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THE EARLY EVOLUTION OF STARS

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RESUMEN

Este resumen describe las propiedades dentro de objetos estelares jóvenes a medida que evolucionan desde su nacimiento núcleos moleculares densos en rotación, hasta ser estrellas completamente formadas y de pre-secuencia principal. La investigación actual sugiere que la mayoría de la masa que compone una estrella completamente formada cae a la superficie de la estrella desde una envolvente aplanada, (de tamaño $\sim$ varios miles de UA) a través de un disco de acreción circunestelar. Resumimos cálculos actuales de la duración de las fases de caída de la envolvente y del disco de acreción y discutimos las implicaciones de estas escalas de tiempo para la formación de estrellas de distintas masas y de sistemas planetarios.

ABSTRACT

This review outlines the observational properties of young stellar objects as they evolve from their birth within dense rotating molecular cores to fully-formed pre-main sequence stars. Current work suggests that most of the mass which ultimately comprises a fully-formed star is transferred from a flattened infalling envelope (of size $\sim$ several thousand AU) through a circumstellar accretion disk to the stellar surface. We summarize current estimates for the duration of the envelope infall and disk accretion phases and discuss the implication of these timescales for the formation of stars of different mass and of planetary systems.

Key words: **STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

The pioneering infrared observations of E.E. Mendoza V. (1966, 1968) led to the discovery that many optically-visible young stars (T Tauri stars and Herbig Ae/Be stars associated with nebulosity) show evidence of strong infrared emission well in excess of expected photospheric levels. As Mendoza noted, such young stellar objects (YSOs) exhibit infrared spectral energy distributions, $\lambda F_\lambda \sim \lambda^s$, characterized by a wide range of spectral indices, s. He speculated that the excesses arise from heated dust grains surrounding newly-formed stars, and that the spectral index might be indicative of the evolutionary state of a YSO, with the youngest stars exhibiting the steepest (most positive) spectral indices. His observational work, a *tour de force* at the time, coupled with this remarkably prescient suggestion, together represented key steps toward developing our current picture of stellar birth:

- Stars are formed in "cores" of dense, rotating molecular gas and dust;
- The low angular momentum material in the core collapses to form a central protostellar "seed", while the high angular momentum core material forms a flattened, infalling envelope of gas and dust which begins to to build and feed an accretion disk which surrounds the central object (see Shu, Adams, & Lizano 1987).
- A star is assembled as material is transferred from the infalling envelope, to the accretion disk and finally to the surface of the central protostellar "seed".
- A star is fully formed when the infall/accretion phase is terminated, either via (1) accretion (or dispersal) of all envelope and disk material; and/or (2) assembly of disk material into a planetary system.

This review will summarize the observational evidence which supports this picture, along with current estimates of the duration of the envelope infall and disk accretion phases for stars of different mass. These estimates provide both insight into the conditions which control the formation of high and low mass stars, and a constraint on the timescales available for assembling disk material into planetesimals.

2. EARLY STELLAR EVOLUTION: AN EMPIRICAL SEQUENCE

Over the past decade, surveys of star-forming complexes using emission lines arising from density-sensitive molecular species, along with *IRAS* and ground-based infrared surveys in combination provide the empirical basis for understanding and modeling the early phases of stellar evolution. Beichmann et al. (1986) and Myers et al. (1987) show that:

• Optically-invisible infrared sources are located near the centers of dense, rotating (Goodman et al. 1993) molecular cores traced by NH_3 and CS.

• Optically-visible stars with infrared excesses are often found within core, but are typically located well away from the center. Quantitatively, an infrared spectral index defined as

$$s \;=\; log\, [25\; F\; (25\; \mu)\; /\; 2.2\; F\; (2.2\; \mu)]$$

is largest ($s\ \sim 2$) for stars located near the geometrical center of the core and decreases to $s\ \sim -1$ for stars located further from the core center;

• Young stars located near to, but outside the boundaries of molecular clouds rarely exhibit measurable infrared excesses (e.g., Walter et al. 1988).

