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Lee Hartmann
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1

Overview

Much of what we presently know or surmise about the physical processes involved in star formation is derived from the detailed study of a few nearby molecular cloud "nurseries". Stars in the solar neighborhood are formed from the gravitationally induced collapse of cold molecular gas. Typical molecular gas clouds must contract by a factor of a million in linear dimensions to form a star. Because of this dramatic (and rapid) reduction in size, any small initial rotation of the star-forming cloud is enormously magnified by conservation of angular momentum during collapse. In this way a modestly rotating gas cloud produces a rapidly rotating object – a disk – in addition to a small, stellar core at the end of gravitational collapse. Probably most of the material of a typical star is accreted through its disk, with a small amount left behind to form planetary systems.

Advances in observational techniques spanning the electromagnetic spectrum have been essential in developing our present understanding of star formation. The launch of the *Infrared Astronomy Satellite* (*IRAS*) in 1983 led to the recognition that dusty disks are common around young stars. The *ISO* infrared satellite provided detailed mid-infrared spectra of many bright disks. The *Spitzer Space Telescope*, the latest in this line of infrared observatories, has now detected mid-infrared disk emission in very large samples of stars spanning a wide range of ages. During the same period, radio-wavelength interferometry developed to a state where it could provide high spatial resolution images of cold dust and gas in outer disks, along with estimates of disk masses. The forthcoming Atacama Large Millimeter Array (ALMA) is expected to produce a major advance in imaging at mm and sub-mm wavelengths. Optical studies using large ground-based telescopes have produced better estimates of stellar masses and ages for large samples of stars, as well as providing new insights into the accretion flows of young stars. The *Hubble Space Telescope* (*HST*) has provided remarkable images of disks in a wide variety of environments, and even has produced important constraints on accretion rates from ultraviolet observations.

Concurrently, our theoretical insight into star formation processes has improved, driven in important ways by the remarkably rapid increase in computing power. The analytic and steady-state models of the previous generation, which served the field so well for many years, are now being supplemented by time-dependent numerical simulations of the complex physical processes involved in star formation and protoplanetary disk evolution.

While a coherent picture of star formation is emerging, many mysteries remain. We do not yet have a conclusive theory explaining the stellar initial mass function, though many ideas have been advanced. Disk accretion is clearly an important part of the star (and planet) formation story; although much progress has been made lately in understanding

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angular momentum transport mechanisms which drive accretion, theories do not yet have predictive power. The powerful, highly collimated outflowing jets observed from young stars were totally unexpected, and additional surprises are probably yet in store. Finally, we now know that extrasolar planetary systems can differ dramatically from our own, providing new challenges to theories of planet formation.

This book attempts to survey our present understanding of the accretion processes involved in star formation, with an extension to a few aspects relevant to planet formation. The present chapter contains a brief outline of the processes discussed in more detail in the rest of the book.

1.1 Molecular clouds

Young stars are not distributed at random in the Milky Way, but are generally found close to or within clouds of relatively dense molecular gas. The Milky Way is a spiral galaxy, probably with a central bar (e.g., Blitz & Spergel 1991; López-Corredoira *et al.* 2007). Most of the gas in the galaxy is distributed near the plane of its disk with most of its molecular gas of the galaxy concentrated to inner regions in the "molecular ring" about 3–5 kpc distant from the center. The most luminous star-forming regions of the galaxy are found in the molecular ring. The surface density of gas near the solar circle is lower than that of the molecular ring; locally, most of the gas is in atomic hydrogen rather than in molecular clouds (e.g., Dame 1993). Our detailed understanding of star formation, which arises from studies of nearby regions, is therefore somewhat biased toward low-density regions with relatively low star formation rates; such regions are probably not typical of the sites where most stars in the galaxy form. While exploring the formation of stars in very dense and active environments is probably best done by studying external galaxies, the solar neighborhood provides by far the most stringent tests of general star formation theory.

