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The Properties and Environment of Primitive Solar Nebulae as Deduced from Observations of Solar-Type Pre-main Sequence Stars[1]

STEPHEN E. STROM
SUZAN EDWARDS[2]
KAREN M. STROM
University of Massachusetts, Amherst

ABSTRACT

This contribution reviews a) current observational evidence for the presence of circumstellar disks associated with solar type pre-main sequence (PMS) stars, b) the properties of such disks, and c) the disk environment. The best evidence suggests that at least 60% of stars with ages $t < 3 \times 10^6$ years are surrounded by disks of sizes ~ 10 to 100 AU and masses ~ 0.01 to 0.1 $M_\odot$. Because there are no known main sequence stars surrounded by this much distributed matter, disks surrounding newborn stars must evolve to a more tenuous state. The time scales for disk survival as massive (M ~ 0.01 to 0.1 $M_\odot$), optically thick structures appear to lie in the range $t \ll 3 \times 10^6$ years to $t \sim 10^7$ years. At present, this represents the best astrophysical constraint on the time scale for assembling planetary systems from distributed material in circumstellar disks. The infrared spectra of some solar-type PMS stars seem to provide evidence of *inner disk clearing*, perhaps indicating the onset of planet-building.

The material in disks may be bombarded by energetic (~ 1 kev) particles from stellar winds driven by pre-main sequence stars. However, it is not known at present whether, or for how long such winds leave the stars a) as highly collimated polar streams which do not interact with disk material, or b) as more isotropic outflows.

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[2] Also at Smith College, Northampton, Massachusetts.

INTRODUCTION

Recent theoretical and observational work suggests that the process of star formation for single stars of low and intermediate mass ($0.1 < M/M_{\odot} < 5$) results naturally in the formation of a circumstellar disk, which may then evolve to form a planetary system. This process appears to involve the following steps (Shu *et al.* 1987):

- The formation of opaque, cold, rotating protostellar "cores" within larger molecular cloud complexes;
- The collapse of a core when self-gravity exceeds internal pressure support;
- The formation within the core of a central star surrounded by a massive (0.01 to 0.1 $M_{\odot}$) circumstellar disk (*embedded* infrared source stage). At this stage, the star/disk system is surrounded by an optically opaque, infalling protostellar envelope. Gas and dust in the envelope rains in upon both the central stellar core and the surrounding disk, thus increasing both the disk and stellar mass. Infall of low angular momentum material directly onto the central star and accretion of high angular momentum material through the disk provide the dominant contributions to the young stellar object's (YSO) luminosity, far exceeding the luminosity produced by gravitational contraction of the stellar core. Because the infalling envelope is optically opaque, such YSOs can be observed only at wavelengths $\lambda > 1\mu$. They exhibit infrared spectral energy distributions, λF_{λ} vs. λ, which are a) broad compared to a blackbody distribution and b) flat, or rising toward long wavelengths (see Figure 1a). At some time during the infall phase, the central PMS star begins to drive an *energetic wind* ($L_{wind} \sim 0.1\ L_{*}$; $v_{wind} \sim 200$ kilometers per second). This is first observable as a highly collimated "molecular outflow" as it transfers momentum to the surrounding protostellar and molecular cloud material and later (in some cases) as a "stellar jet" (Edwards and Strom 1988). The wind momentum is sufficient to reverse infall from the protostellar envelope and eventually dissipates this opaque cocoon, thus revealing the YSO at visible wavelengths (Shu *et al.* 1987).
- The optical appearance of a young stellar object (YSO) whose luminosity may be dominated in the infrared by accretion through the disk, and in the ultraviolet and optical region, by emission from a hot "boundary layer" (*continuum + emission* TTS *phase*). Accretion of material through the still massive (0.01 to 0.1 $M_{\odot}$) disk produces infrared continuum radiation with a total luminosity $\gg 0.5$ times the stellar luminosity. At this stage, the infrared spectrum is still much broader than a single, blackbody spectrum (Myers *et al.* 1987; Adams *et al.* 1986), and in most cases falls

