The Nature of Stars

Star

Ball of gas held together by gravity.

Energy generated in central regions.

Outer layers emit energy transported to them from inner region.

Stars emit a spectrum similar to that of black bodies.

Typical Parameters

Masses:	0.2 to 100 Solar Masses
Luminosities:	0.001 to 10^6 Solar Luminosities
Radii:	0.01 to 1000 Solar Radii
Surface Temperature:	3000 to 100,000 K

Stellar Distances:

Trigonometric Parallax

The *most fundamental method* astronomers use to measure the distances of nearby stars is trigonometric parallax.

Parallax --- the effect that nearby objects appear to move with respect to very distant objects when viewed from a different location.

Trigonometric parallax refers to half the angle through which a star appears to be displaced (in relation to extremely distant stars) as the Earth moves from one side of the Sun to the other.

The distance (d) to a star in parsecs is:

$$d = 1/\ (p / 1'')\ \text{pc}$$

where the parallax (p) is in arc seconds.

One parsec = 2×10^5 astronomical units

= 9.5×10^{12} km

= 3.26 light years

Trigonometric Parallax can only be used to measure distances for the nearest stars.

Measure accurate parallaxes for stars out to 100 parsecs (330 light years)

This is only 1% of the distance to the center of the galaxy.

Hipparcos: High Precision Parallax collecting Satellite

Stellar Motions

Stellar motions [due to e.g.

the orbital motion of one star around another (i.e. binaries);

the orbital motion of the star about the Galactic center]

can be observed in two ways:

1. Stellar motions toward or away from us are **radial** (along our sight line) **motions** --- caused by the stars radial velocity. Radial velocities cause Doppler Effects in the observed spectra of stars.

$$\Delta\lambda / \lambda_o = v_r / c$$

2. Stellar Motions perpendicular to our line of sight are **transverse motions** --- caused by the stars transverse velocities. Transverse velocities are determined from images or pictures of stars. When pictures of stars taken over a long period of time are examined, the nearby stars are found to move. T**his is called proper motion (μ).** Measured in arc sec per year.

   In order to calculate the transverse velocity (v_t) of a star, the star's proper motion and distance must be known.

$$v_t = 4.74\ (\mu / 1\ ''/\mathrm{yr})\ \ (d / 1\mathrm{pc})\ \ \mathrm{km/s}$$

The radial velocity and transverse velocity of a star can be used to determine a star's space velocity or orbit in the Galaxy.

Luminosity and Brightness

Luminosity (L)

Measure of the **total amount of energy emitted by a star per second.**

This is the star's **actual or intrinsic brightness**.

Measured in Watts.

The luminosity (L) of a star depends on its surface temperature (T) and its diameter (D).

NB. The luminosity of a light bulb is identical to its Wattage.

Apparent Brightness

When we measure the amount of energy arriving at the Earth (per unit time) we are measuring the **apparent brightness** of the emitting source.

The **apparent brightness** is distinct from the star's luminosity or intrinsic brightness since a star appears fainter as we move it farther away.

The apparent or perceived brightness of a star depends on:

(1) the star's actual or intrinsic brightness (luminosity)

(2) the star's distance.

If we know the distance to the star its **INTRINSIC LUMINOSITY** can be calculated from its apparent brightness using the *inverse square law.*

Inverse Square Law

The apparent brightness of a star (or any point source of electromagnetic radiation) is proportional to the star's intrinsic luminosity, and inversely proportional to the distance to the object squared.

Mathematically

$$b = L / (4\pi d^2)$$

where **b** is the APPARENT brightness, and L the INTRINSIC luminosity. b has units W / m^2 or Joules/ m^2 / s.

(We generally describe the apparent brightness as an observed energy flux).

Examples

If we were twice as far from the Sun, the Sun would appear $1/2^2 = 1/4$ as bright.

If we were 10 times closer to the Sun, the Sun would appear $10^2 = 100$ times brighter.

Magnitude System

Used to measure both a stars intrinsic and apparent brightness.

The magnitude scale is not linear --- it is logarithmic.

Lower magnitudes means brighter!

If the magnitude of a star ***decreases*** by 1 unit, that corresponds to the star being about **2.5 times *brighter***.

If the magnitude of a star ***decreases*** **by 5 units**, that corresponds to the star being **100 times *brighter.***

Apparent magnitude (m)

Used to specify the apparent or perceived brightness of a star. The apparent magnitude depends both on the star's intrinsic brightness (absolute magnitude) and the star's distance.