Optically-obscured infrared sources located near the center of molecular cores are presumed to represent objects just forming from collapsing molecular material. Their steep ($s > 0$) spectral indices suggest that they are surrounded by optically-opaque infalling envelopes and circumstellar accretion disks (see § 3). Optically-visible stars with infrared spectral indices $s \sim -1$, appear to be older stars whose peculiar motions have carried them away from their birthplaces. While still surrounded by accretion disks, the mass contained in their infalling envelopes (and thus the envelope optical depth) has diminished significantly (see § 4.1). Young, optically-visible stars which lie outside molecular cloud boundaries and which no longer show evidence of infrared excesses indicative of either infall or accretion, are presumably fully-formed stars. The general character of these evolution-driven changes in the IR spectral properties of YSOs were anticipated by Mendoza more than 25 years ago.

3. OPTICALLY-OBSCURED YSOs

3.1. Observations and Recent Modeling

Modern theoretical models of collapsing, rotating molecular cores (for example, Tereby, Shu, & Cassen 1984; Adams & Shu 1986; Shu, Adams, & Lizano 1987) all predict the formation of a star-accretion disk system surrounded by an optically-opaque, flattened envelope of infalling gas and dust. The spectral energy distributions of star-disk-envelope systems during their early evolutionary phases are determined by transfer of radiation from the central star-disk "source" through the much larger, optically-opaque infalling envelope. Adams & Shu (1986), and Adams, Lada, & Shu (1987) were the first to model the spectral energy distributions expected for such objects, and were quite successful in accounting for the general character of the flat or rising infrared spectra characteristic of optically-invisible infrared sources embedded within their parent cores. More recently, Kenyon et al. (1993a) have predicted spectral energy distributions for star-disk-envelope models which (1) have envelope density distributions of the form predicted from the rotationally-flattened infall solutions computed by Tereby, Shu, & Cassen (1984), and (2) in which the infall rate (which controls the envelope optical depth and thus the wavelength of maximum emission) is varied over 2 orders of magnitude. Kenyon et al. (1993a) compare their predicted spectral energy distributions with those observed for 21 optically-obscured YSOs in Taurus-Auriga having source luminosities $0.1 < L/L_{\odot} < 10$, and thus masses, $0.1 < M/M_{\odot} < 1.5$ within a factor of 3, $\dot{M}_{infall} \sim 4 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ for this sample. The envelope infall rates derived by Kenyon et al. (1993a) are in remarkably good agreement with theoretical estimates for thermally supported molecular cores with $T \sim 10$ K (Shu 1977), typical of the molecular core temperatures derived by Myers & Benson (1983) in Taurus-Auriga. Hence it appears as if solar-mass stars may form from thermally-supported cores having relatively low kinetic temperatures. Unfortunately, the Kenyon et al. (1993a) study did not include sources of higher luminosity and thus possibly higher mass, and therefore cannot provide the basis for comparing envelope infall rates for high and low mass stars. However, high mass stars exhibit detectable infrared excesses for times much shorter (typically 10% or less) than those typical of solar-type stars. This result implies that the envelope infall rates during the time that high mass stars are assembled may be as much as 10 times higher. If so, then the effective temperatures of the cores may also be higher (see Myers & Fuller 1993).

Dusty infalling envelopes produce not only strong mid- and far- infrared emission arising from grains embedded within the envelope and heated by the central star-disk source, but near-infrared reflection nebulae, produced as star-disk light is *scattered* by envelope grains as well. An example is provided by the well-known source, L1551 IRS 5, which at a wavelength of 2.2 μ has the appearance of a diffuse, flattened reflection nebula of dimension $\sim$ 1000 AU. The illuminating source is obscured by dust most likely located in the equatorial plane of an infalling, protostellar envelope surrounding the source (Strom et al. 1985; Campbell et al. 1988; Hodapp et al. 1988; Butner et al. 1991). Kenyon et al. (1993b) have used a Monte Carlo radiative transfer code to predict the scattered-light patterns and near-infrared colors expected for star-disk systems surrounded by infalling envelopes characterized by the geometries and density distributions predicted by Tereby et al. (1984), and a variety of assumed envelope infall rates and source inclinations. Comparison of the Kenyon et al. (1993b) simulations with scattered-light patterns and surface brightness distributions observed for optically-obscured solar-type YSOs in Taurus-Auriga again lead to "best-fit" infall rates 2 x 10^{-6} $M_\odot$ yr^{-1} $<$ $\dot{M}_{infall}$ $<$ 10 x 10^{-6} $M_\odot$ yr^{-1}.