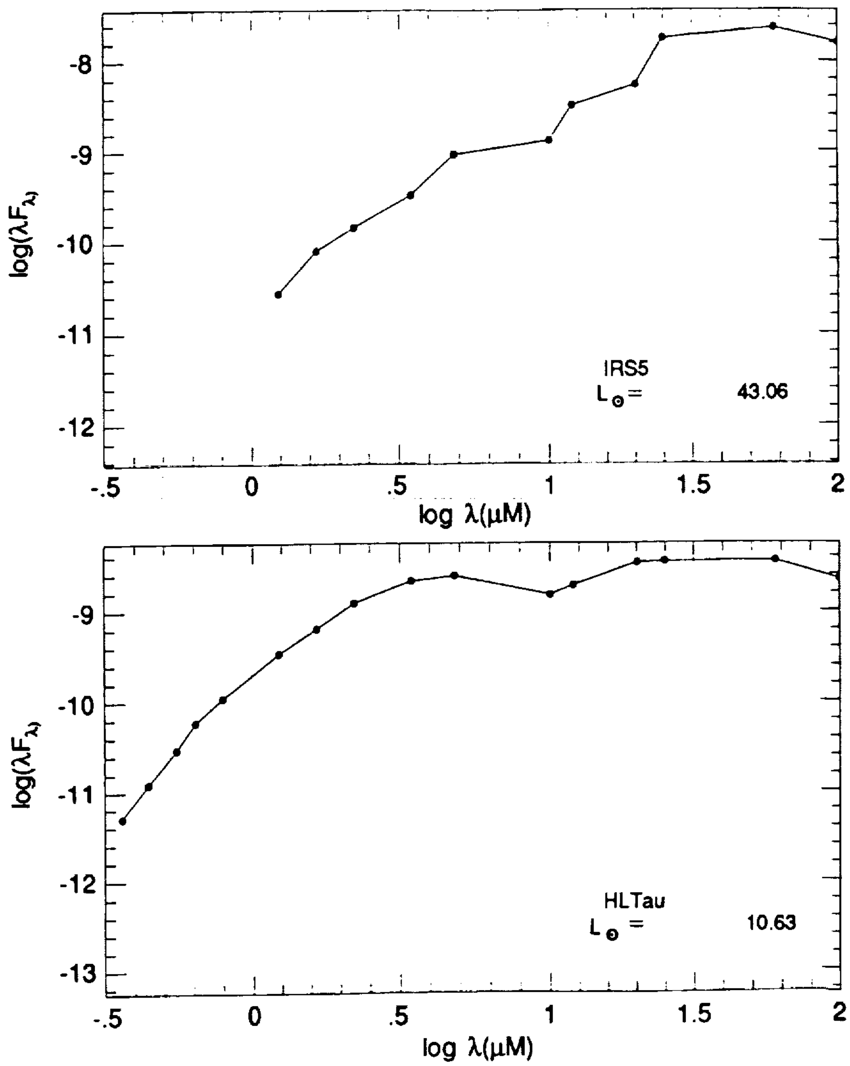

FIGURE 1 (a) A plot of the observed spectral energy distribution for the *embedded infrared source*, L1551/IRS 5. This source drives a well-studied, highly-collimated, bipolar molecular outflow and a stellar jet. Note that the spectrum rises toward longer wavelength, suggesting that IRS 5 is surrounded by a flattened distribution of circumstellar matter, possible remnant material from the protostellar core from which this YSO was assembled. (b) A plot of the observed spectral energy distribution for the *continuum + emmission T Tauri star*, HL Tau. Near-infrared images of HL Tau suggest that this YSO is surrounded by a flattened distribution of circumstellar dust. Its infrared spectrum is nearly flat, which suggests that HL Tau is as well still surrounded by a remnant, partially opaque envelope.

toward longer wavelengths. In a few cases, the spectrum is flat or rises toward long wavelengths, perhaps reflecting the presence of a partially opaque, remnant infalling envelope (Figure 1b).

The accretion of material from the rapidly rotating ($\sim$ 200 kilometers per second), inner regions of the disk to the slowly rotating ($\sim$ 20 kilometers per second) stellar photosphere also produces a narrow, hot ($T \geq 8000$ K) emission region: the "boundary layer" (Kenyon and Hartmann 1987; Bertout *et al.* 1988). Radiation from the boundary layer overwhelms that from the cool PMS star photosphere. Consequently, the photospheric absorption spectrum cannot be seen against the boundary layer emission at $\lambda < 7000$ Å. Strong permitted and forbidden emission lines (perhaps tracing emission associated with energetic stellar winds and the boundary layer) are also present during this phase; hence the classification "continuum + emission" objects. All such objects drive energetic winds, some of which are manifest as highly collimated stellar jets (Strom *et al.* 1988; Cabrit *et al.* 1989).

- The first appearance of the stellar photosphere, as the contribution of the disk to the YSO luminosity decreases *(T Tauri or TTS ($0.2 < M/M_\odot$ Tauri $< 1/5$) and Herbig emission star or HES ($1.5 < M/M_\odot < 5$) phase)*. Relatively massive disks are still present, but the accretion rate and mass outflow rate both diminish. The infrared luminosity from accretion and the boundary layer emission decrease as a consequence of the reduced accretion rate through the disk. "Reprocessing" of stellar radiation absorbed by dust in the accretion disk and re-radiated in the infrared contributes up to 0.5 times the stellar luminosity (depending on the inclination of the star/disk system with respect to the line of sight). The observed infrared spectra show the combined contribution from a Rayleigh-Jeans ($\lambda F_\lambda \sim \lambda^{-3}$) component from the stellar photosphere and a broader, less rapidly falling ($\lambda^{-2/3}$ to $\lambda^{-4/3}$) component arising from both disk accretion and passive reprocessing by circumstellar dust (Figure 2). Photospheric absorption spectra are visible, though sometimes partially "veiled" by the hot boundary layer emission. H emission is strong (typical equivalent widths ranging from $10 < W_\lambda < 100$ Å). In TTS, Ca II and selected forbidden and pace permitted metallic lines are often prominent in emission. Energetic winds persist, although their morphology and interaction with the circumstellar environment is unknown at this stage. Highly collimated optical jets are not seen, but spatially unresolved [O I] line profile structures require that the winds be at least moderately collimated (on scales of $\sim$ 100 AU).
- The settling of dust into the midplane of the disk followed by the clearing of *distributed material* in the disk, as dust agglomerates into planetesimals, first in the inner regions of the disk where terrestrial planets form, and later in the outer disk where giant planets and comets are