The sizes and masses of molecular clouds in the Milky Way span a large range, from giant star-forming molecular cloud complexes of masses $\sim 10^6\, M_\odot$ and sizes ~ 100 pc to clouds of $\lesssim 10^1\, M_\odot$ and $\lesssim 1$ pc and smaller. Three of the best-studied (and closest) molecular cloud complexes forming stars are: Taurus, at a distance of ~ 140 pc, with a mass $\sim 10^4\, M_\odot$ extending over a region 30 pc or more (Ungerechts & Thaddeus 1987; Figure 1.1); Ophiuchus, at a distance similar to that of Taurus, and with a similar mass and overall size, but with much denser concentrations of gas (DeGeus *et al.* 1990; Loren *et al.* 1990); and the Orion complex, at a distance of ~ 450 pc, with a mass $\sim 10^5\, M_\odot$ spread over a region ~ 100 pc, and also possessing very dense star-forming regions (Bally *et al.* 1987; Genzel & Stutzski 1989). An overview of galactic molecular clouds can be found in Dame *et al.* (2001), and references therein.

Most of the gas in a molecular cloud is in H_2, but this species is observable only with great difficulty; other molecules, especially CO, are used as tracers of the dense gas. Figure 1.1 shows a map of ^{12}CO emission from the Taurus molecular cloud complex, with the young stellar population superimposed. The ^{12}CO ground state rotational spectral line at ~ 2.7 mm becomes optically thick at modest column densities, thus highlighting relatively low-density material. Rarer isotopes of CO, such as ^{13}CO and C^{18}O, or other, less abundant, species are used to probe the densest regions of clouds, which occupy relatively small volumes. The temperatures of the molecular gas are generally in the range 10–20 K, unless the material is quite close to luminous stars.

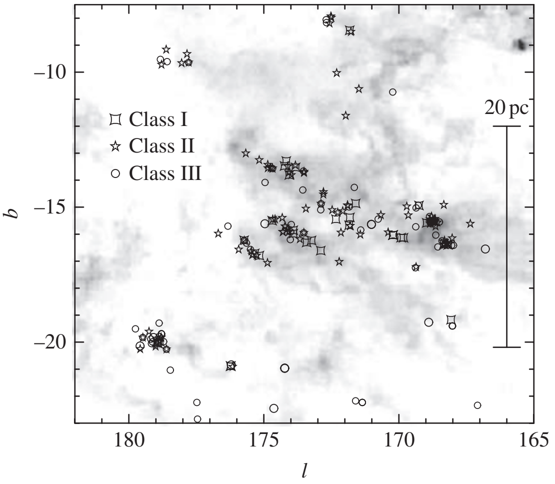

Fig. 1.1. The Taurus–Auriga molecular cloud complex. Grayscale shows integrated ^{12}CO emission, taken from Megeath *et al.* (2001). The positions of known young stars (ages ∼1 Myr) have been superimposed. The pre-main-sequence stars (Classes II and III) are generally clustered near regions of high gas column density; the likely protostars (Class I) are found only in high density regions (e.g., Onishi *et al.* 1998).

The formation of a star requires that gravity overcome the resisting forces of thermal gas pressure, turbulent motions, and magnetic fields. It is therefore not surprising that stars form in dense, cold molecular cloud regions which exhibit reduced turbulent motions. The substantial dust extinction in many molecular cloud complexes (Cernicharo 1991) may play an important role in condensing protostellar gas clouds (e.g., McKee 1989) by shielding the radiative heating by luminous stars and therefore lowering the internal temperature. Dust absorption of external photoionizing radiation fields also strongly reduces the level of ionization in the interiors of molecular clouds. For some time it was thought that this reduced ionization played an important role in star formation by enabling gas to diffuse across magnetic field lines, reducing the magnetic forces which can counteract gravity (Shu *et al.* 1987); however, it now seems more likely that protostellar clouds require little if any magnetic flux loss to allow gravitational collapse.

Molecular clouds have complex spatial structure (Falgarone 1996; Falgarone *et al.* 1998); line-of-sight motions often exceed the local sound speed by as much as an order of magnitude. Supersonic "turbulence" is an important component of the energy balance of molecular clouds (e.g., Larson 1981). The gas from which stars form is highly filamentary in many places. The origin of this structure is not well understood at present, though dynamical and thermal instabilities plus gravitational collapse probably play roles.

