10 Accretion in astrophysics I: star formation

We argued in chapter 6 that accretion flows are common. They are found in many places – from Young Stellar Objects (YSO's), to compact objects (black holes, neutron stars) in galactic binary systems, to massive black holes in Active Galactic Nuclei (AGN). They are potentially important to astrophysics in all settings. In this chapter we'll look at star formation and YSO's, with an eye to the role of accretion in the process. In the next two chapters we'll return to "classical" accretion, as it applies to compact objects and standard accretion disks.

10.1 Star formation, recall the basics

The ISM is the source of new stars. We think these new stars form in some gravitational collapse process . . . and that star formation should be an ongoing process, with each subsequent generation of stars having a somewhat richer heavy element content, due to nuclear processing by previous generations of stars.

Think back to our general discussion of gravitational collapse and star formation (chapters 4, 5). We noted that a piece of the ISM will be gravitationally unstable if "gravity wins"; that is, if its gravitational potential energy exceeds its internal energy. Written in terms of initial density and temperature, this becomes a condition on the size, or mass, of the perturbation. If the initial perturbation has $R > R_J$ (the *Jeans length*), or $M > M_J$, (the *Jeans mass*), where

$$\frac{4\pi}{3} G R_J^2 \rho \simeq \frac{k_B T}{m} \; ; \; M_J \simeq \left(\frac{k_B T}{mG}\right)^{3/2} \left(\frac{3}{4\pi\rho}\right)^{1/2} \tag{10.1}$$

then it is gravitationally unstable.

We also noted, in chapter 5, that two classic problems – conservation of magnetic flux and of angular momentum – make the collapse process more complicated than simple "gravity wins". We suggested that these two problems are probably interrelated – for instance torques exerted by the B field may contribute to slowing down the rotation and transferring angular momentum to the surroundings. Another possibility is that the collapsing cloud is mostly neutral; because B field lines are only tied to the ionized fraction of the cloud, it may be that the neutral gas can "slip through" the ionized fraction. This process goes by the fancy name, "ambipolar diffusion". Both ideas are probably part of the truth. The picture still needs to be expanded, however, and put in the context of star formation research, which is one of the most active areas in current astrophysics. That's where we're going in this chapter.

10.2 Molecular Clouds as Precursors

We know that young stars are gregarious. They do not form singly; rather, they form in clusters, inside dense, molecular clouds (MC's) in the ISM. We therefore need to consider the physical state of the MC's, and how stars — as well as planets and possibly life — form within them.

10.2.1 Observational constraints

Most of what we know about MCs comes directly from observations.

• **Physical conditions**. MC's are found in a range of sizes, from $\sim 10^2\ M_\odot$ to $\sim 10^6\ M_\odot$, with an approximate $\propto M_{mc}^{-3/2}$ number distribution. Interestingly, there seems to be a correlation between cloud mass, cloud distribution in the galaxy, and cloud temperature. There seem to be two populations of MC's: the small clouds (SMC's), which have internal temperatures $\sim$ 10K, and the "giant" clouds (GMC's), which have internal temperatures $\gtrsim$ 20 K. The SMC temperature is consistent with heating by the background cosmic ray population in the galaxy; they do not seem to have any internal energy sources (such as hot stars). This correlates with the absence of young, hot (O and B) stars in these clouds. The SMC population is distributed throughout the galaxy, with no particular preference for spiral arms. The GMC's, on the other hand, require internal energy sources, and we do observe young O and B stars forming in these clouds. Their higher temperature is thought to be due to heating by these massive protostars. GMC's are not distributed uniformly in the galaxy, but are found in spiral arms (they provide the young, bright stars by which we see pretty spiral arms in external galaxies).

• **Lifetimes**. We know that MC's are self-gravitating: their pressure generally exceeds the typical ISM pressure, so they cannot be in pressure balance with the ISM. We also know their mass exceeds the Jeans' mass for their temperatures and densitites. We would expect them to be in a state of gravitational collapse. If this were the case, we can use the free-fall time (check back to equation 4.18) to guesstimate how how quickly they should collapse. We find $t_{ff} \sim 10^7$ years for typical mean MC densities, $n \sim 100\text{cm}^{-3}$. Combining this with the total mass in MC's in our galaxy, $\sim 5 \times 10^9 M_\odot$, we can estimate the current star formation rate that this simple picture (free-fall collapse of all MC's) would predict: we get a rate $\sim 500\ M_\odot$/yr. This prediction is much larger than the observed rate, $\sim$ a few $M_\odot$/yr. Thus, only about one percent of the clouds we know about can be collapsing; the rest must be supported by gravity somehow, and have a lifetime ~ 100 times longer than this prediction.

