Protostars and planets

For review articles on this large but still very much frontier subject, see [1].

A protostar can be defined as a star which, although of normal composition, does not yet burn hydrogen; its luminosity is offset instead by gravitational contraction. The entropy of a protostar is higher than the entropy of a main-sequence star of the same mass. As entropy is lost to radiation and the radius contracts, the central temperature rises until the thermonuclear reaction rate balances the luminosity. At this point the protostar joins the zero-age main sequence (ZAMS).

The astronomical community has yet to settle upon a crisp definition of planet. The distinction between planets and stars seemed too obvious to require precise formulation when the only planets known were those in the Solar System: the most massive of them is only $M_{\rm Jupiter} \approx 10^{-3} M_\odot$, and there are many of them follow approximately circular orbits about the Sun (indeed "planet" comes from Greek "wanderer" because planets appear to move through the fixed stars). Classifications based on mass or orbital properties no longer seem so clear cut. "Extra-solar planets" are detected in orbit around more than one hundred nearby stars, some with much larger eccentricities than any solar-system planet. The masses of these planets[1] extend to $\gtrsim 10\,M_{\rm Jup}$. Also, as discussed in a previous lecture, brown dwarfs have been discovered both in orbit around normal stars and in the field. Brown dwarfs are also of substellar mass, *i.e*, below the hydrogen-burning limit, which is approximately $0.085 M_\odot$ or $85\,M_{\rm Jup}$. However, brown dwarfs in orbit around stellar primaries appear to be rarer by at least one order of magnitude than jovian-mass planets. It is suspected on theoretical grounds that brown dwarfs have compositions and formation mechanisms similar to those of normal stars, but that planets form in disks around protostars and are much more heavily enriched in elements heavier than hydrogen and helium (metals). It has to be admitted that these suspicions are based at present on extrapolation from the Solar System rather than directly observed properties of extrasolar planets.

Star formation

In the present-day Galaxy, star formation occurs mainly in Giant Molecular Clouds (GMCs). GMCs are dense regions of the interstellar medium composed primarily of molecular hydrogen (H_2) rather than atomic (HI) or ionized (HII) hydrogen. Typical masses, diameters, and densities of GMCs are $M \sim 3 \times 10^5 M_\odot$, $D \sim 50\,{\rm pc}$, and $n_H \sim 100\,{\rm cm}^{-3}$. Compare the latter to the number density of hydrogen atoms in the rest of the interstellar medium, $n_H \lesssim 1\,{\rm cm}^{-3}$. The gas temperature is low, $T_{GMC} \lesssim 10\,{\rm K}$ as opposed to $T \sim 6000\,{\rm K}$ for HI in the diffuse ISM. Random velocities within the cloud are highly supersonic, $v \sim (GM/D)^{1/2} \sim 5\,{\rm km\,s^{-1}}$ *vs.* $c_{\rm s} = (1.4 k_{\rm B} T/2m_H)^{1/2} \sim 0.3\,{\rm km\,s^{-1}}$. Thus it is expected that the random motions dissipate *via* shocks on a dynamical timescale $(G\bar\rho)^{-1/2} \sim 10^7\,{\rm yr}$, or possibly slightly longer if the shocks are "cushioned" by magnetic fields, whose energy density in clouds appears to be comparable to that of the random motions.

The above-cited properties of GMCs are measured not by direct observation of H_2, which is a poor emitter and absorber of mm-wave radiation (the appropriate wavelength range at GMC temperatures) but rather by radio observations of carbon monoxide (CO) and other trace molecules.

Turbulence within GMCs somehow leads to cores: gravitationally bound subunits of size $\lesssim 0.1\,{\rm pc}$ and mass $\sim 1 M_\odot$. Low-mass stars, at least, appear to form by collapse of these cores, whose mean gas density $\bar n_{H_2} \gtrsim 10^5\,{\rm cm}^{-3}$ and free-fall time $(G\bar\rho)^{-1/2} \sim \times 10^5\,{\rm yr}$. At these densities, the rotational levels of ammonia (NH_3) are significantly excited by collisions with H_2, and this molecule becomes an important tracer of the gas. Typical linewidths are comparable to the hydrogen sound-speed and to the virial value of the core, indicating that the turbulence is transsonic and that thermal pressure makes a substantial contribution to supporting the core against gravity[4]. It appears that these cores are also often significantly magnetized[3], but at such low temperatures, coupling between the gas and the field is imperfect because the ionization fraction is extremely low, so that the field is expected gradually to slip out of the core through a process called ambipolar diffusion. Loss of magnetic and turbulent support presumably triggers the collapse of these cores.