Substructure within molecular clouds is clearly related to the formation of stars. Older observational estimates suggested that the number of molecular cloud clumps with mass M_c is $dN_c/dM_c \propto M_c^{-1.5}$ (Blitz 1991). This cloud mass spectrum differs strongly from the initial mass function (IMF) of stars (see next section). More recent studies (Bontemps *et al.* 2001; see also Ward-Thompson *et al.* 2007) have suggested a closer correspondence between the densest and smallest clumps – called "cores" – and the stellar IMF. Comparisons between cloud and stellar masses are made difficult by uncertainties in the defining boundaries of actual star-forming clouds (Williams *et al.* 1994).

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More information

Molecular cloud "cores" are condensations in molecular gas with densities $\gtrsim 10^3\ \mathrm{cm}^{-2}$, and are thought to be the predecessors of low-mass stars. Cores are typically found from radio-frequency surveys of spectral lines of NH_3 and other molecules which are excited only at relatively high gas densities. In Taurus, cloud cores found in NH_3 have densities $\gtrsim 10^4\ \mathrm{cm}^{-3}$ and are typically ~ 0.1 pc in size (Myers & Benson 1983; Myers & Goodman 1988a,b). At such high densities, the expected gravitational collapse timescales are only a few hundred thousand years, so that star formation could proceed quite rapidly from these cores. This expectation is borne out by observations which indicate that almost half of these cloud cores in Taurus have heavily extincted (presumably recently formed) stars within their boundaries (Beichman *et al.* 1986).

Bok globules, visually opaque clouds found by their extinction of background stars, were long ago proposed as sites of low-mass star formation (Bok & Reilly 1947). The globules vary in properties, but typically have masses of a few times that of the Sun, with radii of order a few tenths of a pc in size (Clemens & Barvainis 1988). Many of these globules have young stars within them (Yun & Clemens 1990) and some may be undergoing collapse (Wang *et al.* 1995). Molecular cloud cores may be essentially equivalent to dense Bok globules, but have not been catalogued as such because they are superimposed upon regions of generally large visual extinction, and so are difficult to detect optically.

1.2 The IMF, clusters, and binaries

The frequency with which stars of a given mass are produced is called the stellar initial mass function (IMF). The general form of the galactic IMF is that of a broad distribution peaking near $\sim 0.3\, M_\odot$ (Miller & Scalo 1979; Scalo 1986; Kroupa *et al.* 1993; Chabrier 2003). At high masses, the number of stars N of mass M in logarithmic bins appears to follow a nearly power-law shape, with $\xi = d \log N / d \log M \approx -1.35$, the so-called "Salpeter slope". The form of the IMF at low masses is more uncertain, but it is clear that there is a turnover in ξ at masses below about $1\, M_\odot$. Studies of the brown dwarf or substellar mass regime (usually taken to be $0.08\, M_\odot \lesssim M_* \lesssim 0.01\, M_\odot$, bodies which will never fuse hydrogen in their interiors) suggest that the IMF *may* be relatively flat down to planetary masses ($\sim 0.01\, M_\odot$, or about 10 M(Jupiter)).

It is difficult to tell whether the IMF is truly universal, given the difficulty of obtaining sufficient statistics on the high-mass end without studying distant clusters where counts of the much more numerous low-mass population are incomplete due to faintness, crowding, etc. One unresolved issue is whether high-mass stars can form in low-density environments, though it seems unlikely, given the necessity of accreting a large mass from a finite volume. What *is* clear is that low-mass stars are formed in all environments (e.g., Herbig & Terndrup 1986). At present there are many explanations of the IMF; as yet none are wholly satisfying or convincing.

Completely isolated star formation seems to be the exception rather than the rule, though perhaps as much as 30% of all stars currently form in "distributed" rather than clustered environments, if the Orion A cloud is any indication (Figure 1.2; S.T. Megeath, personal communication). In the solar neighborhood, about 10% of recently formed stars are found in clusters of $\sim 10^3$ stars or larger, i.e., open clusters (which can remain gravitationally bound for timescales of order 100 Myr; Adams & Myers 2001). Most nearby stars are probably formed in clusters of 10^2–10^3 members (e.g., Lada & Lada 2003), although much larger clusters may be found near the galactic center. A small fraction of stars appear to be formed