Examples:

Vega (α Lyrae) has $m_v = 0$

Sun: $m_v = -26.8$

Moon: $m_v = -12.6$

Venus at maximum brightness: $m_v = -4.4$

Sirius (the brightest star): $m_v = -1.4$

The faintest stars we can see with the unaided eye: $m_v = 6$.

The apparent magnitude (m) and brightness (b) of 2 stars are related by the formula:

$$m_2 - m_1 = 2.5 \log (b_1 / b_2)$$

Photometry

Technique astronomers use to measure the apparent brightness (or apparent magnitude) of an object. Usually done with a filter that only allows light from a very specific band of wavelengths to be measured. By making several measurements in different color filters a star's color and hence temperature can be measured.

Most common filters are U(λ_c=3600), B(λ_c=4300), and V(λ_c=5500).

By convention an (average) A0 star has U=B=V=0

Absolute magnitude (M)

Used to specify the intrinsic brightness (luminosity) of a star. The absolute magnitude of a star is defined to be the same as the apparent magnitude of the star at 10 parsec.

Example:

Sun: 4.8

Sirius: 1.4

The absolute and apparent magnitudes are related by

$$m - M = 5 \log (d / 10pc)$$

Bolometric Magnitude (M_{bol})

Special name for the Absolute Magnitude as measured over all wavelengths. It is total energy emitted at all wavelengths.

$$M_{bol} = 4.72 - 2.5 \log (L / L_{sun})$$

Absolute Visual Magnitude (M_v)

Intrinsic Luminosity through the V filter. The absolute visual magnitude and bolometric magnitude are related by:

$$M_{bol} = M_v + BC$$

BC is the bolometric correction (typically less than zero) and accounts for that fact that stars of different temperatures emit different amounts of energy in the IR and UV relative to the visible band. The BC is a function of the stars temperature.

Stellar Spectra

A star is not a perfect Black Body however a stars continuous spectrum is generally shaped like that emitted by a Black Body. A real stellar spectrum contains absorption (and/or emission) lines. These features allow us to deduce the composition and pressure of the stars atmosphere.

Spectra of different stars shows different absorption lines. We can classify the stars by lumping them into groups so that the stars in each group show the same absorption lines.

The stellar classification scheme, *from hottest to coolest,* is as follows:

O B A F G K M.

Some people memorize this by saying: `Oh, Be A Fine Girl/Guy, Kiss Me.'

The classification is a temperature classification because stars of the same surface temperature show approximately the same set of absorption lines.

Each spectral class is further divided into 10 subclasses. eg.

B0 (hottest), B1, B2, ... B9(coolest)

A0 follows B9

The shapes of the absorption lines are influenced by the size of the star. Therefore stars have been further classified based on their line shape. Roman symbols are used to indicate whether the star is a dwarf (V), giant (III) , or supergiant (I)

e.g.

Sun: G2 V star (i.e. G2 dwarf, T=5800K)

Because a supergiant is brighter than a dwarf (with the same temperature) the I, III, and V are know n as the luminosity class.

The spectra of a star changes with temperature since the population of the energy levels change with temperature. As a star becomes hotter, collisions can excite the “lazy” electrons into higher energy orbits.

e.g. In the Sun, most of the hydrogen is in the ground state. The Balmer series (level 2-n) appear only weakly in absorption, since there a very few atoms with electrons in the n=2 orbit.

On the other hand, hydrogen can be seen strongly in absorption in the atmospheres of A stars (10,000 degrees Kelvin).

Molecules can be seen in the atmospheres of M stars (3,500 degrees Kelvin).

Summary of Fundamental Stellar Properties

We have discussed 3 fundamental stellar properties which can be determined from observations:

1. **Spectral Type.** This is a measure of a star's surface temperature. It can be determined from a star's color and spectral lines. The spectral lines also provide some information on the size/luminosity of the emitting stars.

2. **Luminosity** (or Absolute Magnitude). This is a measure of a star's actual or intrinsic brightness. It can be determined from a star's apparent brightness (or apparent magnitude) and its distance from the Earth by applying the inverse square law.

3. **Stellar Diameter**. A star's diameter (D) can sometimes be observed or it can be determined once a star's surface temperature (T) and luminosity (L) are known.

Recall:

The Stefan-Boltzmann Law ($E = \sigma T^4$) helps us calculate the luminosity of a star of a given surface temperature and radius ($L = E4\pi R^2$).

Hence if the surface temperature is known from spectral observations, the radius of a star can be inferred from its luminosity.

The Hertzsprung-Russell Diagram

The Hertzsprung-Russell Diagram (or HR diagram) is formed by making a plot or graph of:

1. Absolute Magnitude vs. Spectral Type, or

2. Absolute Magnitude vs. color or

3. Luminosity vs. Surface Temperature

HR diagrams are the most fundamental tool that astronomers have for studying the properties and evolution of stars.

