stellar spectra; Optical, UV, Radio

- **DUST**:

  Solid particles, d $\sim$ 0.1 to 1 micron [um]
  H2O (ice), silicates, C (graphite) w/impurities

  Typical particle density $10^{-13}$/cm$^3 = 100$/km$^3$
  (mass density $\sim 10^{-23}$ kg/m$^3$)

  Studied: by absorption and scattering of starlight, reddening, polarization, infrared emission
Gas Structures in the ISM

Emission Nebulae or H II Regions

Regions of gas and dust near stars just formed.

The Hydrogen is almost fully ionized.

Temperatures near 10,000 K

Sizes about 1-20 pc.

Hot tenuous gas => emission lines (Kirchhoff’s Laws)
Rosette Nebula

Lagoon Nebula

Tarantula Nebula

Red color comes from one emission line of H (tiny fraction of H is atoms, not ionized).
Why red? From one bright emission line of H. But that requires H atoms, and isn't all the H ionized? Not quite.

Once in a while, a proton and electron will rejoin to form H atom. Can rejoin to any energy level. Then electron moves to lower levels.

Emits photon when it moves downwards. One transition produces red photon. This dominates emission from nebula.
Why is the gas ionized? How does it trace star formation?

Remember, takes energetic UV photons to ionize H. Hot, massive stars produce huge amounts of these.

Such short-lived stars spend all their lives in the stellar nursery of their birth, so emission nebulae mark sites of ongoing star formation.

Many stars of lower mass are forming too, but emit few UV photons.

Why "H II" Region?

H I: Hydrogen atom
H II: Ionized Hydrogen
... O III: Oxygen missing two electrons etc.
Reflection Nebulae: Example

Blue light reflected near stars in Pleiades
Light along LOS is reddened, some extinction (absorption + scatter)
Atomic Gas and 21-cm radiation
Gas in which H is atomic.

Fills much (most?) of interstellar space. Density \( \sim 1 \text{ atom / cm}^3 \).
Too cold (\( \sim 100 \text{ K} \)) to give optical emission lines.
Primarily observed through radiation of H at wavelength of 21 cm.

Accounts for almost half the mass in the ISM: about \( 2 \times 10^9 \text{ M}_{\text{Sun}} \)!
Molecular Gas

It's in the form of cold (about 10 K) dense (about $10^3 - 10^7$ molecules / cm$^3$) clouds.

Molecular cloud masses:
$10^3 - 10^6 \, M_{\text{Sun}}$

Sizes: a few to 100 pc.

1000 or so molecular clouds in ISM.
Total mass about equal to atomic mass.
Optically, seen as dark dust clouds.
Molecular Hydrogen = $H_2$
The ISM is both complex and dynamic.

Schematic of a kiloparsec-scale region

- WIM: "Warm" Interstellar Medium
- GMC: Giant Molecular Complex
- SNR: Supernova remnant
- HI: neutral hydrogen region

Schematic of a typical ISM region

GMC : Giant Molecular Complex
WIM : "Warm" Interstellar Medium
SNR : Supernova remnant
HI : neutral hydrogen region
We can observe emission from molecules. Most abundant is H$_2$ (don't confuse with H II), but its emission is extremely weak, so other "trace" molecules observed:

- CO (carbon monoxide)
- H$_2$O (water vapor)
- HCN (hydrogen cyanide)
- NH$_3$ (ammonia)
- etc.

These emit photons with wavelengths near 1 mm when they make a rotational energy level transition. Observed with radio telescopes.
False-color of CO emission from Orion molecular cloud complex. Best studied case. 500 pc away. 400,000 $M_{\text{Sun}}$ of gas. Note complicated structure!

approximate position of Orion nebula
Star Formation

Stars form out of molecular gas clouds. Clouds collapse to form stars (remember, stars are $\sim 10^{20} \times$ denser than a molecular cloud).

Probably new molecular clouds form continually out of less dense gas. Some collapse under their own gravity. Others may be more stable. Not well understood.
Fragments in Orion molecular cloud, about 1000 x denser than average gas in cloud.
Thackeray globules in IC 2944

HST [ACS]
STSCI
When a cloud starts to collapse, it should fragment. Fragments then collapse on their own, fragmenting further.

End product is 100’s or 1000’s of dense clumps each destined to form star, binary star, etc.

Hence a cloud gives birth to a cluster of stars.
As a clump collapses, it starts to heat up. Eventually hot and dense enough => spectrum approximately black-body. Becomes very luminous.

Now a protostar. May form proto-planetary disk.

Can place on HR diagram. Protostar follows “Hayashi tracks”
Finally, fusion starts, stopping collapse: a star!

Star reaches Main Sequence at end of Hayashi Track

One cloud \((10^3 - 10^6 \, M_{\text{Sun}})\) forms many stars, mainly in clusters, in different parts at different times.

Massive stars \((50-100 \, M_{\text{Sun}})\) take about \(10^6\) years to form, least massive \((0.1 \, M_{\text{Sun}})\) about \(10^9\) years. Lower mass stars more likely to form.

In Milky Way, a few stars form every year.
Brown Dwarfs

Some protostars not massive (< 0.08 \(M_{\text{Sun}}\)) enough to begin fusion. These are Brown Dwarfs or failed stars. Very difficult to detect because so faint. First seen in 1994 with Hubble.

How many are there?

Brown Dwarf Gliese 229B

Palomar Observatory  Hubble Space Telescope
Molecular cloud surface illuminated by nearby hot stars.

Radiation evaporates the surface, revealing a dense globule - a protostar.

Shadow of the protostar protects a column of gas behind it.

Eventually structure separates from the cloud, and the protostar will be uncovered.
Newly formed stars in Orion with Protoplanetary Disks (Hubble)
Example Stellar Debris/Planetary Disk

Beta Pictoris [A6V] system

\[ [1.8 \, M_{\text{SUN}} , 8.7 \, L_{\text{SUN}} ] \]
\[ [D = 63.4 \, \text{LY}] \]

Candidate planet “Beta Pic b” estimated to be \(~ 8 \, \text{Jupiter masses at a}

distance of \(~ 8 \, \text{AU from star} \)

It is approx. 1/1000 the brightness of the star

Composite image using 3.6 m and 8.2m [VLT] telescopes

Outer image: 1 – 2.5 um

Inner image: 3.6 um

[European Southern Observatory]