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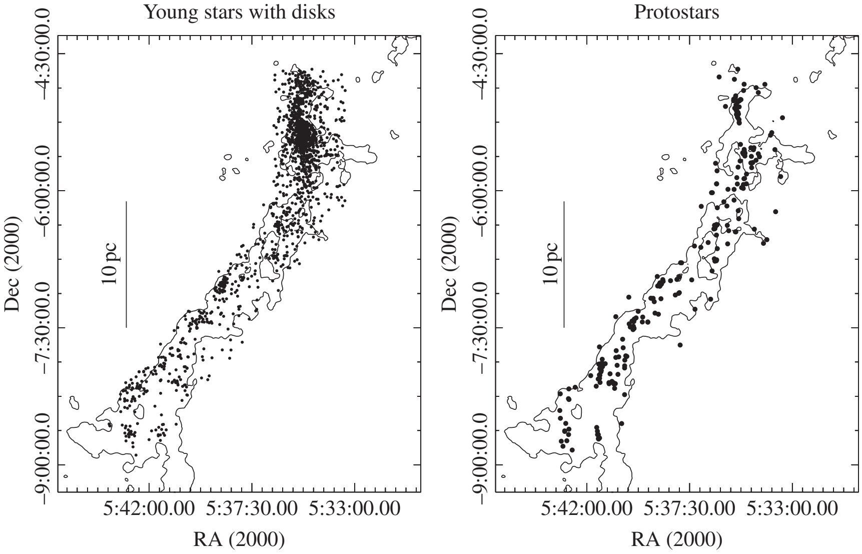

Fig. 1.2. Young stars in the Orion A molecular cloud (shown by contours outlining the main molecular emission) identified via their infrared excesses detected with the *Spitzer Space Telescope*. The left panel shows stars with disk emission, while the right panel shows likely protostars (§§1.4, 1.5). Most of the stars in the cloud reside in the clustered northern region (the Orion Nebula Cluster), but a significant fraction are "distributed" along the cloud. From Megeath *et al.* 2008 (in preparation).

in low-density environments like Taurus. Even in Taurus, the stars are not randomly distributed, but most are situated in extended filaments (Figure 1.1); such regions constitute the closest approximation to isolated star formation.

Most young solar-type stars are members of binary or multiple stellar systems (Ghez *et al.* 1993; Leinert *et al.* 1993; Reipurth & Zinnecker 1993; Mathieu 1994; Simon *et al.* 1995). The multiplicity of solar-type (F–G main sequence) field stars, the sample for which we have the best statistics, is roughly 57:38:4:1 single:binary:triple:quadruple (Duquennoy & Mayor 1991). The distribution of binary orbits is roughly Gaussian, with a median semi-major axis of order 30 AU; this result may be affected by tidal disruption of wide binaries with separations $\gtrsim$1000 AU over time. The mass ratios in multiple systems are not well constrained, but are roughly consistent with the companion being drawn randomly from the IMF. Observations of low-density star-forming regions suggest that, within certain separations, the frequency of binaries may be higher than in the field (Simon *et al.* 1995), while studies of dense clustered regions like the Orion Nebula Cluster suggest a smaller binary fraction (Köhler *et al.* 2006). Binary frequencies among very low-mass stars may be considerably lower (e.g., Ahmic *et al.* 2007).

1.3 Young stars

Young low-mass stars were originally recognized as a subset of optical emission-line objects, typically exhibiting strong hydrogen (Balmer α or Hα) line emission at 6563 Å $=$ 0.6563 μm. The youth of these stars was suggested by their spatial correlation with reflection nebulae and dark clouds (Joy 1945), which could be remnant natal material,

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and by their concentration near associations of high-mass stars which must necessarily be young (Ambartsumian 1947). This grouping is now understood as the result of star formation in molecular clouds; stars of ages $\lesssim 10^6$ yr cannot travel far from their formation sites with typical small velocities ($\lesssim$1–2 km s^{-1}) relative to the molecular gas (Herbig 1977a; Jones & Herbig 1979; Hartmann *et al.* 1986).