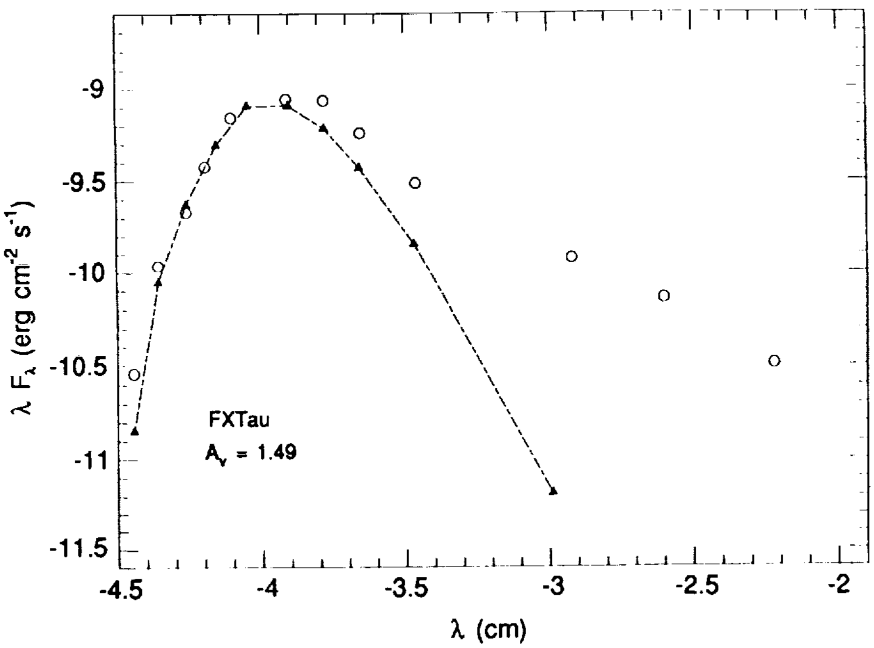

FIGURE 2 A plot of the reddening-corrected spectral energy distribution ($0.35\mu < \lambda \leq 100\ \mu$) for the *T Tauri star*, FX Tau (open circles). Also plotted is the spectral energy distribution of a dwarf standard star (filled triangles) of spectral type M1 V corresponding to that of FX Tau. The flux of the TTS and the standard star have been forced to agree at R (0.65μ).

assembled. The disappearance of accretion signatures and energetic winds (*"naked" T Tauri or NTTS phase?*).

• The appearance of the star on the hydrogen-burning main sequence, accompanied by its planetary system and possibly by a tenuous remnant or secondary dust disk (analogous to the edge-on disk surrounding B. Pictoris imaged recently by Smith and Terrile 1984).

Is this picture correct even in broad outline for all single stars? Are disks formed around members of binary and multiple star systems (which constitute at least 50% of the stellar population in the solar neighborhood)? For those stars that form disks, what is the range of disk sizes and masses? What is the range in time scales for disk evolution in the inner and outer disks, and how do these time scales compare with those inferred for our solar system from meteoritic and primitive body studies, and theoretical modeling of the early solar nebula? In what fraction of star/disk systems can the gas in the outer disk regions survive removal by energetic winds long enough to be assembled into analogs of the giant planets?

RECENT OBSERVATIONAL RESULTS

Current Observational Evidence for Disks Associated with Pre-Main Sequence Stars

Observations carried out over the past five years provide strong evidence for circumstellar disks associated with many young stars (ages $< 3 \times 10^6$ years) of a wide range of masses. These disks appear to be massive (M $\sim$ 0.01 to 0.1 $M_\odot$) precursor structures to the highly evolved, low-mass (M $\sim 10^{-7}$ $M_\odot$)) disks discovered recently around B-Pictoris and its analogs (Smith and Terrile 1984; Backman and Gillett 1988):

- The direct and speckle imaging at near-infrared wavelengths (Grasdalen *et al.* 1984; Beckwith *et al.* 1984; Strom *et al.* 1985) reveal flattened, disk-like structures associated with three YSOs: HL Tau (a low-mass continuum + emission star), R Mon (an intermediate-mass continuum + emission star), and L1551/IRS 5 (a low-mass embedded infrared source). These structures are seen via light scattered in our direction by sub-micron and micron-size dust grains. Associated structures are also seen in mm-continuum and CO line images obtained with the Owens Valley interferometer (Sargent and Beckwith 1987), although the relationship between the optical and near-infrared and mm-region structures is not clear at this point. Shu (1987, private communication) has argued that the flattened, scattered light structures detected to date trace not disks, but rather remnants of infalling, protostellar cores (see also Grasdalen *et al.* 1989).
- The high-spectral resolution observations of [O I] and [S II] lines in continuum + emission, T Tauri, and Herbig emission stars provide indirect but compelling evidence of such disks. The forbidden line emission is associated with the outer (r $\sim$ 10 to 100 AU) regions of winds driven by PMS stars. However, in nearly all cases studied to date, only blue-shifted emission is observed (see Figure 3) thus requiring the presence of structures whose opacity and dimension is sufficient to obscure the receding part of the outflowing gas diagnosed by the forbidden lines (Edwards *et al.* 1987; Appenzeller *et al.* 1984).
- The broad, far-infrared ($\lambda > 10\mu$) spectra characteristic of *all* continuum + emission, T Tauri, and Herbig emission stars arise from heated dust located over a wide range of distances ($\sim$ 0.1 to $>$ 100 AU) from a central pre-main sequence (PMS) star (Rucinski 1985; Rydgren and Zak 1986). In order to account for the fact that these IR-luminous YSOs are visible at optical wavelengths, it is necessary to assume that the observed far-IR radiation arises in an optically thick but *physically thin* circumstellar envelope: a disk. If the heated circumstellar dust responsible for the observed far-infrared radiation intercepted a large solid angle, the

