## Star Formation

Much of this is taken from Matthew Bate's lectures. Emphasize that the study of star formation is *very* much a work in progress, and there is a lot that is not known.

Start with context, then questions we want to answer.

The study of star formation is of course intrinsically interesting, but it also touches on a wide variety of other interesting questions in astronomy. Intrinsically, it involves physical processes such as gravity, magnetic fields and MHD, radiative transfer, chemical evolution, accretion disks, and jets. It has major impact on our understanding of stellar populations (for example, globular clusters and other star clusters, plus the binaries which make up most of the stars in the universe). It is also important for understanding chemical evolution and galaxy evolution, as well as the formation of planets. A hot topic in cosmology is understanding the first generation of stars, the so-called "Population III" stars, which formed in the presence of few metals and may have helped reionized the universe (although present understanding suggests it was indirect, happening because of formation of massive black holes from the first massive stars).

**Framing questions**

**Ask class:** what are some of the framing questions they're interested in? Can't promise to get to all those, but it's useful in a field such as this to at least write down the questions.

(1) What determines when and where stars form?

(2) How efficiently is mass turned into stars?

(3) What is the star formation rate? It is apparently much less now than it was at a redshift of $\sim 1-2$, for example.

(4) What is the initial mass function, and on what does it depend?

(5) How do clusters form? Is that the way most stars form, or do they usually form in isolation?

(6) Is the formation of massive stars the same as the formation of low-mass stars?

(7) How does metallicity affect star formation? Pop III, again.

(8) Does gravitational collapse need to be triggered (e.g., by shocks) or can it happen in a quasi-equilibrium fashion?

(9) What role does rotation or magnetic flux play in star formation?

(10) How do binary and multiple systems form?

(11) What is the role of circumstellar disks and jets/outflows?

(12) What determines the spin rate of a star?

(13) How do planets form, and what is their mass distribution?

We are not going to answer all of these questions. Note, however, that there are a *ton* of unresolved issues related to star formation. Observationally and theoretically, there is a lot of progress to be made! Some of these topics, such as planet formation and the formation of the first generation of stars, are considered by many to be among the most important current questions in astronomy.

**Observational probes of molecular clouds**

**Ask class:** where do stars form? Molecular clouds. **Ask class:** how do we know? We can look at stars we think are young, and determine where they are. **Ask class:** how can we tell if a star is young? There are now a variety of ways, such as the spectral sequence from Class 0 to I to II to III stars, but as a first step we can look at stars that live very short lifetimes and are therefore always young. This would mean the most massive, brightest stars, i.e., O or B stars. Studies of such stars show that they are located near molecular clouds, so people have focused on MC as stellar birthplaces.

Put another way, there are two ways you can think of studying star formation. (1) Look at young stars, or (2) look at molecular clouds. Young stars have already formed, so little information about initial conditions or the star formation process, therefore have to work backwards. Molecular clouds give lots of info on initial conditions, but it's not clear which portions will form stars, it is hard to establish properties, and therefore have to work forwards.

Now, first give overview of numbers, then think about how they can be derived from observations.

Give typical numbers for molecular clouds: mass, density, temperature, magnetic field, size, number density. Giant molecular cloud (e.g., Orion): mass $M \sim 10^5 - 3 \times 10^6\,M_\odot$, size of tens of parsecs, temperature ∼10 K. These are made up of subunits (cores) with typical mass $\sim 5000\,M_\odot$ and typical size $\sim 1$ pc. Number densities of these cores is fairly high, $10^4 - 10^6$ cm$^{-3}$, and smaller subunits can have even higher density ($10^7$). Compare this with the overall $0.1 - 1$ cm$^{-3}$ density of the ISM. Much substructure as well. Molecular clouds generally have a low filling factor, except for dense cores.

**Ask class:** what ways might we use to get information about molecular clouds? A problem is that most of the mass of molecular clouds is invisible, because the $H_2$ and He are not excited enough to emit (too cold, and UV doesn't penetrate the bulk of the cloud). Absorption by $H_2$ is also not major, because dust obscures it. Therefore, need to rely on trace constituents, such as dust and other molecules. Gamma-rays produced by cosmic ray interactions with nuclei do probe all the material in the clouds, but they have very low spatial resolution.

**Ask class:** what other options for tracing molecular clouds might there be? Dust, other molecules.

An issue is that dust extinction is strongest at short wavelengths, so can see farther in IR than in optical; reradiation happens in the far IR to mm. Thus, we'd like to think of what kind of transitions occur at these low temperatures and low photon energies. Electronic transitions are usually at higher energies, meaning that we look instead for rotational or vibrational transitions. Note: at extreme squiggle level, one can estimate the energy of some rotational levels by assuming that a given molecule can't have angular momentum less than $\hbar$, and using that to determine the energy for a given moment of inertia (calculated classically for a given molecule).

The other choice is to use trace parts of the gas, which emit in rotational transitions at mm or sub-mm. Technique was first used with OH in 1964, now many other molecules are used.