Objective prism surveys for stars with strong emission lines (mostly Hα) led to the first extensive catalogs of young stars. With the advent of infrared techniques, many additional objects (heavily obscured by dust at optical wavelengths) were found. Some of the densest known clusters of newly formed stars were only detected once infrared arrays were employed to image molecular cloud complexes (Lada *et al.* 1991). X-ray emission has also been used to identify many additional young objects, especially stars which do not exhibit strong excess infrared or optical emission (e.g., Montmerle *et al.* 1983; Feigelson *et al.* 1987; Walter *et al.* 1988).

Stellar luminosities and effective temperatures, or equivalently positions in the Hertzsprung–Russell (HR) diagram, provide important clues to the evolutionary states of young stars. Effective temperatures are determined from spectroscopic measurements of optical (and now infrared) absorption line strengths; usually, spectral line ratios are used to determine the stellar spectral type and luminosity class, which can be associated with the stellar surface effective temperature and surface gravity. Stellar luminosities are determined from observed optical and infrared fluxes corrected for the dimming and reddening effects of intervening dust. Using these methods, many surveys of the properties of young stellar populations have been made (e.g., the seminal work of Cohen & Kuhi (1979)).

Many low-mass stars associated with molecular clouds lie above the hydrogen-fusion main-sequence in the HR diagram (Figure 1.3); their low masses M_* and moderately large radii R_* indicate central temperatures too low to fuse hydrogen into helium (since the internal temperatures tend to scale as M_*/R_*). Deuterium fusion can occur at lower temperatures than hydrogen fusion; but because the deuterium abundance is relatively low, the luminosities of typical young stars can be powered by deuterium fusion for only a million years or less. Without fusion energy release, the young star must contract, generating gravitational potential energy to replace the energy lost by the radiation of the stellar photosphere. This contraction corresponds to moving downward in the HR diagram (Figure 1.3), and thus the positions of young stars in the HR diagram can be used to estimate ages. (Stars with masses $\gtrsim 0.8\, M_\odot$ eventually develop radiative cores, at which point they contract in radius but increase slowly in luminosity, moving mostly right to left in the HR diagram, as shown in Figure 1.3.) Contraction stops when stars arrive on the main sequence, at which point hydrogen fusion energy release replaces the energy radiated into space by the stellar photosphere. Thus the ages of stars near the "zero-age main sequence" (ZAMS) are difficult to determine, especially when uncertainties in stellar luminosities due to distance and dust extinction errors are taken into account.

The lowest-mass stars, the so-called "brown dwarfs" (usually taken to have masses between 0.08 and 0.01 $M_\odot$), exhibit slightly different behavior. By definition, brown dwarfs never fuse hydrogen in their interiors; thus, apart from a brief energy release from deuterium fusion, they can only replace the energy radiated from their surfaces by contracting, as with the higher-mass stars. Instead of halting contraction with the onset of hydrogen fusion, internal degeneracy pressure eventually slows brown dwarf contraction, with a final cooling at a roughly constant radius, of the order of the size of Jupiter. Evolutionary tracks for

