From Collapse to the Main Sequence

Fission versus fragmentation.—As part of the general deal of getting rid of angular momentum, there are a couple of different scenarios that have been proposed for what happens when a molecular cloud condenses. One way would be for splitting of two or more components in a state of unstable equilibrium. This is called fission. Imagine a rapidly rotating blob which splits because of its rotation, and you have fission. The other scenario is that as a cloud collapses it fragments into a number of independent entities ("fragmentation"). At one point (1970s) it was thought that binaries with periods < 100 yr form by fission because the numerical simulations of the time seemed to give equal-mass binaries through fission, as observed. However, more recent simulations show that you'd really get rings and disks instead. In addition, it appears that T Tauris (young stars) start their PMS contraction with fairly small radii and slow rotation rates, which is not good for fission at AU scales.

Singular isothermal spheres.—Many numerical simulations of protostellar collapse show that the density profiles established are isothermal. Put this way, it sounds reasonable. However, **Ask class:** if we assume some kind of virial equilibrium, what mass distribution will make the gravitational potential energy the same at all radii? GM/r=const, so $r \propto M$. **Ask class:** what does that mean about the density distribution? $\rho \propto 1/r^2$. This is called the singular isothermal sphere, and it has apparently fatal problems in two directions: infinite density at the center, and infinite total mass. However, it is useful as a general approximation in many settings. For example, in some galaxy mass profiles this is used with the modification that there is a core radius, so $\rho \propto 1/(r^2 + r_c^2)$. The SIS profile is also very simple to deal with. For the SIS, if the isothermal sound speed is $a/(kT/m)^{1/2}$, then $\rho = a^2/2\pi G r^2$.

The collapse of a singular isothermal sphere proceeds inside-out, and in a self-similar fashion that allows analytic solution. In such a scaling solution, there are no characteristic length or time scales, and therefore all quantities must be functions of $x \equiv r/at$. The mass accretion rate in this system is a constant, $\dot{M} = 0.975a^3/G$.

Disks and Outflows

As we found last time, getting rid of angular momentum is one of the major problems of star formation. The high angular momentum means that as clouds collapse they tend to form a disk. Matter flows through the disk and accretes on the central object, so it is called an accretion disk. Accretion disks are common in many astronomical settings, including mass transfer systems (some binaries) and active galactic nuclei.

Disks are observed directly by imaging (cf Hubble), and indirectly because of their spectral energy distribution (IR excess). Their presence can also be inferred indirectly by asymmetric line profiles: if there is a wind from the young star it should be bipolar, so we should see both the blueshifted and redshifted components, but instead we see only the blueshifted because the disk blocks the part going away from us.

Disks usually rotate such that each fluid element is moving almost (but not exactly!) in a circular orbit. If there were no interactions between fluid elements, **Ask class:** what would the angular velocity be as a function of radius? $\Omega \propto R^{-3/2}$, so there is a shearing flow. This means that coupling between adjacent radii exerts a force. **Ask class:** given that the outer parts rotate more slowly, in which direction will the force be and what will be the effect on the angular momentum and on the movement of mass? Inner tries to speed up outer, giving it a higher velocity. This increases the angular momentum of the outer, decreases the angular momentum of the inner, so net result is that angular momentum is transferred outwards and mass flows inwards (some subtleties, of course). The disk spreads as a result. **Mention:** this has similarities to the effect of "shepherd moons" except there the coupling is purely gravitational.

The amount of coupling is often handled phenomenologically. The type of disks considered in a protostellar context are usually geometrically thin disks, with half-thickness $H \ll R$. For these disks, the coupling depends on the kinematic viscosity of the fluid, and is usually parameterized in terms of the famous "alpha parameter" of Shakura and Sunyaev (1973): $\nu = \alpha c_s H$, where c_s is the sound speed. In many circumstances $\alpha \sim 0.01 - 1$. For such a disk we have

$$c_s \approx (H/R) v_K \ , \tag{1}$$

where v_K is the local Kepler velocity. Therefore, the orbital motion is highly supersonic. The radial velocity is much smaller still:

$$v_r \sim \nu/R \sim \alpha (H/R)^2 v_K \ . \tag{2}$$

But what is the actual source of this viscosity? Kinematic viscosity, i.e., normal interactions between particles, is way too small in pretty much any disks in astrophysics. You might consider convection, but (1) the disks can be convectively stable, (2) numerical simulations show the angular momentum is transported the wrong way, and (3) the magnitude is too small anyhow. Therefore, especially in the last decade, MHD turbulence has been the favored mechanism. There is an instability (called the magnetorotational instability or Balbus-Hawley mechanism) by which a seed magnetic field can be amplified rapidly to a magnitude such that it dominated intradisk interactions. Jim Stone is one of the world's experts on numerical simulations of this mechanism and of accretion disks generally, as is Eve Ostriker.

On a more global level, gravitational torques from a companion star might also play a role in some circumstances.

Outflows

Two types, jets and outflows of molecular gas. Jets are highly collimated, and high velocity (around 400 km/s is typical). They are thought to be mostly (95-99%) neutral gas, and are usually bipolar. Outflows are poorly collimated and lower velocity (100 km/s). They are thought to be driven by the jets. The power in jets/outflows diminishes with time, and the opening angle is thought to increase with time. The total energy in a protostellar jet can be 10^{43-47} erg.

