Okay, so we've seen that star's use up their nuclear fuel (on vastly different timescales for low- and high mass-stars) and that they turn light elements into heavy elements as a byproduct of producing energy which is, itself, in some sense just a byproduct of hydrostatic equilibrium's demand for pressure.

We next want to see how stars form, how they change as they age, and how they die. But the formation piece involves understanding a bit about the gas (and dust) in the *interstellar medium* (ISM), the substrate out of which stars form. And incidentally, the ISM is replenished with gas enriched in heavy elements when stars die.

So we will first take an important and interesting detour into the ISM.

Here I provide some notes on five topics we'll discuss in class. I'm putting page breaks between them and leaving blank space below my notes. I suggest you print these out and bring them to class and take your own notes directly on them, elaborating on what I've written.

(1) Big picture

Thinking about the *context* in which a star lives its life, is like thinking about a tree in a forest. The big picture is the forest ecosystem – individual trees come and go but there are always trees. A dead tree decays and nourishes the soil out of which new trees grow. The forest may change over time but it's on a timescale much longer than the lifespan of an individual tree.

In this analogy, the Galaxy is like the forest ecosystem, the stars are like trees, and the interstellar medium plays the role of the soil (and maybe the air and water too).

One dramatic way to see the ISM is via dark clouds that block the starlight behind them, revealing their forms as silhouettes:

Molecular cloud Barnard 68, is less than a light-year across: http://apod.nasa.gov/apod/ap141214.html

Our goals in studying the ISM are to characterize (measure) its properties and to understand the processes that shape the ISM-plus-stars system that is the Galactic ecosystem. Questions astronomers would like to answer include things like – Where will stars form? How many will form out of a cloud of a given mass? Over what span of time?

(2) Dust

Interstellar dust is smaller than household dust - it is microscopic. It is more like particulate soot (hydrocarbon molecules that weigh hundreds of atomic masses) or silicates. Dust grains exist over a range of sizes (at least 10s of Å to a few microns) and are essentially small bits of matter in solid form.

They scatter and absorb light, with characteristic behavior that is largely a function of the dust grain size – dust acts like a solid obstacle to light with wavelengths shorter than the dust grain size but brings out the wave-like properties of light for light with long wavelengths. Longer wavelength light has an easier time "jumping over" dust grains than short wavelength light does.

Dust grains condense out of cooling gas, and so form in environments like the stellar winds of red giants.

Makes sure you carefully read the four lines of evidence for dust's existence at the beginning of the chapter. And make sure you understand what *extinction* is. Study Fig. 16.1 and be prepared to answer or ask questions about it.

Dust reddens starlight that passes through it. Extinction (A) can be accounted for in the distance modulus (eqn. 16.5) but extinction can't be independently determined. Instead, we estimate extinction by measuring the *color excess*, $E(B-V)$ (eqn. 16.8). We know what color a star should have by measuring its spectral type. Note that the parameter R has to be guessed/estimated.

(3) Gas

Gas can be detected in the ISM by various means, listed on pp. 380-82. You're already familiar with number 1, which is important and generally good for measuring the properties of cold and warm clouds. Focus on methods 2, 4, and 5 as you re-read this material.

We'll go into some detail (next two pages) about cold clouds (observed via radio emission and absorption) – since they are where stars form – and H II regions (hot clouds around UV-emitting stars) – since they are so prominent (the Orion Nebula is a famous H II region).

When thinking about interstellar gas, it's good think about different *components* of the ISM (see the bullet points at the bottom of p. 382 and top of p. 383). A general pressure equilibrium holds among the components, with the hotter components being less dense so the product of density and temperature (which is proportional to pressure) is about the same for each component.

It's also interesting to think about the role each component plays in the longer term evolution of the ISM and the "Galactic ecosystem" (e.g. cold molecular clouds are where stars will form; H II regions indicate that stars have recently formed there; the hot ISM component is largely heated by supernova explosions and so is the product of stellar death).

(4) Cold gas observed in the radio

When gas is cold it is very difficult to excite electrons into higher orbitals, so the emission lines we're used to – that come from electrons moving from one orbital energy level to another – aren't usually observed.

But, there are other ways for electrons in atoms to be excited. An important example is the 21 cm (that's its wavelength) "spin-flip" transition of hydrogen. An electron in the lowest orbital of a neutral hydrogen atom – the ground state – can actually have one of two different spin orientations: spin-up (aligned with the spin of the nucleus) or spin-down (anti-aligned with the nucleus's spin). The anti-aligned spin actually has a slightly lower energy than the aligned spin configuration. The spin-up state is thus an excited state but its excitation energy is low – so it can be collisionally excited even if temperatures are low (like just a few degrees K). Once excited, the electron can flip back to the spin-down state, spontaneously, and in doing so, it emits a photon with $\lambda = 21$ cm in order to conserve energy.

Radio telescopes can be used to trace out this cold, neutral atomic hydrogen in the Galaxy (and beyond).

Cold and even denser gas (still very, very low density by earthly (or even Solar) standards) will form molecules. It shouldn't be surprising that atoms bind together only under cold, dense conditions. Molecules also have excited states that are accessible at low temperatures and which are not the usual atomic orbitals related to the positions of bound electrons. Rather they are states that store energy in the rotation of a molecule (won't work for an atom, which is basically spherical). The deexcitation of these rotationally excited states (which have quite modest energies) lead to the emission of a radio photon. So, radio telescopes are used to measure molecular gas.

Two things to note: (1) these radio transitions (21 cm atomic hydrogen and rotational transitions of molecules) can also be seen in absorption if there is a chance alignment with a background object that is a strong radio continuum emitter; and (2) the spin of the H-atom's electron is quantized (only spin-up and spin-down are allowed, not a continuous array of alignments in between those two extremes) and the rotational states of molecules are also quantized. In both cases, this means that photons that are emitted or absorbed are *line* photons not continuum photons.

(5) H II regions

Here you should focus on §16.3.1 and the concept of the Stromgren sphere (and Stromgren radius). What two quantities are equated in order to derive the Stromgren sphere radius (eqn. 16.19)? Do the various parameter dependencies in that equation make sense to you? For example, why should a larger density lead to a smaller Stromgren sphere?

O stars emit a lot of UV photons; photons with enough energy to ionize hydrogen. So O stars are always surrounded by clouds of ionized H. When this H recombines, it can emit a Balmer-α photon (6563 Å). Study Fig. 16.5. So H II regions look pink.

Temperature equilibrium in H II regions is governed by a balance between heating due to photoionization and cooling due to collisional excitation of bound electrons in *metals* (elements heavier than helium).

The Orion Nebula – closest H II region to the Earth: http://apod.nasa.gov/apod/ap120715.html