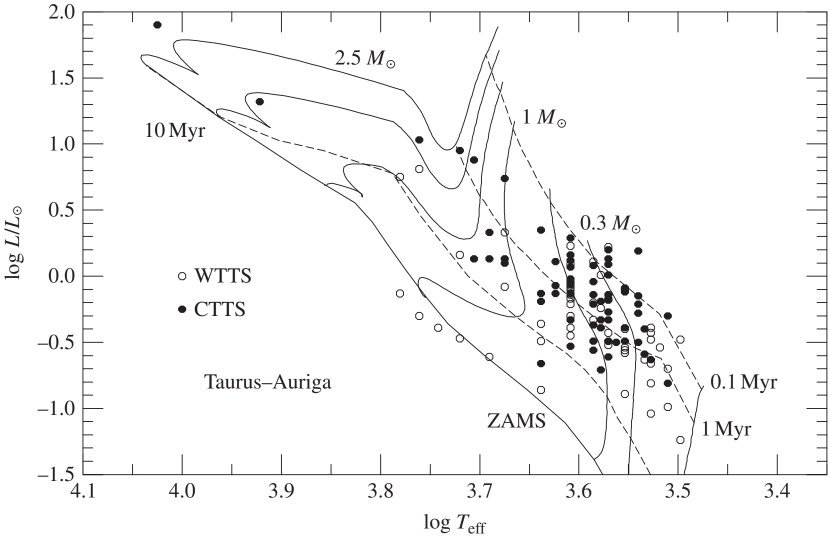

Fig. 1.3. HR diagram positions of young stars lying within the Taurus–Auriga molecular cloud complex (Figure 1.1). For comparison, theoretical evolutionary tracks for pre-main-sequence stars of masses 2.5, 2.0, 1.5, 1.0, 0.5, 0.3, and 0.1 $M_\odot$ are shown. The dashed lines are isochrones for ages of 10^5, 10^6, and 10^7 yr (0.1, 1, and 10 Myr), with the hydrogen-fusion "zero-age main sequence" or ZAMS shown as the lowest line running from upper left to lower right. The open circles refer to weak-emission T Tauri stars (WTTS; see text), while the filled circles denote the positions of the classical T Tauri stars (CTTS). Stellar properties taken from Kenyon and Hartmann (1995); evolutionary tracks are from D'Antona and Mazzitelli (1994).

these objects are particularly uncertain due to the difficulty in treating the complex molecular opacities in the atmospheres of these objects; representative calculations are shown in Figure 1.4. The rapid cooling of brown dwarfs means that it is much easier to detect them when they are very young and proportionately much brighter.

Low-mass ($M \lesssim 2\ M_\odot$), pre-main-sequence stars, having stellar spectral types F–M (corresponding to surface effective temperatures ~7000–3000 K), are called "T Tauri" stars (Joy 1945; Herbig 1962; Bertout 1989); higher-mass ~2–10 $M_\odot$ pre-main-sequence stars are labeled "Herbig Ae/Be" stars (Herbig 1960) to distinguish them from other types of emission-line A-B stars (effective temperatures ~8000–30 000 K) which are presumably more evolved. (The mass ranges are not exact because the classification depends upon the optical stellar spectral type or effective temperature, which can vary substantially as a ~2 $M_\odot$ star evolves; see Figure 1.3.) The rapidity with which massive stars evolve makes study of their pre-main-sequence evolution more difficult. Stars with masses $>2\ M_\odot$ are typically found near the ZAMS (Figure 1.3; Hillenbrand *et al.* 1992); age estimates for these objects are especially uncertain.

The old systematic catalog of pre-main-sequence stars, that of Herbig and Bell (1988 = HBC), is very useful for the best-studied pre-main-sequence stars, but it is now highly incomplete given the vastly increased number of young stars since discovered. Many

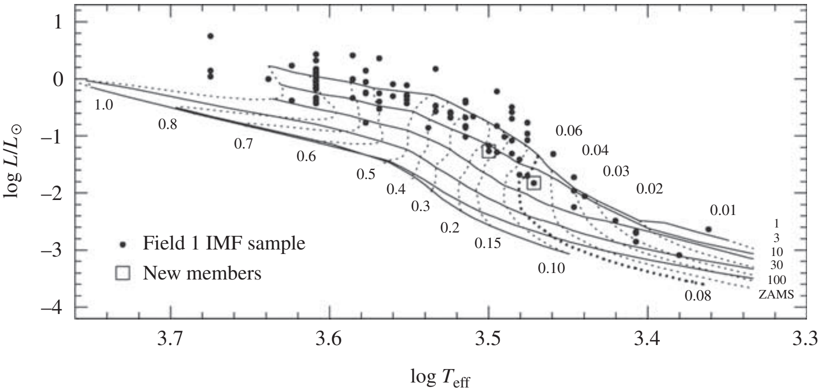

Fig. 1.4. A recent placement of the low-mass population of Taurus on an HR diagram, with evolutionary tracks from Baraffe *et al.* (2002). Modified from Luhman (2004).

young stars have only been detected as infrared sources, so their effective temperatures, masses, and often luminosities are poorly known.

The term “young stellar objects”, or YSOs (Strom 1972), was coined partly in the recognition that the appearance of young stars may be strongly affected or altered by their circumstellar material. It also serves as a relatively neutral term to identify objects whose underlying nature – T Tauri star, Herbig Ae/Be star, protostar (§1.3), pre-main-sequence accretion disk (§1.4) – is not yet understood. In this book the term YSO is used sparingly, since it does not discriminate clearly between objects which can be intrinsically quite different.

