Star Formation

Now that we have armed ourselves with an understanding of stellar energy generation, equations of state, and opacities, it is time to turn our attention to the formation of stars. 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 magnetohydrodynamics, 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 reionize the universe (although present understanding suggests it was indirect, happening because of formation of massive black holes from the first massive stars).

Framing questions

1. What determines when and where stars form?
2. How efficiently is mass turned into stars?
3. What is the star formation rate, in solar masses per year per mass of the host galaxy? It is apparently much less now than it was at a redshift of $z \sim 1 - 2$, for example.
4. What is the initial mass function (IMF) of stars, and on what does the IMF depend?
5. How do stellar clusters form? Is that the way most stars form, or do they usually form in isolation?
6. Is the formation of high-mass stars the same as the formation of low-mass stars?
7. How does metallicity affect star formation?
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, and does that rate evolve significantly over the life 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

Stars form in molecular clouds (MCs). How do we know? We can look at stars we think are young, and determine where they are. 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 MCs 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 they present us with little information about initial conditions or the star formation process and thus we have to work backwards. Molecular clouds give us lots of info on initial conditions, but it's not clear which portions will form stars and therefore have to work forwards.

Giant molecular clouds (think, e.g., of the Orion nebula) have masses $M \sim 10^5 - 3 \times 10^6\, M_\odot$, sizes of tens of parsecs, and average temperatures $\sim$10 K. The clouds are made up of subunits (cores) with typical mass $\sim 5000\, M_\odot$ and typical size ~ 1 pc. The number densities of these cores are fairly high, $10^4 - 10^6$ cm^{-3}, and smaller subunits can have even higher densities (10^8 cm^{-3}). In comparison, the overall average number density of the interstellar medium in our Galaxy is $0.1 - 1$ cm^{-3}.

We give these numbers, but how can we obtain them observationally? A problem is that most of the mass of molecular clouds is invisible. Almost all of the mass in the clouds is in H_2 (because hydrogen is the most common element in the universe and at these temperatures it forms molecules) or He (because this is the second most common element in the universe and helium does not form molecules under those circumstances). That poses a difficulty, because at ~ 10 K, neither H_2 nor He go into excited states (from which they could emit by going down to the ground state). You might hope that ultraviolet radiation from other stars could ionize H_2 or He, or put them into excited states, but the bulk of the cloud is highly opaque to UV. You might instead look for *absorption* of background light. However, dust can obscure such absorption, and there is so much H_2 in molecular clouds that you can't easily tell the difference between a lot and a little in a given line of sight; at some point, you've absorbed all that you can absorb.

Observers therefore have to get more creative. For example, cosmic rays can penetrate all the way through molecular clouds and interact with nuclei in ways the produce gamma rays. These gamma rays are then visible through the clouds. However, for reasons having to do with how we detect gamma rays, the resulting spatial resolution is very poor.

As a result, much of the information we have on molecular clouds comes from other molecules than H_2. To understand why, we need to take a bit of a diversion to think about molecular emission and absorption.

When a molecule has more than one atom, it can vibrate and rotate rather than just having its electrons change states. Let's first consider vibration. We can get an order of magnitude idea about vibrational energies using a semiclassical model. In this case, we imagine that the nuclei vibrate by moving back and forth in a potential, which we can treat as a harmonic oscillator (e.g., a spring). In a classical harmonic oscillator we can figure out the frequency $\omega = \sqrt{k/M}$ if we know the spring constant k and the mass M. In our case, the mass is roughly the mass of a nucleus. We can estimate the spring constant if we know a typical energy E at a typical distance x; then $E = \frac{1}{2}kx^2$. Our rough estimate could be that the energy is the binding energy $E = m_e e^4/2\hbar^2$ of hydrogen, and the distance is the Bohr radius $a_0 = \hbar^2/(m_e e^2)$ (i.e., about the radius of a ground-state hydrogen atom). Solving, $k = m_e^3 e^8/\hbar^6$, so the vibrational energy is

$$E_{\rm vib} = \hbar\omega = \hbar\sqrt{k/M} \sim (m_e/M)^{1/2} m_e e^4/\hbar^2 \sim (m_e/M)^{1/2} E_{\rm elect}\ , \tag{1}$$

where $E_{\rm elect}$ is a typical electron binding energy, e.g., 13.6 eV for hydrogen. Since $m_e/M \sim 1/(1800A)$, where A is the atomic weight of the nucleus, these vibrational energies are a few percent to a few tenths of a percent of the electronic transition energies, or tenths to hundredths of an eV compared with a few eV for electronic transitions. Vibrational transitions are therefore in the infrared.