• **Turbulence**. This support against gravity almost certainly is provided by internal random motions in the clouds, which are generically called "turbulence". We can measure internal Δv's, from linewidths; we find $\Delta v \gg v_{th} \simeq (k_B T/m)^{1/2}$. Thus, the internal motions are highly supersonic. Further, the linewidth does not come from rotation (which could be detected), nor does is come from free-fall collapse (from the argument above). Thus, it must be from random internal motions – the clouds must contain subclumps, or waves, which move through the "cloud" at supersonic velocities, $v_{ran} \sim \Delta v$. These random velocities do appear able to provide the virial support: the correlation $\Delta v^2 \propto nR^2 \propto M_{mc}/R$ is observed, consistent with virial balance; the numbers also work out, to have $v_{ran}^2 \simeq GM_{mc}/R$.

MC's are also magnetized. We know this from Zeeman splitting of spectral lines, also from polarization of starlight, which comes from dust grain alignment with the magnetic field (the grains are dielectrics). The fields can, in principle, also help support the cloud against collapse. In practice, the fields and turbulence are probably intimately mixed (gas flows stretch and twist field lines; the field fights back and limits turbulent velocities). We also know that turbulent (and thus magnetic) decay times are very likely short compared to the MC lifetimes. Thus "turbulence" or "B fields" aren't the full answer; something inside the cloud must drive the turbulence. Current thinking has the driver being newly formed YSOs within the cloud – their winds and jets may dump enough energy back into the MC to stabilize it.

10.2.2 How do they fragment?

We know that the Jeams mass in a MC is much larger than the mass of a single star (even a big one). We also know that stars form in large numbers within MCs. It follows that the gravitational collapse process within the MC must involve fragmentation into a large number of star-sized structures. We don't know how this happens, but can find a couple of hints in the data.

•**The Jeans mass depends on temperature and density**, as $M_J \propto T^{3/2}/\rho^{1/2}$. Thus, as a large cloud collapses, and its density increases, M_J will drop *if* the cloud stays cool. This should allow smaller and smaller subclumps to become unstable, and fragment out of the larger-scale collapse (recalling $t_{ff} \propto 1/\rho^{1/2}$, so that denser subclumps fragment faster). This process should continue as long as the collapsing cloud can stay cool. People tend to argue that the cloud will stay cool as long as it stays transparent, and can radiate effectively. Once it goes opaque (noting that opacity $\propto \rho R \propto M/R^2$ for a cloud of fixed mass[1]), it may have trouble radiating away the energy generated by the gravitational collapse. If this happens, T will increase, and M_J will increase; this will provide a smallest fragment size. This process is called "opacity-limited fragmentation".

• **The Initial Mass Function** (IMF), which describes the mass distribution of newly formed stars, can be determined from the mass distribution of stars that are currently around. If a star has a visible lifetime $\tau(m)$ (which is a function of the mass m of the star), and if stars are created in the galaxy at a rate $S(m,t)$, the current distribution of stars $N(m,t)$ is given by

$$\frac{dN(m,t)}{dt} = S(m,t) - \frac{N(m,t)}{\tau(m)} \qquad (10.2)$$

If $S(m,t)$ is not varying in time, this has the simple solution

$$N(m,t) = S(m)\left[1 - e^{-t/\tau(m)}\right] \qquad (10.3)$$

which allows us to relate $N(m,t)$ (which can, in principle, be observed) to $S(m)$, the *initial mass function* (which we want to know).

In general $S(m)$ is expected to be a decreasing function of m, giving many low-mass stars and few high-mass stars. It is determined by the complex interplay between fragmentation, coalescence, accretion, and outflow, so at present it is quite poorly understood but is held to be one of the holy grails of astrophysics. From the observational side it seems that at high masses ($m \gtrsim M_\odot$), $S(m)$ can be approximated by a power law. The form $S(m) \propto m^{-2.35}$ is called the *Salpeter initial mass function*, and has

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[1] We'll see what this means next term

been around for a long time. Below $m \sim M_\odot$, it gets harder to determine $N(m,t)$ accurately. It is clear that $S(m)$ flattens out; whether or not if turns down below $m \sim 0.1 - 0.3\ M_\odot$ is less clear. In addition, several people have suggested that the locally measured IMF being the superposition of two IMF's, resulting from two types or modes of star formation. The suggestion is that low-mass stars (compared to $\sim 1 M_\odot$) form in one region – probably the SMC's – and that high-mass stars (above $\sim 1 M_\odot$) form elsewhere – probably the GMC's – and that different physics governs the two modes. This is called *bimodal star formation*.

The range of allowed stellar masses is, on the other hand, fairly well determined by the physics of the stars themselves. At the high-mass end, stars with $M \gtrsim 60 M_\odot$ are unstable; their own luminosity generates too much radiation pressure for the star to be able to attain hydrostatic equilibrium from its own gravity. At the low-mass end, $0.1\ M_\odot$ is about the lowest mass object which can sustain hydrogen fusion. Objects with masses lower than that certainly do exist but are not called stars. If they can fuse deuterium they're called brown dwarfs, and if they are too low mass for that they're planets.