The T Tauri stars originally were identified as late-type stars with strong emission lines and irregular light variations associated with dark or bright nebulosities (see Bertout 1989 for a discussion). Since that time, the term “T Tauri star” has come to be synonymous with low-mass pre-main-sequence stars, whether or not they are associated with nebulosity or have strong emission lines. Most of the variable stars first identified as T Tauri stars are currently called “strong-emission” or “classical” T Tauri stars (CTTS), to distinguish them from “weak-emission” pre-main-sequence stars (WTTS). The distinction between strong and weak emission stars is usually made on the basis of Hα emission. The original definition assigned the WTTS label to stars with Hα equivalent widths less than 10 Å but we now know that the boundary between weak- and strong-emission stars depends upon spectral type (White & Basri 2003). It appears that the excess emission of many WTTS can be explained in terms of enhanced solar-type magnetic activity (Walter *et al.* 1988), while the extreme levels of excess emission at optical and infrared wavelengths of many CTTS require an external energy source. *Accretion* from a circumstellar disk appears to supply the energy needed for the non-photospheric emission of CTTS (§1.7).

High-mass stars are by definition young, since they exhaust their hydrogen rapidly via fusion. It appears that early B and O stars start their lives near or on the zero-age main sequence, although it is difficult to say more because of the rapidity with which these stars form and would pass through any pre-main-sequence phase. In addition, there are severe observational difficulties in studying very young massive stars because they are generally

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Excerpt
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heavily extincted. Moreover, the scarcity of massive stars results in the need to study these objects at much larger distances than those of the nearest low-mass star-forming regions. These problems have made it difficult to tell whether the accretion disk paradigm of low-mass stars applies to high-mass stars as well. Recent interferometric studies have yielded indications of the presence of disks around some young massive stars (Shepherd *et al.* 2001; Patel *et al.* 2005; Reid *et al.* 2007), as well as bipolar outflows suggesting collimated flows from accretion disks (e.g., Shepherd & Churchwell 1996).

1.4 Protostars

Dramatic improvements in infrared detector technology over the last three decades have enabled astronomers to find YSOs hidden by dust absorption at optical wavelengths. The measurement of far-infrared emission, which can penetrate through the most opaque dust clouds, was enormously enhanced by the launch of the *IRAS*. In orbit, *IRAS* could be more effectively shielded from the intense thermal emission of the Earth than was possible with ground-based telescopes, and it was actively cooled to liquid He temperatures. *IRAS* produced a survey of the sky at wavelengths of 12, 25, 60, and 100 μm with enough sensitivity to detect many pre-main-sequence stars; the launch of the *ISO* satellite produced further advances in characterizing infrared excess objects.

One of the major results of *IRAS* was the discovery of infrared sources with luminosities typical of T Tauri stars, but with spectral energy distributions peaking at 60–100 μm (Beichman *et al.* 1986). Most of these objects are now generally identified as protostars, with dusty envelopes that absorb energy from the central star at short wavelengths and re-emit this energy at far-infrared wavelengths, where the envelope is sufficiently transparent for the radiation to escape (Figure 1.5). The protostellar phase of star formation is thought to involve the free-fall collapse of dusty material to stellar dimensions, resulting in very large extinctions toward the central energy source (e.g., Larson 1969a,b; Appenzeller & Tscharnuter 1974). Theoretical models of the dust emission from protostellar envelopes in gravitational free-fall can reproduce the observed infrared emission of these heavily extincted young stellar objects (Adams *et al.* 1987 = ALS; Butner *et al.* 1991; Kenyon *et al.* 1993). So far it has not been easy to demonstrate that these dusty envelopes are actually falling in, although continuing efforts to observe small velocity shifts in radio-wavelength emission lines have provided additional support for the collapse model (Walker *et al.* 1986; Hayashi *et al.* 1993; Zhou *et al.* 1993; Zhou & Evans 1994; Mardones *et al.* 1997; Di Francesco *et al.* 2001).