According to Kenyon et al. (1993b), matching the range of near-infrared colors ($J-H$ and $H-K$) observed for embedded YSOs in Taurus-Auriga requires not only the flattened envelope geometries predicted by Tereby et al. (1984), but in addition, an evacuated cone centered on the rotational axis of the infalling envelope. Such "polar holes" might be produced naturally by a collimated, bi-polar mass outflow which emerges along the rotational axis of the star-disk-envelope system, and sweeps out the envelope material along its path. Indeed, molecular line observations of the environs of optically-obscured YSOs whose spectral energy distributions suggest the presence of infalling envelopes, invariably show a velocity pattern indicative of ambient material accelerated and swept up by bipolar winds. These winds are believed to be driven by processes related to accretion of material through a circumstellar disk and characterize all YSOs from the time just after birth when they are visible only at far-infrared and sub-millimeter wavelengths, until the end of the disk accretion phase (e.g., Edwards, Ray, & Mundt 1993).

3.2. Evolutionary Timescales

As the star-disk-envelope system evolves, the material in the envelope is (1) depleted via infall onto the star-disk system, and (2) removed along the envelope rotational axis by collimated energetic winds powered by the disk accretion process. As a result, the envelope optical depth decreases (most rapidly along the poles; less rapidly in the equatorial plane) until the star-disk system is revealed first at near-infrared, and later at optical wavelengths. During this phase, the excess mid- and far- infrared emission which originates in the infalling envelope decreases in proportion to the envelope optical depth.

The length of time that a forming star spends obscured by an optically-opaque infalling envelope can be estimated from (1) the relative number of optically-invisible and optically-visible YSOs observed among an infrared-selected sample of stars which exhibit excess infrared emission; and (2) the average age of an optically-visible star which exhibits an infrared excess as determined derived from its location in the HR diagram (see Myers et al. 1987; Kenyon et al. 1990). In Taurus-Auriga, the number of optically-invisible YSOs is approximately 10 – 20 % of the number of optically-visible T Tauri stars (approximate age, t $\sim$ 1 Myr), thus leading to t_{infall} $\sim$ 0.1 – 0.2 Myr for the envelope infall phase for stars in the mass range 0.1 $<$ $M/M_\odot$ $<$1.5. The duration of the envelope infall phase for more massive stars has not been well established, both because such stars are relatively rare, and because the infall/disk accretion phase may be considerably shorter for such stars (see § 4.2).

4. OPTICALLY-VISIBLE PRE-MAIN SEQUENCE STARS

4.1. Observations and Recent Modeling

YSOs which lie on the earthward side of their parent molecular clouds and cores, and which can be viewed along the polar axes of their infalling envelopes, will be the first to become visible optically. HL Tau appears to be an example of such a favorably-oriented, and thus optically-visible YSO which is located well away from its parent molecular core, and is just emerging from its optically-opaque infalling envelope. It exhibits (1) significant near-infrared (λ $<$ 3 μ) excess emission and an infrared spectral energy distribution which rises steeply from $\sim$ 3μ toward longer wavelengths. These observations suggest the presence of heated dust located both (a) within a circumstellar accretion disk (which dominates the near-IR emission from the system), and (b) in a flattened infalling envelope (which dominates the mid- and far- IR emission); (2) an *optical* scattered-light and polarization pattern suggestive of a star-disk-flattened envelope structure with a polar cavity (Grasdalen et al. 1984; Beckwith et al. 1984; Kenyon et al. 1993a, b) and viewed within 20° to 30° of the polar axis; (3) a stellar jet indicative of a highly collimated outflow emerging along the polar axis of the star-disk-envelope system (Mundt & Fried 1983); (4) kinematic evidence of envelope infall provided by redshifted molecular absorption lines viewed against the stellar photosphere; the inferred mass infall rate is $\dot{M}_{infall} \sim 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Grasdalen et al. 1989); (5) optical evidence of energy released as material accreted through the circumstellar accretion disk is channeled toward the stellar surface along magnetospheric loops and arrives on the photosphere at free-fall velocity; the accretion rate deduced from the excess optical luminosity produced by this "boundary layer" emission is $\dot{M}_{acc} \sim 0.5 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$. The favorable location and orientation of HL Tau thus provides us with a nearby "case study" of a YSO in transition between the optically-obscured infall phase, and the phase when disk accretion rather than envelope infall dominates the observed infrared spectral energy distribution. Further detailed study of HL Tau and its analogs offers the promise of deeper understanding of the major physical processes which dominate the optically-obscured infall phase: (1) envelope infall; (2) rapid disk accretion and associated strong boundary layer emission; and (3) highly-collimated, energetic mass outflow.