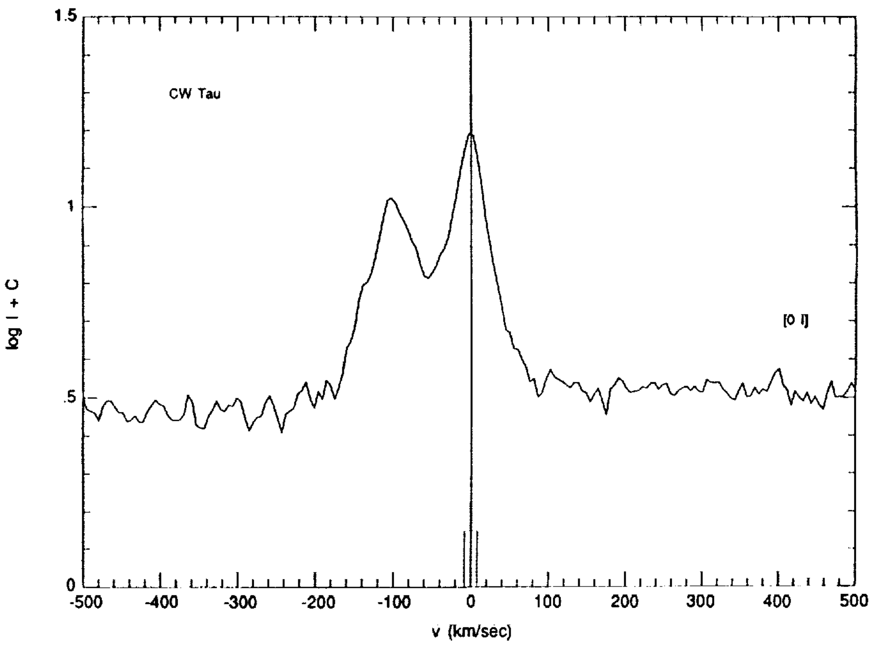

FIGURE 3 A plot of the [0 I] λ 6300 Å profile observed for the T Tauri star, CW Tau. Note the broad, double-peaked profile extending to blue-shifted (negative) velocities; there is no corresponding red-shifted emission. The [0 I] emission is believed to trace low density, outflowing gas located at distances $r > 10$ AU from the surface of CW Tau. The absence of red-shifted emission is attributed to the presence of an opaque circumstellar disk whose size is comparable to or larger than the region in which [0 I] emission is produced.

associated PMS stars could not be seen optically (Myers *et al.* 1987; Adams *et al.* 1987). The observed far-IR fluxes require a mass of emitting dust 10^{-3} to 10^{-4} $M_\odot$ or a total disk mass of 0.1 to 0.01 $M_\odot$ (assuming a gas/dust ratio appropriate to the interstellar medium).

- The optical and infrared spectra of a class of photometrically eruptive YSOs known as FU Ori objects appear to arise in self-luminous, viscous accretion disks characterized by a temperature-radius relation of the form $T \sim r^{-3/4}$ (Hartmann and Kenyon 1987a,b; Lynden-Bell and Pringle 1974). Because material in this disk must be in Keplerian motion about a central PMS star, absorption lines formed in the disk reflect the local rotational velocity. High spectral resolution observations show that lines formed in the outer, cooler regions of the disk are narrower than absorption features formed in the inner, hotter, more rapidly rotating disk regions (Hartmann and Kenyon 1987a,b; Welty *et al.* 1989), thus providing important *kinematic* confirmation of disk structures associated with PMS stars.

• The mm-line and continuum observations of HL Tau and L1551/ IRS 5 made with the OVRO mm interferometer suggest that circumstellar gas and dust is bound to the central PMS star and, in the case of HL Tau, in Keplerian motion about the central object (Beckwith and Sargent 1987).

Frequency of Disk Occurrence

What fraction of stars are surrounded by disks of distributed gas and dust at birth? If excess infrared and mm-wave continuum emission is produced by heated dust in disks, then all continuum + emission, T Tauri, and Herbig emission stars must be surrounded by disks. The inferred disk masses ($0.01 < M_{disk}/M_{\odot} < 0.1$, comparable to the expected mass of the primitive solar nebula) and optical depths ($\tau_V \sim 1000$) for TTS and HES are relatively large (Beckwith *et al.* 1989 and Edwards *et al.* 1987 for estimates based on mm-continuum and far-IR measurements respectively).