IRAS surveys of Taurus (Beichman *et al.* 1986; Cohen *et al.* 1989; Kenyon *et al.* 1990, 1994; Beichman *et al.* 1992) indicate that the number of protostellar sources is ≈10% of the total pre-main-sequence population. This suggests that the time for protostellar collapse is similarly about 10% of the age of the pre-main-sequence stars in the region. The resulting estimate of $\sim 10^5$ yr for the protostellar infall phase is roughly consistent with the expected timescale of collapse for the formation of a typical low-mass T Tauri star (Larson 1969a,b; Shu 1977). Forthcoming results on embedded stellar populations from the *Spitzer Space Telescope* should add to these results, but are unlikely to result in major revisions.

The behavior of high-mass protostars is much less clear, due in part to the observational problems mentioned in the previous section. Nevertheless, observations of the so-called “hot cores” (e.g., Kurtz *et al.* 2000) show that massive stars are formed in very dense clouds.

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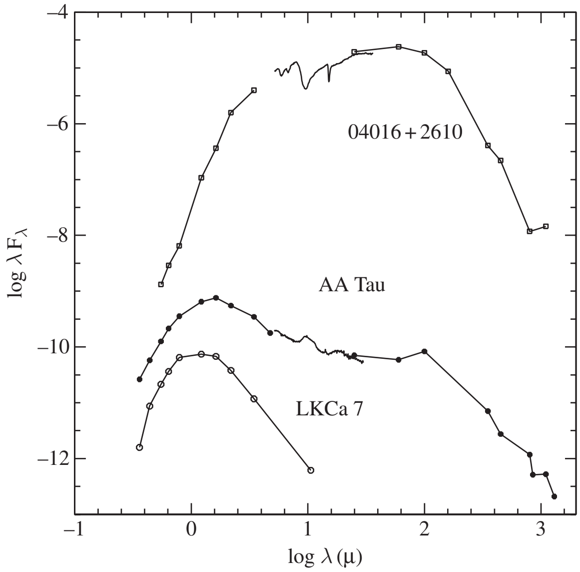

Fig. 1.5. Spectral energy distributions (SEDs) of three young stellar objects which typify the infrared classification system. The vertical axis is the flux at the Earth in arbitrary units. The Class I object IRAS 04016 + 2610 is a protostar hidden at optical wavelengths by its dusty infalling envelope; the dust absorbs the radiation from the central regions and re-emits it in the far-infrared. The CTTS or Class II object AA Tau is optically visible, but exhibits long-wavelength dust emission generally attributed to a circumstellar disk (see text). The WTTS or Class III object LkCa 7 does not exhibit detectable dust emission; its SED is nearly that of a single temperature blackbody, and is typical of the photospheric emission of low-mass pre-main-sequence stars. Note the 10 μm silicate feature, which is in absorption in the Class I object and in emission in the Class II star AA Tau (and the 15 μm CO_2 ice feature absorption in 04016 + 2610). Data from Kenyon and Hartmann (1995) and IRS Spitzer spectra from Furlan *et al.* (2006).

1.5 Long-wavelength emission: dusty envelopes and disks

YSOs are frequently classified in the literature based on the shape of the emitted spectrum from near- to far-infrared spectral regions, which emphasizes the properties of circumstellar dust (Lada & Wilking 1984; Lada 1987). The emitted spectrum is usually discussed in terms of the "spectral energy distribution" or SED, which is a frequently used shorthand for either the flux distribution λF_λ observed at the Earth, or the luminosity distribution λL_λ, depending upon the context.*

The infrared classification scheme depends upon the spectral index s of the emitted flux F of the object, $\nu F_\nu = \lambda F_\lambda \propto \lambda^s$, typically measured between $\lambda \sim 2\,\mu$m and ~50–100 μm. Class I sources correspond to objects with $s > 0$, i.e., the SED rises toward long wavelengths. An example of such a Class I source is the Taurus YSO IRAS 04016 + 2610 (shown in Figure 1.5); this heavily extincted object is one of the protostar candidates discussed in the previous section. The SEDs of such objects can be explained with emission from dusty infalling envelopes.

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* In this book we follow the typical astronomical convention of using cgs units. Thus, the flux λF_λ has units of erg cm^{-2} s^{-1}, while the luminosity λL_λ has units of erg s^{-1}.