[1] inferred from small radial-velocity variations they cause in the stars they orbit, which is also the method by which most of the exoplanets are detected

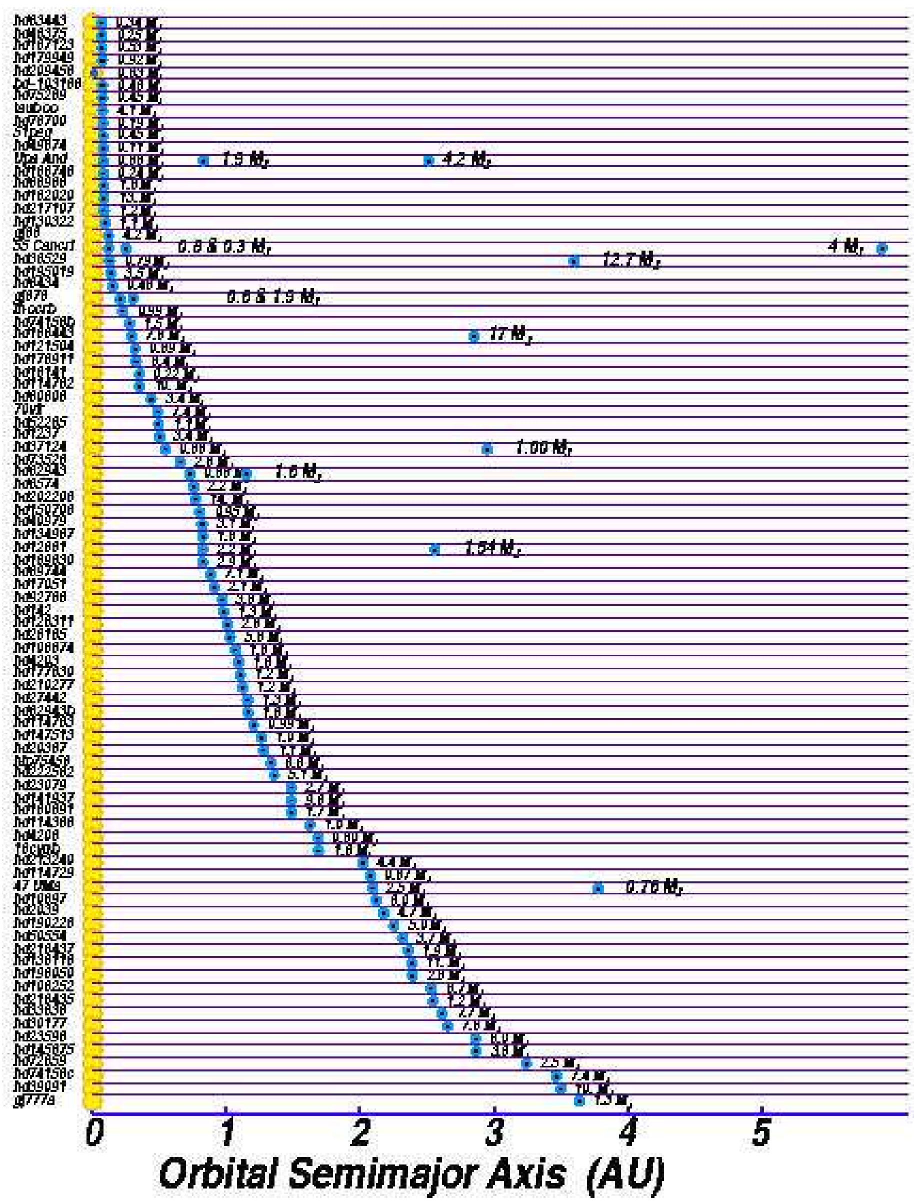

Figure 1: Known extra-solar planets as of 2004 sorted by semi-major axis and labeled (illegibly) by their masses in units of Jupiter's mass, and by the names or catalog numbers of their primary stars. Source: `www.exoplanets.org`.