However, the HR diagram presented by Walter *et al.* (1988) suggests that ~ 50% of low mass pre-main sequence stars with ages comparable to those characterizing TTS ($t < 3 \times 10^6$ years) are "naked" T Tauri stars (NTTS) which lack measureable infrared emission, and therefore *massive*, optically thick disks. The observations of Warner *et al.* (1977) suggest that a comparable percentage (50% to 70%) of young ($t < 3 \times 10^6$ years) intermediate mass stars ($M \sim 1.5{-}2.0\ M_{\odot}$) also lack infrared excesses.

Recently, Strom *et al.* (1989) examined the frequency distribution of near-IR (2.2μ) excesses, $\Delta K \equiv \log \{F_{2.2\mu}$ (PMS star)/ $F_{2.2\mu}$ (standard star)$\}$, associated with 47 NTTS and 36 TTS in Taurus-Auriga (see Figure 4). They find that 84% of the TTS and 36% of the NTTS have significant excesses, $\Delta K \geq 0.10$ dex. Thus, nearly 60% of solar-type PMS stars with ages $t < 3 \times 10^6$ years located in this nearby star-forming complex have *measurable*[3] infrared excesses; these excesses most plausibly arise in disks. However, the sample includes only *known* PMS stars for which adequate photometry is available; more NTTS may yet be discovered when more complete x-ray and proper motion searches of the Taurus-Auriga clouds become available. It is also important to note that these disk frequency statistics *exclude* several PMS stars which show small or undetectable near IR excesses, but relatively strong mid- to far-IR excesses (see Figure 5):

[3] Objects that lack measurable infrared excesses *could be* surrounded by low mass, tenuous disks ($M \ll 10^{-5}\ M_{\odot}$) disks. For example, a disk of mass comparable to that surrounding β Pic ($M \sim 10^{-7}\ M_{\odot}$) could not be detected around a PMS star in the Taurus-Auriga clouds given the current sensitivity of IR measurements.

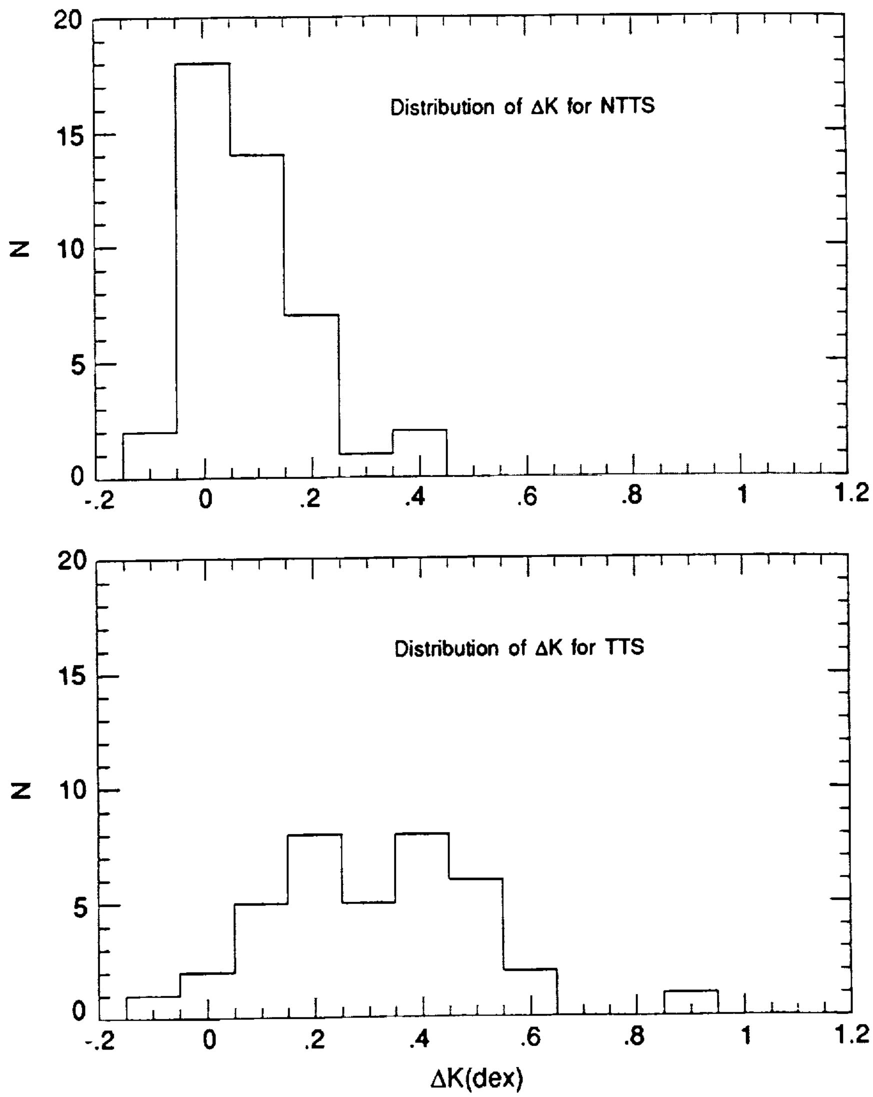

FIGURE 4 The frequency distribution of the 2.2μ excess, $\Delta K \equiv \log\{F_{2.2\mu}\ (PMS)/F_{2.2\mu}\ (standard)\}$, for NTTS (top) and TTS (bottom). Note that a) 36% of the NTTS show excesses, $\Delta K \geq 0.10$ dex, and b) that while the distribution for the NTTS peaks toward smaller values of ΔK, there is significant overlap in the two distribution. It does not appear as if NTTS as a class lack infrared excesses.

these objects may represent PMS stars surrounded by circumstellar disks which are optically thin near the star (and therefore produce too little near-IR radiation to be detected), but optically thick at distances $r > 1$ AU (see below).