As the mass of material in the infalling envelope surrounding the YSO decreases further still, all star-disk systems are eventually revealed optically. At the same time, the excess infrared emission from the envelope (which dominates emission at long wavelengths) decreases as well. The observed spectral index, s, for optically-visible stars, is thus expected to approach the value characteristic of an optically thick, geometrically-thin accretion disk: $s = -4/3$. Indeed, most optically-visible YSOs that exhibit infrared excesses (T Tauri stars and Herbig Ae/Be stars) show infrared spectral energy distributions with $-4/3 < s < 0$, which suggests that most of the excess infrared emission in such YSOs arises in a circumstellar accretion disk. By the time the IR spectrum of a YSO becomes disk —as opposed to envelope— dominated, the YSO is typically located at a distance of several core radii from the center of its parent molecular core.

High spectral resolution observations of optically-revealed YSOs enable reliable estimates of accretion luminosity (and thus disk accretion rates). Such spectra can diagnose and accurately measure excess optical continuum emission produced in a "boundary layer" (or more accurately in multiple "boundary spots") as material passing through the accretion disk lands at highly supersonic speeds on the stellar surface, releases its kinetic energy and locally heats the photosphere. The featureless continuum radiation produced in the hot boundary layer when added to the photospheric spectrum, acts to decrease the residual intensity of individual photospheric absorption features, producing a spectrum which appears washed-out or "veiled" (Joy 1945; Hartigan et al. 1990, 1991; Bertout, Basri, & Bouvier 1988; Bertout 1989). Quantitative measurements of "spectral veiling" provide far less ambiguous estimates of accretion luminosity than do measurements of excess infrared emission, which can include contributions not only from grains heated viscously in an accretion disk, but from grains located both in and above the disk and heated radiatively by the central star. Hartigan et al. (1991) derive spectral energy distributions for the excess optical emission for T Tauri stars by dividing high resolution echelle spectrograms of these stars by those of standard stars of identical spectral type; the ratio provides a measure of the excess optical emission required to account for the decreased residual intensity of photospheric absorption features. In turn, estimates of excess optical emission as a function of wavelength enable determination of both the temperature and thus the bolometric luminosity of the excess optical continuum radiation. These measurements thus yield an estimate of the accretion luminosity, L_{acc}, which in turn is related directly to the accretion rate: $L_{acc} = 1/2\ G\ M_{\odot}\ \dot{M}_{acc}/R_*$.

Bertout et al. (1988), Hartmann & Kenyon (1990) and Hartigan et al. (1991) use this procedure to derive disk accretion rates for solar type ($0.1 < M/M_{\odot} < 1.5$) pre-main sequence stars: $10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1} < \dot{M}_{acc} < 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$. A "typical" steady-state value is $10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$. Over the range of disk lifetimes characteristic of solar-type pre-main sequence stars, $t_{disk} \sim 1 - 5$ Myr, between 0.1 and 0.5 $M_{\odot}$ can thus be added to the central star via steady-state accretion of material through the disk. A comparable amount of material may in fact be added during transient ($t \sim 100$ yr) phases of elevated accretion (FU Orionis events during which disk accretion rates, $\dot{M}_{acc}$ can reach values as large as $10^{-4}\ M_{\odot}\ \mathrm{yr}^{-1}$; Hartmann & Kenyon 1987; Kenyon, Hartmann, & Hewitt 1988; Hartmann et al. 1989). Solar-type PMS stars may experience 10 to 20 such events during their disk-envelope evolutionary phases, and thus may accrete an additional 0.1 to 0.2 $M_{\odot}$ during FU Ori outbursts. *Hence, most of the material comprising a solar-type star must pass through a circumstellar accretion disk.* Indeed, the steady-state disk accretion rates estimated for solar-type stars suggest that even optically-visible PMS stars are still gaining significant mass from material passing through an accretion disk. Since "instantaneous" disk masses derived from mm-continuum measurements of both embedded and optically-visible solar-type YSOs are typically $M_{disk} \sim 0.1\ M_{\odot}$ (Beckwith et al. 1990), until the final phases of disk accretion (when the "last" $\sim 0.1\ M_{\odot}$ is accreted or assembled into larger bodies), accretion disk must be fed continuously by material stored in a larger and more massive, flattened infalling envelope.

