LECTURE 13: STELLAR ASTRONOMY: OBSERVATION AND THEORY

## 13.1 MEASURING STELLAR PROPERTIES

We can learn about stars from careful measurements of positions, fluxes, colors, and spectra, and by tying these observations together with theoretical interpretations.

parallax $\longrightarrow$ distance

distance and apparent flux $\longrightarrow$ luminosity

orbits of binary stars $\longrightarrow$ mass

duration of eclipses in eclipsing binaries $\longrightarrow$ radius

color $\longrightarrow$ surface temperature

spectral lines $\longrightarrow$ surface temperature, composition, size

Doppler shifts $\longrightarrow$ radial (line-of-sight) velocity

## 13.2 CORRELATIONS OF OBSERVABLE PROPERTIES

We can build our observational picture by studying correlations of stellar properties, plotting one observable quantity against another.

The most important such correlation is the Hertzsprung-Russell diagram, luminosity vs. surface temperature. This diagram is inspired by the equation for the luminosity of a spherical blackbody, $L = (4\pi\sigma)R^2T^4$. Any star with a measured luminosity (from flux and distance) and measured surface temperature (from spectral type or color) can be plotted on an HR diagram.

The HR diagram reveals the existence of a main sequence, red giants, and white dwarfs.

Other important correlations are the mass-luminosity relation and the mass-radius relation for main sequence stars. These show that the main sequence is primarily a sequence of increasing mass (low-mass $\longrightarrow$ cool, faint; high-mass $\longrightarrow$ hot, bright).

## 13.3 HR DIAGRAMS OF STAR CLUSTERS

For a star cluster, we can get an HR diagram by plotting apparent flux (instead of intrinsic luminosity) against color, since the cluster stars are at a common distance.

The HR diagram of an open cluster typically has relatively few red giants and a main sequence that extends to blue, luminous stars.

The HR diagram of a globular cluster typically has no blue stars on the main sequence, an extensive red giant branch, and a horizontal branch of bright stars.

## 13.4 TESTING THE BASICS

The division between "observation" and "theory" is not a clear one. Our observational inferences about stars involve a lot of interpretation.

Our "measurements" are based on the assumption that the laws of physics that apply on earth and in the solar system also apply to other star systems.

The coherence of our observational picture supports the validity of this assumption:

- Diagrams *do* show strong correlations between measured properties, implying that they have physical meaning.
- The sun fits onto the relations derived from other systems, even though we determine its properties by quite different techniques.
- Colors and spectral types lead to consistent estimates of surface temperatures, even though these estimates are based on different physical principles.
- Stellar radii measured in eclipsing binaries agree with those inferred from the blackbody equation, $L = (4\pi\sigma)R^2T^4$.

## 13.5 PHYSICAL THEORY OF MAIN SEQUENCE STARS

Historically, the theory of stars has grown in parallel with observational developments.

Starting hypothesis: a star is a ball of gas held together by gravity.

We develop this hypothesis into a theory of main sequence stars by applying known physics. The basic principles are:

- pressure balances gravity
- luminosity is carried from the hot core by "leaking photons" and radiated from the star's surface
- nuclear fusion replenishes the lost thermal energy

Given the mass and composition of a main sequence star, one can assume a radius and compute

- the central temperature, by requiring that pressure balance gravity
- an "emitted luminosity" = (energy in photons)/(escape time of photons)
- a "produced luminosity" from the rate of nuclear fusion

The radius of the star is the one at which the emitted luminosity and produced luminosity match, indicating that fusion energy can supply the star's luminosity. If the star did not have this radius, it would expand or contract until it did.

## 13.6 TESTS OF MAIN SEQUENCE THEORY

Qualitative successes of the theory:

- Fusion energy can explain great age of solar system.
- Experiments detect neutrinos from the sun, direct evidence for fusion.

Quantitative successes of the theory:

- Explains luminosity and radius of the sun.
- Excellent agreement with solar oscillation measurements.
- Explains mass-luminosity relation.
- Explains mass-radius relation.
- Explains existence and location of main sequence in HR diagram.

## 13.7 THE SOLAR NEUTRINO PROBLEM

Quantitative failure of the theory:

- Predicts more solar neutrinos than are detected (by factor of 2-4).

It is unclear whether this failure reflects a problem with stellar structure theory, with our current theory of neutrinos, or with the experimental data (the least likely option, since four independent experiments show similar results).

Given the other successes, it seems unlikely that the solar neutrino problem will lead us to reject our basic theory of stars. However, it might yet lead to interesting and important modifications of the theory.

## 13.8 THEORY OF STELLAR EVOLUTION

Stellar evolution theory is built on the principles of stellar structure and our understanding of nuclear physics.

The evolution of a star is driven by the competition between gravity and pressure.

In order to maintain its central temperature, a star must replenish the thermal energy that it is radiating to outer space. It can do so using nuclear fusion or gravitational contraction.

The most basic prediction of stellar evolution theory is that more massive stars use up their fuel supplies and advance through the stages of stellar evolution more rapidly.

## 13.9 STAGES OF STELLAR EVOLUTION

Evolution of a low-mass star:
protostar
$\longrightarrow$ main sequence (core hydrogen)
$\longrightarrow$ red giant (shell hydrogen$\rightarrow$core helium$\rightarrow$shell helium)
$\longrightarrow$ planetary nebula/white dwarf

Evolution of a high-mass ($M > 8M_\odot$) star:
protostar
$\longrightarrow$ main sequence (core hydrogen)
$\longrightarrow$ red giant (shell hydrogen$\rightarrow$core helium$\rightarrow$shell helium$\rightarrow$core carbon$\rightarrow$etc.$\rightarrow$inert iron core)
$\longrightarrow$ supernova
$\longrightarrow$ supernova remnant/neutron star/black hole

### 13.10 TESTS OF STELLAR EVOLUTION THEORY

Successes of theory:

- Explains existence of main sequence stars, red giants, and white dwarfs.
- Accounts quite well for HR diagram of nearby stars.
- Explains variety of cluster HR diagrams primarily as a sequence of cluster *age*.

In young clusters, massive, blue stars are still on the main sequence, and there are few red giants.

As a cluster ages, the main sequence "peels away" from the top, as the massive stars evolve into red giants and then "die," quietly or with a bang.

In old clusters, only fairly red stars are left on the main sequence, and there are many red giants.

In comparing open clusters to globular clusters, the difference in chemical composition is also important. Globular cluster stars have very few metals, which is the main reason globular clusters have a horizontal branch while open clusters have a red giant clump.

### 13.11 EVALUATION OF STELLAR EVOLUTION THEORY

Overall, stellar evolution theory is impressively successful.

There are some nagging disagreements between the predicted and observed brightnesses and colors of some stars.

There is a possible conflict between the inferred ages of the oldest star clusters and the age of the universe inferred from cosmological observations.

There are many frontier problems, theoretical and observational, in the study of post-main-sequence evolution, supernovae, and star clusters.