Do pre-main sequence stars with ages $t \leq 3 \times 10^6$ years that lack infrared excesses (40% of all solar-type PMS stars) represent a population of stars born without disks? Or have their disks been destroyed by tides raised by a companion star? Or have some fraction of these young PMS stars already built planetary systems?

The Effect of Stellar Companions on Disk Survival

Do disks form around members of binary and multiple star systems? If so, are these disks perturbed by tidal forces and perhaps disrupted when the disk size is comparable to the separation between stellar components? To date, the overwhelming majority of binaries discovered among low- and intermediate-mass PMS stars in nearby star-forming complexes have been wide ($\Delta\theta > 1''$; $r > 150$ AU) doubles with separations well in excess of the radius of our solar system (and thus possibly of lesser interest to addressing the above questions). In the last few years, ground-based observations have uncovered a few examples of a) spectroscopic binaries with velocity amplitudes, $\Delta v > 10$ km/s (separations < 3 AU; Hartmann *et al.* 1986); b) binaries with separations in the range 0.1 to 50 AU detected from lunar occultation observations of YSOs in Taurus-Auriga and Ophiuchus (Simon, private communication); and c) binaries discovered in the course of optical and infrared speckle interferometric observations (Chelli *et al.* 1988). Of the known binaries in Taurus-Auriga with observed or inferred separations $\Delta\theta < 0.5''$ ($r < 70$ AU; DF Tau, FF Tau, HV Tau, HQ Tau, T Tau), all but FF Tau appear to have IR excesses similar to those of TTS thought to be surrounded by disks. This somewhat surprising result implies that circumstellar envelopes of mass $> 10^{-4}$ $M_\odot$ and of dimension 10 to 100 AU are present *even in close binary systems.*

Disk Evolutionary Time Scales

On what time scales do disks evolve from massive "primitive" to low mass, perhaps "post planet-building" disks? Current observations suggest that more than 50% of low- to intermediate-mass PMS stars with ages $t < 3 \times 10^6$ years are surrounded by disks with masses in excess of 0.01 $M_\odot$ of distributed material (see above). There are *no* known main sequence stars surrounded by this much distributed matter, although a few stars such as Vega and β Pictoris (Smith and Terrile 1984; Backman and Gillett 1988)