Note the H-R diagram is a Log-Log plot.

In very general terms, stars fall in three areas on the HR diagram:

1.The main sequence.

These are normal stars living out their lives generating nuclear energy by converting hydrogen to helium. IT IS NOT AN EVOLUTIONARY TRACK. Stars spend most of their life on the Main sequence.

2. Above the main sequence.

These are large stars called giants or supergiants that have just recently used up the main supply of their nuclear fuel

or

they are large proto-stars in the process of forming.

3. Below the main sequence.

These are small stars like white dwarfs or neutron stars that have finished the main parts of their stellar lives.

Notes:

1. Because of

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

stars of constant radius lie on straight lines in the HR-diagram(Temperature vs Luminosity).

2. Stars on the main sequence have luminosity class V. Stars above the main sequence have luminosity classes I through IV.

Measuring Stellar Distances

Spectroscopic Parallax (Method of Standard Candles)

Used to measure stellar distances when the star is too distant for trigonometric parallax.

Method uses a star's spectrum to determine the intrinsic nature of the object. From its known intrinsic properties (as calibrated by other stars) we can determine its distance.

The steps can be summarized as follows:

Locate the stars position on the HR diagram using its spectrum (color and spectral lines). Once this is done, the star's luminosity (or absolute magnitude) is also known.

Measure the star's apparent brightness (or apparent magnitude) using photometry.

The inverse square law can then be used to calculate the star's distance.

NB.

Spectroscopic parallax requires calibration.

It relies on trigonometric parallaxes for this calibration.

Binary Stars

Two stars which orbit about their common center of mass because of their mutual gravitational attraction.

They provide fundamental information on stars; e.g.

Mass (Only direct means)

Stellar diameters.

There are 4 main types, classified according to their observed properties.

1. Visual Binary.

Binary star system seen to be double through a telescope.

2. Spectroscopic Binary.

Known to be double because the Doppler shifts in the spectral lines are observed to change with time. The Doppler shifts change because the stars alternatively come toward and go away from the Sun-Earth system while the stars orbit each other.

If only one set of spectral lines is seen, it is a single-line spectroscopic binary.

If two sets of spectral lines are seen, it is a double-line spectroscopic binary. In this case the mass ratio of the two components can be determined. Only when we know the orbit inclination, can we determine the individual masses.

A plot of the velocity versus time for a binary system is called a radial velocity curve.

3. Eclipsing Binary.

System in which one star periodically eclipses (hides or occults) the other. This causes periodic light variations.

The shape of the light curve of an eclipsing binary system depends on the diameters of the stars and the angle from which we view them.

(Note: A light curve is a plot or graph of apparent brightness [or apparent magnitude] as a function of time)

4. Astrometric Binary.

A star that is part of an astrometric binary star system `wiggles' as it moves across the sky (proper motion) because it is orbiting around another star. The other star may or may not be visible.

Notes:

It is possible for a binary to be of more than one type.

An optical double is a system which appears double to the eye or through a telescope (as on same sight line) but in which the alignment is due to chance only (i.e. the stars are unrelated).

Analyzing a light curve is a common way for astronomers to study any object that changes its brightness as a function of time.

Measuring Stellar Masses using Binaries.

Consider a Binary in which

P is the Period (same for both stars!) in years,

a_1 is the semi-major axis of star 1 about the center of mass (in A.U.) and

a_2 is the semi-major axis of star 2 about the center of mass (in A.U.).

The Generalized from of Kepler's Law states that

$$(m+M)P^2 = (a_1+a_2)^3$$

a_1+a_2 is the semi-major axis of the orbit of one star about the other star.

Stellar Masses

By using the theory of gravity, the mass of each individual star in a binary system can be calculated provided the orbital parameters are known.

Stellar orbits can be determined if the system is:

A Visual binary (Period < 100 years)

Both a *spectroscopic binary* and an *eclipsing binary*.

Observations of binaries indicate that there are many more low mass stars than high mass stars. Stars may have masses as low as 0.2 solar masses and as high as 100 solar masses.

Mass-Luminosity Relation

For **main sequence** stars, there is a correlation between the luminosity (L) of a star and its mass (M).

The mass-luminosity relation indicates that the luminosity of a main sequence star increases rapidly as the mass of the star increases. Roughly

$$L = M^{3.5}$$

where L is measured in solar luminosities, and M is in Solar masses.

On the *main sequence*, the spectral sequence

O, B, A, F, G, K, M.

represents a sequence of decreasing temperature, decreasing mass, decreasing luminosity, and decreasing diameter.