LECTURE 10: STELLAR EVOLUTION I. THE MAIN SEQUENCE

10.1 A THEME

The inside of a star must be hot, so that pressure can support it against gravitational collapse.

However, a star is constantly losing heat to outer space.

The competition between gravity and pressure drives the various stages of stellar evolution.

10.2 COMPRESSION AND HEATING

When a gas is compressed, its temperature rises.

This process is easy to understand in the case of a piston. The piston moves in to compress the gas, and when an atom bounces off the piston it moves faster than before it hit the piston.

As the piston moves in, the average speed of the atoms goes up, meaning that the temperature goes up.

This is the physical mechanism behind equation # 5, $T_c \propto M/R_{\rm avg}$.

10.3 SOURCES OF ENERGY FOR A STAR

A star has several possible sources of energy.

Thermal energy (or *heat energy*): energy stored in the motions of atoms and the energy of photons.

Nuclear energy: energy available from fusing light elements into heavier elements, e.g. hydrogen into helium.

Gravitational potential energy: energy that the star can tap by contracting.

A star is constantly losing its thermal energy supply to outer space, because it is luminous. It can replenish this thermal energy either by nuclear fusion or by contraction. A star heats up when it contracts, turning gravitational potential energy into thermal energy.

10.4 A (VERY) SIMPLIFIED PICTURE OF STAR FORMATION

With the equation $T_c \propto M/R_{\rm avg}$, we can build a simplified picture of star formation.

(1) Start with diffuse, spherical cloud of gas, which is contracting under its own gravity.

(2) As the cloud contracts, the gas is compressed, and it heats up (gravitational energy $\longrightarrow$ thermal energy)

(3) Some of this thermal energy escapes ("leaking photons"), so the *protostar* radiates energy. It replaces this energy by contracting further, raising its central temperature.

(4) Eventually, the center of the star gets hot enough for fusion to occur. Now thermal energy can be replenished by nuclear energy, instead of by gravitational contraction.

As long as the nuclear energy supply lasts, the star can shine without contracting further.

Note: The behavior in step (3) is completely different from that of a glowing piece of charcoal, which gets *cooler* as it radiates energy. As a protostar radiates, it gets *hotter* because of gravitational contraction.

This sketch of star formation captures some important features of the process, but it ignores rotation and magnetic fields, both of which play critical roles during the formation of real stars.

10.5 THE RADIUS OF A MAIN SEQUENCE STAR

As a protostar contracts, its central temperature goes up, and the rate of nuclear fusion goes up. The rate at which photons can escape from the center of the star goes down.

A star stops contracting when the rate at which energy is produced by fusion just balances the rate at which energy is lost by escaping photons. *The star has precisely the radius that allows nuclear energy to produce its luminosity.*

This radius is stable:

Star expands slightly: T_c drops $\longrightarrow$ fusion rate drops, central pressure drops, star contracts

Star contracts slightly: T_c rises $\longrightarrow$ fusion rate rises, central pressure rises, star reexpands.

10.6 THE MASS-RADIUS RELATION

We can derive a rough approximation of the mass-radius relation by knowing that the rate of nuclear reactions is *very* sensitive to temperature. Raising the central temperature slightly raises the energy production enormously.

$\Longrightarrow$ Stars with very different luminosities have quite similar central temperatures.

Since $T_c \propto M/R$, condition $T_c \approx constant$ implies $R \propto M$.

For very hot stars, pressure is dominated by photons instead of by moving atoms, and the equation $T_c \propto M/R$ does not apply. For these stars, a similar physical argument gives $R \propto \sqrt{M}$.

These approximate arguments reproduce the observed mass-radius relation of main sequence stars fairly well.

10.7 THE MASS-LUMINOSITY RELATION

In 7.5, we saw how to compute the luminosity of a star given its mass *and* radius.

We now see how the mass of a star determines its radius, making it possible to compute the luminosity from the mass alone.

A more massive main sequence star is more luminous primarily because it is bigger. The larger core contains more photons and more thermal energy.

Calculations using these principles reproduce the observed mass-luminosity relation.

10.8 WHY IS THERE A MAIN SEQUENCE?

The mass of a main sequence star determines its radius and its luminosity.

Since $L = (4\pi\sigma)R^2T^4$, the mass also determines the surface temperature T, hence the color and spectral type.

The mass of a main sequence star determines its position on the HR diagram.

Stars lie on a narrow sequence because luminosity and temperature climb *steadily* with mass.

10.9 MAIN SEQUENCE STARS

A main sequence star is a star that is sustaining its luminosity by fusing hydrogen into helium in its core.

Hydrogen fusion can sustain a star for a long time, which is why most stars are found on main sequence.

As core turns from hydrogen into helium, the structure of the star changes slightly, and it evolves slightly away from "zero age" main sequence. However, it does *not* evolve *up* or *down* the main sequence.

Eventually, the supply of hydrogen in the core runs out. At this point, the star begins to evolve much more rapidly.

10.10 SUMMARY

Sources of energy available to a star are thermal energy, nuclear energy, and gravitational potential energy.

As a protostar contracts it heats up, using gravitational energy to replenish thermal energy. When the core gets hot enough, hydrogen fusion begins.

A protostar stops contracting (reaches the main sequence) when the energy produced by hydrogen fusion matches the star's luminosity. The match of fusion rate to luminosity determines a star's radius.

The mass of a main sequence star determines its radius, its luminosity, and its temperature, thus its position in the HR diagram.

A star can live happily on the main sequence until the supply of hydrogen fuel in its core runs out.