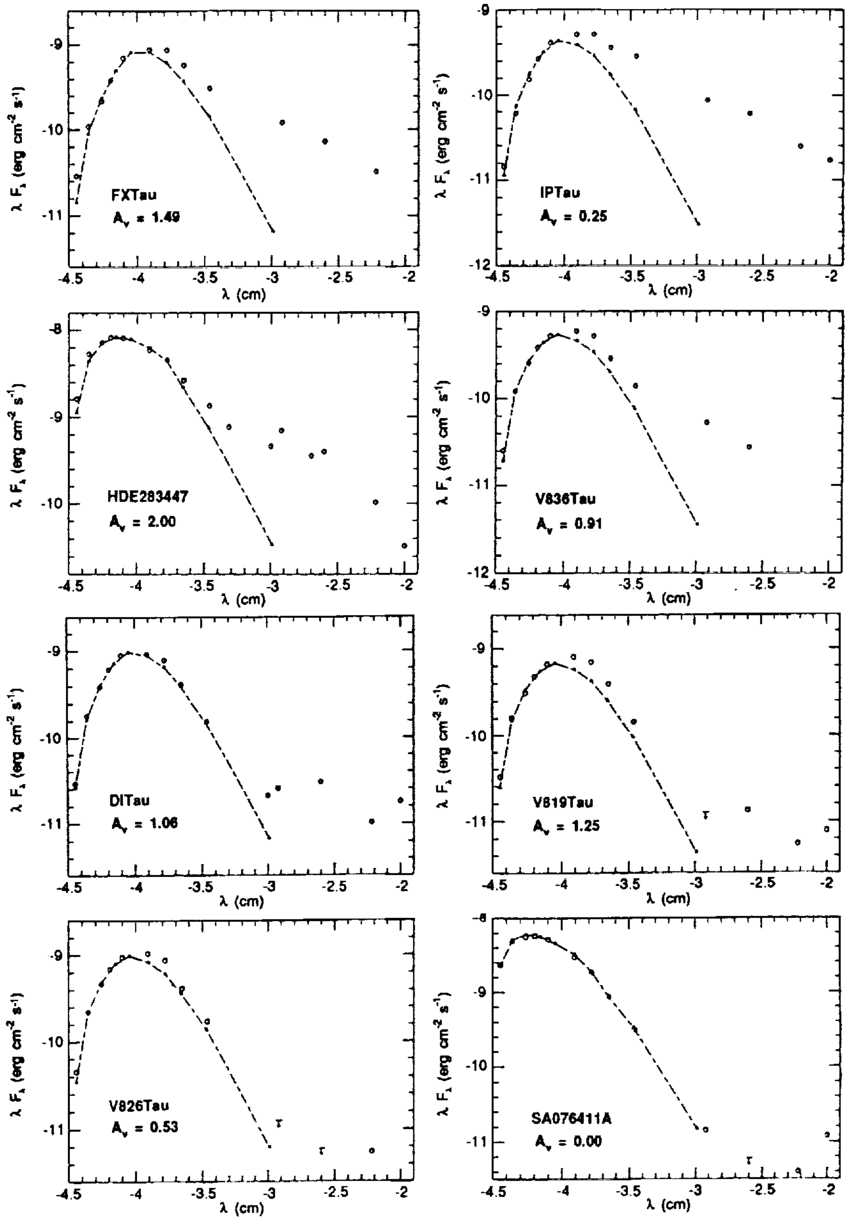

FIGURE 5 A plot of the reddening-corrected spectral energy distributions ($0.35\mu < \lambda \leq 100\mu$) for 7 NTTS and the T Tauri star, FX Tau (see Figure 2); the observed points for the NTTS and TTS are plotted as open circles. Also plotted are the spectral energy distributions of dwarf standard stars (filled triangles) of spectral types corresponding to those of the NTTS and TTS. The fluxes of the NTTS and those of the standard stars have been forced to agree at R (0.65μ). Note the small *near*-infrared excess and relatively large mid- to far-infrared excesses for several of the NTTS. A spectral energy distribution of this character might be produced by a circumstellar disk in which the optical depth of emitting material in the inner disk is small, while that in the outer disk is large.

are surrounded by disks with masses $\sim 10^{-7}$ $M_{\odot}$ ($\sim$ 0.1 Earth masses). Thus, *disks surrounding newborn stars must evolve to a more tenuous state.*

Recent work by Strom *et al.* (1989) suggests that nearly 60% of PMS stars in Taurus-Auriga with ages younger than 3×10^6 years, and only 40% of older stars, show evidence of significant near-infrared excesses $\Delta K \geq 0.1$ dex (see above). These results are illustrated in Figure 6. *Fewer than 10% of PMS stars older than 10^7 years show $\Delta K \geq 0.1$.* If excess near-IR emission arises in the warm, inner regions of circumstellar disks, then we can use these statistics to discuss the range of time scales for disks to evolve from massive, optically thick structures (with large K values) to low-mass, tenuous entities (with small ΔK values).

If *all* solar-type stars form massive (0.01 to 0.1 $M_{\odot}$ disks, then by $t = 3 \times 10^6$ years, 40% of PMS stars (the fraction of young PMS stars with $\Delta K < 0.10$) are surrounded by remnant disks too tenuous to detect. The evolutionary time scale for such rapidly evolving disks must be $t \ll 3 \times 10^6$ years. Because fewer than 10% of PMS stars *older* than 10^7 years show $\Delta K \geq 0.1$ (Strom *et al.* 1989), the disks surrounding all but 10% of PMS stars must have completed their evolution by this time. The majority of disks must have evolutionary time scales in the range 3×10^6 to 10^7 years. This range represents the best astrophysical constraint on the likely time scale for planet building available at present.

As noted earlier, the above statistics obtain for all *known* TTS and NTTS in Taurus-Auriga for which adequate photometry is available. Although the exact fraction of PMS stars surrounded by disks may change somewhat as more complete surveys for PMS stars become available, our qualitative conclusions regarding the *approximate* time scale range for disk evolution are unlikely to be vitiated.

Disk Sizes and Morphologies

In our solar system, all known planets lie within 40 AU of the Sun. Yet the circumstellar disk imaged around β Pic extends to a distance approximately several thousand AU from the central star. Do primitive solar nebulae typically extend to radii considerably larger than our own planetary system? If so, how far, and how much material do they contain? How do properties such as size and surface mass distribution change with time? Do such changes reflect the consequences of angular momentum transport within the disk? Of planet building episodes?

Current estimates of disk sizes are indirect, and are based on: (1) the size of the YSO wind region required to account for the observed blue-shifted [O I] and [S II] forbidden line emission fluxes; disks must be large enough to occult the receding portion of the stellar wind (Appenzeller *et al.* 1984; Edwards *et al.* 1987) and (2) the projected radiating area required to