There is a strong theoretical link between accretion and outflow, in the sense that accretion powers outflows (inference: decrease in outflow power with time means that the accretion rate drops with time). This link is much more difficult to establish observationally:

(1) Correlation between Hα and OI line luminosities (tracing jet) with IR excess emission (inner regions of disks).

(2) Correlation between bolometric luminosity of deeply embedded objects (which is supposed to be mainly accretion luminosity) with the power of CO outflows.

Mass loss from outflows is $\sim 10^{-6}\, M_\odot$ yr^{-1}. Mean accretion rate during embedded phase is $\sim 10^{-5}\, M_\odot$ yr^{-1}, so mass loss rate in winds is $\sim 0.1 M_{\rm acc}$.

Theories for Jets

Jets across astrophysics have certain things in common. The speed of the jet seems correlated with the escape speed at the surface of the star. This is true from protostellar jets up to jets from black hole sources such as AGN, where the projected motion can be faster than the speed of light by factors up to $\sim 20-30$ (**Ask class:** how is this possible? Because of special relativistic effects, maximum projected apparent velocity is $\sim \gamma c$.). Anyway, this suggests that jets are formed deep in the potential well, meaning near the star or in the innermost portions of the disk.

The problem of the formation of jets is twofold: acceleration and collimation. There are three general ways that have been proposed to form jets:

(1) Hydrodynamic acceleration. If the jet material starts flowing outwards in a region with sufficient external pressure, its cross-sectional area decreases and its velocity increases. Then, when the speed reaches the speed of sound, Bernoulli's equations show that the cross-sectional area increases (but not faster than the radius, so the collimation angle is small) and the speed also increases. A converging-diverging channel like this is called a de Laval nozzle, and is an essential principle behind rockets. This is therefore an efficient way to produce fast, collimated jets. In some cases (e.g., extragalactic jets) the external gas pressure cannot be high enough to provide the required initial collimation, because if it were then the gas would radiate a higher X-ray flux than observed. It might, however, play

some role in protostellar jets.

(2) Radiative acceleration. Another possibility is that radiation from the central object can accelerate matter, which is separately collimated by a surrounding torus of gas. **Ask class:** suppose we had a gas of fully ionized hydrogen; what approximate luminosity would be required for such acceleration? About the Eddington luminosity, or around 10^{38} erg s^{-1} for a solar mass. This can be decreased if higher cross section absorption processes dominate, but not enough in protostellar systems. It is thought that interactions with the radiation may explain why the maximum Lorentz factor is around 20 in AGN: higher than that, and radiation *drag* slows down the jet.

(3) Hydromagnetic acceleration. Power comes from, and symmetry is provided by, the rotation of the accretion disk. In AGN, the rotational energy of the black hole itself could be important.

The general model is that of Blandford & Payne (1982). The disk is threaded by a poloidal field, and material is accelerated and collimated by the magnetic funnel (toroidal fields). The less-collimated wind may be generated from a wider variety of radii in the disk and may be caused by strong gradients in the magnetic pressure close to the star/disk boundary.

Protostar to the main sequence

High-mass stars are believed to join the main sequence while they are still in the accretion phase. They therefore do not convey much information about their origins when they become visible as optical objects. The study of pre-main-sequence stars is therefore confined primarily to low-mass stars.

Initial stellar core has $M \ll M_\odot$. It accretes gas directly from the envelope, and also from the circumstellar disk. The star is not in thermal equilibrium: energy is dumped into the outer portions by accretion. Star is fully convective, and adjusts towards thermal equilibrium on the Kelvin-Helmholtz (gravitational contraction) timescale:

$$t_{\rm KH} = \frac{GM_*^2}{R_* L_*} \sim 3 \times 10^7\,{\rm yr} \tag{3}$$

for a solar-type star, less for higher mass (much higher luminosity compensates for the greater amount of gravitational energy).

The temperature increases as the star contracts, until it gets to the point where it can burn deuterium ($T \approx 10^6$ K). At that point, contraction stops because of the energy input. It takes $\sim 1 t_{\rm KH}$ to burn all the deuterium, then contraction starts again. When the center becomes hot enough for fusion of hydrogen (few$\times 10^6$ K), contraction stops again and the star moves to the main sequence. On the main sequence, the star is in thermal equilibrium. Stars aren't observed above (i.e., before) the deuterium burning sequence. An explanation for this is that younger stars are obscured by dust envelopes, and that when D burning commences it blows away the envelope. But if so, why should the wind start just when the deuterium burning happens? May also be that the pre-D stars evolve rapidly down the Hayashi tracks and are obscured, so they are difficult to see.

Classification of protostars

(1) Class 0. Energy is provided by accretion, and the full stellar mass has not yet been accumulated. Phenomenologically, it is a sub-mm source ($\lambda > 350\mu$m has more than 5×10^{-3} of the bolometric luminosity) and has a blackbody spectrum characteristic of $T \sim 15 - 30$ K. This is primarily a useful concept for low-mass stars: high-mass stars at such a young age may already be burning hydrogen, so things are more confusing.

(2) Class I. IR excess, spectral flux increases with longer wavelength into the infrared, associated with dense molecular cores.

(3) Class II. IR excess but flux decreases with longer wavelength into the infrared. Optically visible.

(4) Class III. Spectra similar to blackbody, seen in visible light, may have a small optically thin disk around them.