10.3 Young Stellar Objects: how do they evolve?

Somehow or other, a star-sized fragment of a MC separates out and collapses to form the star. Current thinking — based on an impressive amount of new data, as well as theory — identifies four stages of this process[2] (as illustrated in Figure 10.1). A caveat: what follows is thought to describe the formation process for *low-mass* stars only.

(1) Initial Contraction and core collapse. When the protostar first detaches from its MC environment and starts to collapse, it's probably still nearly spherical, and collapsing only slowly. Refer back to chapter 4, where we discussed self-gravitating isothermal spheres. These are characterized by a core of size $r_o \propto (T/\rho_o)^{1/2}$; they are probably a good approximation to the initial state of the protostar. As the cloud slowly gets denser (and/or cools), the core gets smaller; so we expect an inside-out collapse (the core collapses most rapidly, the outer layers follow later). Much of the MC magnetic field must be lost in this stage, possibly by ambipolar diffusion. Note the protostellar core is well hidden at this stage, being shrouded by its dusty outer envelope.

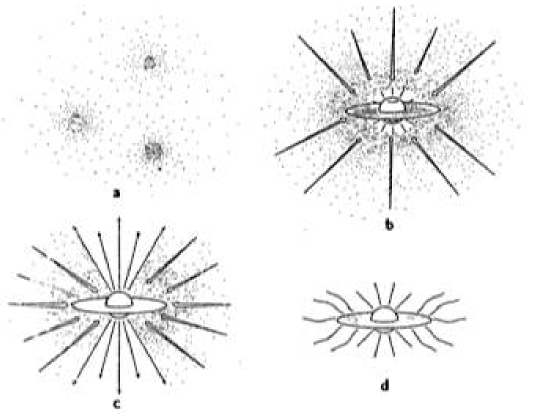

Figure 10.1 Illustrating the four likely stages of low-mass star formation; from Shu etal, *Ann.Rev.Ast.Ap*, 1987. See text for details. Note, this cartoon needs to be updated, to include outflows, which we now know are an important part of the process.

(2) Disk formation and outflows. As the inside-out collapse proceeds, the inner parts settle into what will become the core of the protostar. Material continues to accrete from the surroundings, but now — due to angular momentum — it settles into a disk around the core. That was expected; but here's where the surprise came. People did not expect gravitational collapse also to involve outflow (it is the wrong direction), but it does. Observations show that just about every protostar has *bipolar outflows*, which can be quite broad, not well collimated. They are usually seen in molecular lines. Some YSOs also produce well-collimated *jets*, usually seen in the optical. The optically bright "nebulae" called *Herbig-Haro objects*, which used to seem only a curiosity, are now known to be associated with shocks in these YSO jets.

In addition, some YSO's are found to have a *disk* structure, oriented perpendicular to the jet or bipolar outflow. These are presumably the accretion disks — or at least the rotation-supported outer regions of the "reservoir" from which material accretes to form the star. Some authors estimate that $\sim 1/3$ of the infalling matter goes out again in the outflow/jet, and $\sim 2/3$ makes it onto the protostar. Because there is still a lot of (dusty) reservoir material, YSOs in this stage are mostly shrouded objects, detectable only in radio/molecular lines; one author talks about "deeply

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[2] Jargon warning: many authors break YSOs up into Class 0, Class I, Class II, Class III objects. These Classes correlate decently with the four phases I list here, but are more observationally based — so I won't describe them in detail here.

buried protostars with their infalling envelopes and associated bipolar outflows".

(4) Post-outflow, pre-Main Sequence star. Eventually, the outflow slows, as does the general infall of matter. At some point the YSO becomes visible in optical and IR, as the surrounding dust/gas is cleared away. When nuclear burning starts, these young stars[3] appear on the HR diagram. They still have disks and outflows; T Tauri stars are examples here (several of them have detectable disks). Finally, the outflows reduce to normal stellar-wind level, and the disk either is all accreted or (mostly) dissipates. Remnants of these circumstellar disks, presumably, become planetary systems.

Caveat 1: magnetic activity. It seems that YSOs, at least in the PMS/T Tauri stage, have unusually high levels of magnetic activity (think of solar flares, eruptive prominences, but at a much stronger level). They can show strong X-ray emission (which requires plasma much hotter than the conventional picture, above, would predict), and also nonthermal radio emission (which requires relativistic electrons and a magnetic field). This interesting area is just starting to be explored ... stay tuned.

Caveat 2: what about high mass stars? High-mass star formation seems still to be less well understood; the problem is that the strong radiation pressure after nuclear burning starts disrupts the inflow/accretion process ... and people do not seem sure of what happens at that point. Once again, stay tuned.

Key points

- Basic gravitational (in)stability criteria;
- Isothermal spheres: what they are, what characterizes the solution;
- Molecular clouds: their general nature, how they relate to the YSO's which they contain;
- YSO's: what we observe, and what we think their evolutionary stages are.

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[3] alternatively, pre-main-sequence, "PMS", star