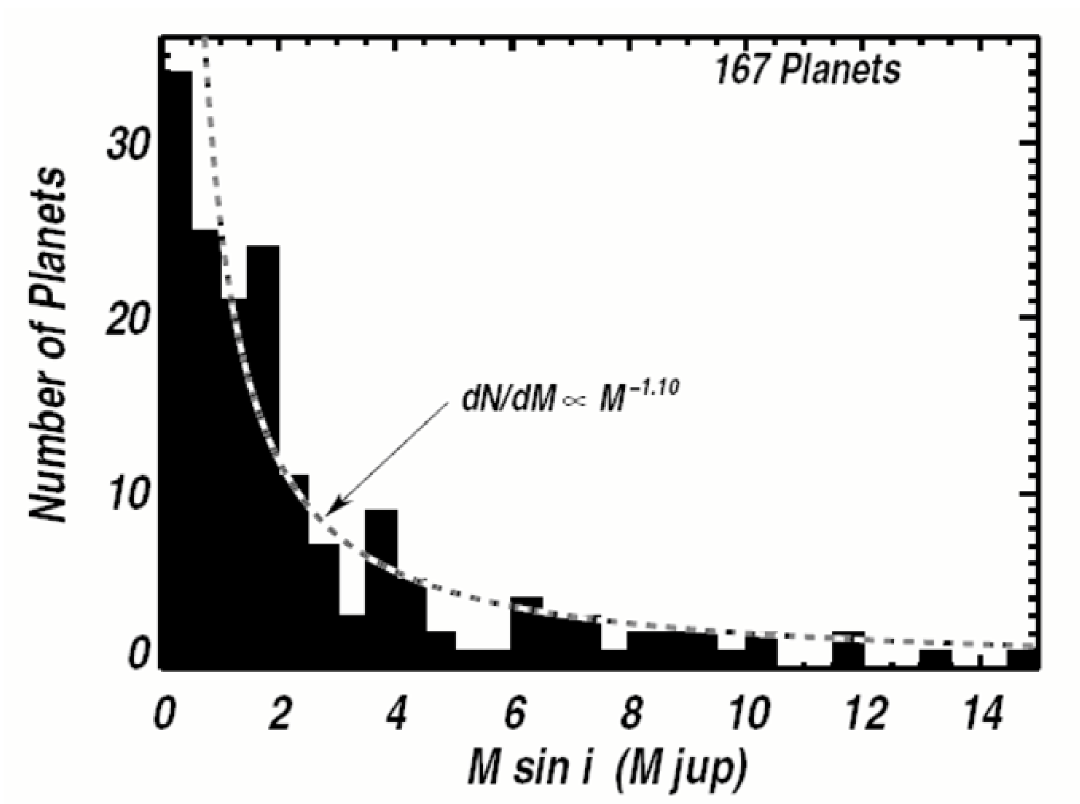

Figure 2: Histogram of exoplanet masses as of 2006. Source: `www.exoplanets.org`.

Before collapse, when the core is presumably in approximate hydrostatic equilibrium, it may exchange angular momentum with its environment *via* the magnetic field. But once collapse begins, it is likely that the angular momentum of the core is approximately conserved, because the collapse timescale scales as $R^{-3/2}$ as the radius (R) of the core shrinks, so that it becomes much shorter than the propagation time of magnetic disturbances in the exterior medium. At constant total angular momentum J, centrifugal forces scale as $J^2M^{-1}R^{-3}$, so they increase more rapidly with decreasing radius than the gravitational force GM^2R^{-2}. The two forces come into balance at $R_{\rm centrifugal} \sim J^2/GM^3$, so that further collapse becomes impossible without loss or redistribution of angular momentum. It can be shown that R_J is typically much larger than a stellar radius: Except by a rare fluke, the GMC and the cores within it are unlikely to rotate more slowly than the local interstellar medium and the Galaxy as a whole,

$$\Omega_{\rm Gal} \approx \frac{220\,{\rm km\,s^{-1}}}{8\,{\rm kpc}} \approx \frac{2\pi}{2\times10^8\,{\rm yr}}\,, \tag{1}$$

and they could well rotate a good deal more rapidly because of turbulent motions and partial preservation of their angular momenta as they were formed out of their much-less-dense surroundings. At the rate (1), the rotational velocity of a core would be only $3\,(R/0.1\,{\rm pc})\,{\rm m\,s^{-1}}$—two orders of magnitude less than its thermal or virial velocity—so centrifugal forces would be negligible until deep into its collapse. We may estimate the centrifugal radius $R_{\rm cent}$ in terms of the initial radius and angular velocity of the core (R_0, Ω_0) as follows:

$$\begin{aligned} J &\sim \frac{2}{5}MR_0^2\Omega_0 \\ R_{\rm cent} &\sim 0.6\left(\frac{R_0}{0.1\,{\rm pc}}\right)^4\left(\frac{\Omega_0}{\Omega_{\rm Gal}}\right)^2\left(\frac{M_\odot}{M}\right)\ {\rm AU.} \end{aligned} \tag{2}$$

In response to this "centrifugal barrier," the collapsing core may fragment into two or more objects in orbit about one another, or form a rotating disk. The details, however, are still very obscure.