What about rotation? When you think about rotation, you think about angular momentum. From quantum mechanics, the minimum possible change in angular momentum is something like $\hbar$. We can use this to estimate rotational energies by estimating the rotational energy that corresponds to an angular momentum of $\hbar$ for a given molecule. If the molecule has a moment of inertia I and rotational frequency Ω, then its angular momentum is $L = I\Omega$ and its rotational energy is $\frac{1}{2}I\Omega^2 = L^2/(2I)$. The moment of inertia of a molecule of mass M and dimension a is $\sim Ma^2$, so the energy is of order $E_{\rm rot} = \hbar^2/(Ma^2)$. If $a \sim a_0$, we then find

$$E_{\rm rot} \sim (m_e/M) E_{\rm elect}\ . \tag{2}$$

These are usually in the 10^{-3} eV range, putting the transitions in the radio.

We are therefore fortunate in that there is a clear hierarchy of energies:

$$E_{\rm elect} : E_{\rm vib} : E_{\rm rot} = 1 : \left(\frac{m_e}{M}\right)^{1/2} : \left(\frac{m_e}{M}\right)\ . \tag{3}$$

Moreover, when the temperature is low, as it is in molecular clouds, the lines produced by vibrational or rotational transitions are very narrow. All of this leads to several important consequences for the observations of molecular clouds:

1. Because the rotational (especially) transition energies are low, they can be excited, and lines can be emitted, even at the low temperatures of molecular clouds.
2. Because the energy depends inversely on the mass of the molecule (like $1/M$ for rotation or $1/M^{1/2}$ for vibration), heavier molecules have lower transitional energies. In turn, this actually means that the *cooling* of molecular clouds depends on these heavy molecules; for light molecules such as H_2, states cannot be excited, and thus cooling cannot happen, below a few hundred Kelvin, whereas for heavier but still common molecules such as CO, cooling is efficient down to a few to tens of Kelvin.
3. Because the spectral lines are very narrow, it is possible to distinguish the difference between "isotopologues", which are the same molecule but with different isotopes (e.g., ^{13}CO versus the more normal ^{12}CO).

Let's now explore some of this in more detail.

The most abundant molecule after H_2 is CO, usually ^{12}C^{16}O (about 3×10^{-4} times the abundance of H_2, with a factor ~ 3 uncertainty). **Ask class:** in general, in what rough range of optical depth would one expect line measurements to be most useful? The answer is: when the optical depth isn't too different from unity. If the line is really saturated ($\tau \gg 1$), only a lower bound is possible on the number of molecules per area in the direction, whereas if $\tau \ll 1$ the line is tough to measure because we see very little of it. So what should be done if, say, ^{12}C^{16}O is saturated, i.e., if $\tau \gg 1$ for that molecule? In that case, we look for transitions of rarer isotopes in the molecule, to probe deeper into the cloud. For example, we could use ^{13}C^{16}O for somewhat higher column depth regions, or ^{12}C^{18}O or ^{12}C^{17}O for yet denser regions. All of this works fairly well for the inner regions of clouds. However, for outer parts, photodissociation messes things up; that is, the illumination by stars means that the distribution of the states of molecules isn't necessarily the equilibrium distribution. In such cases, the conversion to total column depth can be a bit tricky.

These tracer molecules can then be used to map out the cloud, and can also be used to estimate the total mass in the cloud by, for example, assuming that the cloud is spherical. But this means that if the cloud is *not* spherical, then our task is more difficult. Line widths are an indication of the typical line-of-sight velocity (caused by motion due to gravitation), so another way to estimate the mass is to use the size, the speed, and the virial theorem. The mass can also be estimated if we have a decent idea of the ratio between the number of CO molecules (which we see due to their transitions) and the number of H_2 molecules (which carry most of the mass). Clearly, there are ways that our estimates could be off, but usually not by a large factor.

The net result of all this is that the differential number-mass relation is $dN(M) \propto M^{-\alpha} dM$, where $1.5 \leq \alpha \leq 1.9$. There could be a cutoff at $\sim 6 \times 10^6\, M_\odot$, i.e., there might be a sharp drop in the number of molecular clouds heavier than this. The star formation rate per unit mass appears independent of cloud mass. In addition, most of the mass in a given molecular cloud is in dense clumps, and most star formation occurs in those clumps, which is believed to typically produce stellar clusters.

As an aside, although we have focused on CO due to its abundance and utility, more than 200 other molecules have been identified in interstellar space. What do you think that we could learn from them?

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 would be degenerate between the temperature T and the number density n, but with many molecular energy levels 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.

We now ask the eternal question: what about magnetic fields? In particular, what are some ways that we might 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 (which is wavelength-dependent). Typical inferred strengths range from about 10 microgauss in the least dense regions (for context: the magnetic field strength at Earth's magnetic poles is about 0.5 Gauss) 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 observation.

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 gas, and other things. Here, optical, IR, and mm/sub-mm observations are especially useful.