The most abundant molecule after $H_2$ is CO, usually $^{12}C^{16}O$ (about $3 \times 10^{-4}$ times the abundance of $H_2$, with factor 3 uncertainty). On large scales, this correlates well with gamma-ray data, so the overall mass can be measured even if the line is very opaque. **Ask class:** in general, in what rough range of optical depth would one expect line measurements to be most useful? When it isn't too different from unity. If the line is really saturated ($\tau \gg 1$), only a lower bound is possible, whereas if $\tau \ll 1$ the line is tough to measure. So, **Ask class:** what should be done if, say, $^{12}C^{16}O$ is saturated? Look for transitions of rarer isotopes in the molecule, to probe further. For example, $^{13}C^{16}O$ for somewhat higher column depth regions, or $^{12}C^{18}O$ or $^{12}C^{17}O$ for yet denser. Good for the inner regions; for outer parts, photodissociation messes things up. In these cases, the conversion to total column depth can be a bit tricky.

The cloud is then mapped in this tracer, and the total mass is calculated from the column depth and the projected size. **Ask class:** what are some ways this can be made more difficult? Non-spherical cloud will be a problem, because we often don't know the line-of-sight depth (although $H_3^+$ might be a decent tracer). The size and line width (which is a measure of the velocity, caused by gravitation) can be used to estimate the virial mass. Can also estimate the mass by using an empirical relation between the mass and the CO luminosity; note, however, that this requires knowledge of the abundance of CO. The net result of all this is that the differential number-mass relation is $dN(M) \propto M^{-\alpha} dM$, where $1.5 \leq \alpha \leq 1.9$. Cutoff at $\sim 6 \times 10^6\, M_\odot$. This may be indicative of a fractal distribution of interstellar gas, but it isn't clear yet. **Mention:** power laws are in general scale free. Star formation rate per unit mass appears independent of cloud mass; $\alpha < 2$ means that most of the mass, and therefore most of the star formation, probably occurs in massive clouds.

In addition, most mass in a molecular cloud is in a dense clump, and most star formation occurs in those clumps, leading to stellar clusters. However, this is tricky, because the SFR per unit mass varies by a factor of $> 10^2$ at a given mass; also, most molecular gas is sterile. Note the different scaling from the stellar mass distribution $dN/dM \propto M^{-2.35}$ (Salpeter), which puts most of the mass at low-mass end. Apparently, some recent results for very high-density low-mass clumps suggests these may have a mass distribution similar to that of stars.

Thus, CO and its isotopomers, plus dust, are the ones used to constrain the column depth and the mass. Abundances of other molecules are poorly constrained, but there are $>100$ others; what use can they be? **Ask class:** what other physical information might we want to know? Temperature, density, velocity, magnetic field, ionization.

**Ask class:** by analogy with the Saha equation, how would one constrain the temperature and density of the clouds? By looking at the relative populations of different energy levels in molecules. If we had only one level, the ionization fraction is degenerate between T and n, but with many the degeneracy is lifted. Within bound atoms, of course, the Boltzmann equation is all you need for the temperature if the molecules are in equilibrium.

Temperature tracers include CO, $NH_3$, and others. A complicating factor of density determinations is that many of the transitions of interest are not in LTE; in such a case, the rate equations must be used. Typically, the density in star-forming regions exceeds $10^4$ cm$^{-3}$, whereas sterile regions are at $n \sim 10^2 - 10^3$ cm$^{-3}$.

Determining the velocity profile is easy in principle, tough in practice. **Ask class:** how would you determine the velocity profile? You would see Doppler shifts in the line profile. **Ask class:** what problems might this encounter in reality? (1) only line-of-sight velocities enter, and (2) what you see is an average over the beam. In addition, the velocity fields of many clouds appear to be dominated by turbulence.

**Ask class:** what ways might we estimate the magnetic fields in star-forming regions? Observations of magnetic fields in star-forming regions are possible because of Zeeman splitting, polarization of radio spectral lines (because of radiative transfer), polarization caused by aligned grains, and some other indirect indications including the angular distribution of masers and Faraday rotation (wavelength-dependent). Typical inferred strengths range from about 10 microgauss in the least dense regions to 30 milligauss in masers (compared to 3 microgauss in the ISM and probably less than a nanogauss in the ICM). As with the velocity profile, determination of the magnetic field can be complicated if the field structure is turbulent because then again you only see an average over your beam.

Overall, most of the useful information on molecular clouds comes from studying molecular lines in the mm and sub-mm. Interferometric arrays are really helpful for high resolution.

### Other probes of star formation

A few nearby star-forming regions, such as Orion, Taurus-Auriga, and Ophiuchus, have been studied extensively because they are relatively accessible and can be resolved into structures. These bright regions have star formation happening right now, so we can see pre-main-sequence stars, disks, jets, infall of gass, and other things. Here, optical, IR, and mm/sub-mm observations are especially useful.