Empirically, young stellar objects (YSOs) are classified according to the observed properties at millimeter, infrared, and optical wavelengths[2]:

- Class 0 sources: These are cores that show evidence for an embedded protostar—for example, outflows and jets—but the sub-mm emission is extended, and the protostar appears to have a minor fraction of the total mass of the core, $M_{\rm envelope}/M_* > 1$. Most of the luminosity of the protostar is probably derived from accretion, $L \sim GM_*\dot{M}_*/R_*$. Based on the abundance of such sources relative to the later classes below, the lifetime of this phase is $\sim 10^4$ yr.

- Class I: The infrared spectral index

$$\alpha_{\rm IR} \equiv \frac{d\log(\lambda F_\lambda)}{d\log\lambda}\,, \qquad 2.2\,\mu{\rm m} \le \lambda \le 25\,\mu{\rm m}$$

  is positive, so that the bulk of the luminosity emerges at the longer IR wavelengths. The inferred lifetime is $\sim 10^5$ yr, *i.e.*, comparable to the collapse time of the core.

- Class II: These are the "classical" T-Tauri Stars. The stellar photosphere is revealed at optical wavelengths accompanied by strong Balmer emission lines and photometric variability, but the IR luminosity is far larger than can be explained by the photometric temperature and radius, with $1.5 < \alpha_{\rm IR} < 0$. The IR comes from an optically thick disk of dust and gas surrounding the star. Estimated disk masses and accretion rates are $10^{-3} - 10^{-1}M_\odot$ and $10^{-8}M_\odot\,{\rm yr}^{-1}$, respectively. The luminosity derived from accretion and from contraction of the protostar are often comparable, and the lifetime is a few times longer than that of Class I.

- Class III: The "weak-lined" T Tauri stars show Hα equivalent widths < 10 Å, and their disks are optically thin. Most of the luminosity derives from protostellar contraction, and the lifetime of this phase is $\gtrsim 10^6$ yr.

Judged by their IR emission, which is dominated by the dust rather than the gas, protostellar disks last for a few million years. It is not clear what process dominates the depletion of the gas; accretion onto the star, stellar winds, and photoevaporation (by the central star or nearby hot stars) likely all play a role, with varying degrees of importance depending upon the mass and environment of the protostar. There is also evidence that the small grains agglomerate into larger bodies, which would decrease the IR emission even if the mass in solids were constant. In at least $\sim 7\%$ of solar-type stars, this process ultimately results in planets. Since radial-velocity surveys are insensitive to planets of terrestrial mass ($\lesssim 10^{-5} M_\odot$), it is possible that the incidence of such planets is much higher than that of gas giants.

High-mass star formation

The above narrative pertains mostly to stars of mass comparable to that of the Sun, or less ("low-mass star formation"). The formation of high-mass stars is even less well understood. In part this is because high-mass stars are rarer, and therefore must be studied at greater distance: the Orion Nebula at $\approx 500\,\mathrm{pc}$ is a favorite, as opposed to the canonical low-mass star formation site in Taurus Aurigae at $\approx 150\,\mathrm{pc}$. Also, the protostellar phase of high mass stars appears to be briefer.

An outstanding theoretical difficulty in high-mass star formation is to understand how accretion proceeds despite radiation pressure. High-mass stars approach the Eddington limit,

$$L_{\mathrm{Edd}} \equiv \frac{4\pi G M c}{\kappa},$$

in which the opacity κ is approximately the electron-scattering value $\kappa_{\mathrm{e.s.}} = 0.4\mu_e^{-1}\,\mathrm{cm}^2\,\mathrm{g}^{-1}$. However, at temperatures $\lesssim 1500\,\mathrm{K}$, the opacity of accreting gas is dominated by dust (at higher temperatures, dust sublimes) and is typically several times larger than $\kappa_{\mathrm{e.s.}}$. In spherical symmetry, therefore, one would expect the outer parts of high-mass protostellar cores to be driven off by radiation pressure rather than accrete. This probably does happen and limits the ultimate stellar mass, but the problem is to explain quantitatively how observed final masses up to $\sim 80 M_\odot$ are achieved. Strong departures from spherical symmetry, either on large angular scales or on small, may allow partial segregation of inflowing mass and outgoing radiative flux.

References

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[4] A. A. Goodman, J. A. Barranco, D. J. Wilner, and M. H. Heyer. Coherence in Dense Cores. II. The Transition to Coherence. *ApJ*, 504:223–246, 1998.