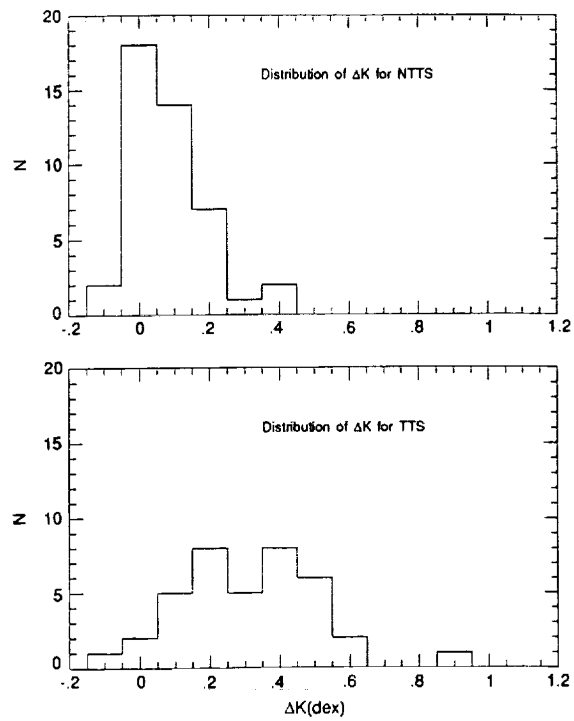

FIGURE 6 The frequency distribution of the near-infrared excess ΔK (see text) for stars with ages $t > 3 \times 10^6$ years and $t \leq 3 \times 10^6$ years. Note that a) nearly 60% of young PMS stars have measurable ($\Delta K > 0.10$) near-infrared excesses and b) that the fraction of PMS stars with such excesses decreases for ages $t \gg 3 \times 10^6$ years. If IR excesses derive from emitting dust embedded in massive, optically thick circumstellar disks surrounding PMS stars, then the fraction of stars surrounded by such disks must decrease with time. Our data suggests that the time scales for evolving from a massive, optically thick disk to a low mass, tenuous disk must range from $\sim 3 \times 10^6$ to 10^7 years. This range represents the best available astrophysical constraint on the time scale for planet building.

explain the observed far-infrared radiation emanating from optically thick, cool dust in the outer disk regions (Myers *et al.* 1987; Adams *et al.* 1987). In both cases, these estimates provide lower limits to the true extent of the disk. Edwards *et al.* (1987) have shown that these independent methods predict comparable lower limit disk size estimates: $r_{disk} > 10$ to 100 AU, for a sample of continuum + emission, T Tauri, and Herbig emission stars. At the distance of the nearest star-forming regions, such disks intercept an angular radius, $r > 0.07$ to 0.7 arc seconds. Thus far, it has proven difficult to image disks of this size from the ground. Decisive information regarding disk isophotal sizes and surface brightnesses must await sensitive imaging with HST, whose stable point spread function and high angular resolution will permit imaging of low-surface brightness circumstellar disks around bright PMS stars. When available, HST measurements of disk sizes will prove an invaluable complement to ground-based sub-mm and mm-continuum measurements which provide strong constraints on the disk *mass*, but which lack the spatial resolution to determine *size*. Together, these data will yield average surface mass densities and estimates of midplane optical depths—critical parameters for modeling the evolution of primitive solar nebulae.

Prior to HST, ground-based observations of the ratio of near- to far-IR excess radiation may provide a qualitative indication of the distribution of material in circumstellar disks. For example, Strom *et al.* (1989) discuss several solar-type PMS stars which show small near-IR excesses compared to far-IR excesses (Figure 5). They suggest that the disks surrounding these stars have developed *central holes* as a first step in their evolution from massive, optically thick structures (such as those surrounding TTS) to tenuous structures (such as those surrounding β Pic and Vega). Such central holes may provide the first observational evidence of planet-building around young stars.

The Disk Environment

High resolution ground-based spectra suggest that energetic winds ($L_{wind} > 0.01\ L_*$; $v \sim 200$ kilometers per second) characterize all TTS and HES (Edwards and Strom 1988). However, mass-loss rates are not well determined: estimates range from 10^{-6} to $10^{-9}\ M_\odot$ per year and are greatly hampered by uncertainties in our knowledge of the wind geometry. The broad, blueshifted, often double-peaked forbidden line profiles of [O I] and [S II] (see Figure 3), suggest that typical TTS and HES winds are not spherically symmetric and may be at least moderately collimated. The models proposed to account for the forbidden line profiles include a) latitude-dependent winds characterized by higher velocities and lower densities in the polar regions, b) sub-arc second, highly collimated polar jets; and c) largely equatorial mass outflows obliquely shocking gas located at the raised surface of a slightly flaring disk (Hartmann and Raymond 1988).

Knowledge of the wind geometry is necessary if we are to derive more accurate estimates of PMS star mass loss rates from [O I] profiles. Depending on their mass loss rate and geometry, PMS star winds may have a profound effect on the survival of gas in circumstellar disks and on the physical and chemical characteristics of the grains:

- Energetic winds can remove gas from the disk during the epoch of planet building, thereby eliminating an essential "raw material" for assembling massive giant planets in the outer disk.
- Exposure of interstellar grains to $\sim$ 1 kev wind particles carried by a wind with M $\sim 10^{-9}$ $M_{\odot}$ per year for times of 10^6 to 10^7 years, can alter the chemical composition of grain mantles. For a grain with a water-ammonia-methane-ice mantle, energetic particle irradiation can in principle: (1) create large quantities of complex organic compounds on grain surface and (2) drastically reduce the grain albedo (Greenberg 1982; Lanzerotti *et al.* 1985; Strazzula 1985). Recent observations of the dust released from the nucleus of comet Halley show these grains to be "black" (albedos of $\sim$ 0.02 to 0.05) and probably rich in organic material (Chyba and Sagan 1987). Does this cometary dust owe its origin to irradiation of grains by the Sun's T Tauri wind during the early lifetime of the primitive solar nebula?

HST will allow us to image low-density, outflowing ionized gas in the light of [O I] λ6300 Å and thus allow us to trace YSO wind morphologies directly. HST observations will determine whether energetic outflows interact with the disk (as opposed to leaving the system in highly collimated polar jets). In combination with improved estimates of mass outflow rates, we can then determine the integrated flux of energetic particles *through the disk* for a sample of PMS objects of differing age and thus assess the role of winds in the evolution of disks.

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