For stars with masses $M > 1.5\ M_{\odot}$, disk accretion rates cannot be estimated directly from measurement of boundary layer emission. Indeed, such objects appear to lack measureable excess emission at optical or near ultraviolet wavelengths (Hartmann, Kenyon, & Calvet 1993). The infrared excesses derived for more massive stars imply accretion rates which could be 10 to 100 times higher than those characterizing their lower mass analogs (Hillenbrand et al. 1992). However, infrared excesses in young massive stars reflect not only contributions from viscously heated grains contained within disk, but from (1) heated micron-size disk and envelope grains in radiative equilibrium with the stellar radiation field, and (2) transiently heated smaller particles and molecular complexes which are excited by the copious ultraviolet radiation emitted by these stars (Natta 1994; Hartmann, Kenyon, & Calvet 1993). Consequently, estimates of accretion luminosities (and thus mass accretion rates) based on infrared excesses are problematical at present. However, if high mass stars are also built largely from material which passes through disks, and if their disk lifetimes are as short as 0.1 Myr (see § 4.2), time-averaged disk accretion rates must be large ($\dot{M}_{acc} \sim 1\ M_{\odot}$ / 0.1 Myr $\sim\ 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$).

4.2. Evolutionary Timescales

The duration of the disk accretion phase (and thus the timescale to fully assemble a star) is estimated by determining the fraction of young stars surrounded by accretion disks as a function of stellar age. Establishing the presence of an accretion disk *definitively* requires spectroscopic and photometric measurements of several indicators of disk accretion: optical excess emission arising from boundary layer emission; forbidden line emission arising in accretion-driven winds; hydrogen line emission arising in accretion columns; infrared excess emission (Edwards et al. 1993). However, careful study of a selection of nearby solar-type YSOs suggests that solar-type stars which show significant excess infrared emission above photospheric levels typically exhibit all other accretion signatures. Hence, the presence or absence of a cirumstellar accretion disk can be inferred with considerable confidence by determining whether a star shows an infrared excess or normal photospheric colors.

Over the past five years, infrared and optical surveys of solar-type pre-main sequence stars in nearby star-forming regions have provided accurate measurements of infrared excess emission at $\lambda < 3.5\ \mu$ for several hundred stars. For young (ages t < 3 Myr) optically-visible stars in the mass range $0.2 < M/M_{\odot} < 1.5$, approximately 50% show evidence of significant near-infrared excesses. Among this sample, some stars which show no evidence of excess emission appear to be as young as 0.3 Myr. For older stars (ages 3 < t < 10 Myr), only 10% show evidence of excess infrared emission (Strom et al. 1989). No stars older than 10 Myr in this mass range exhibit infrared excesses (Strom, Edwards, & Skrutskie 1993; Dutkevitch et al. 1994). These results suggest that for solar-type stars, disk accretion can persist for as long as 10 Myr or be terminated at ages 0.3 Myr or less.

Surveys aimed at diagnosing infrared excess emission among young, higher mass optically visible stars suggest that for stars with $M > 3\ M_{\odot}$, accretion disks survive for much shorter times, t << 1 Myr. From their study of the young cluster NGC 6611, Hillenbrand et al. (1993) argue that among a sample of optically-visible pre-main sequence stars with masses 3–5 $M_{\odot}$ and ages t ~ 0.1–0.2 Myr, only 10% show evidence of significant excess infrared emission. This result suggests that the disk accretion (and the envelope infall) phase lasts no more than 0.1 Myr for a typical high mass star. If so, the envelope infall and disk accretion rates must be large ($\dot{M}_{acc}$, $\dot{M}_{infall} > 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$).

5. IMPLICATIONS FOR PLANET BUILDING

The timescales for accretion disk survival summarized in section 4.2 provide an important astronomical constraint on the time available for planet building. During the time that young stars show evidence of measurable near-infrared excesses, mm-continuum measurements suggest that their disks appear to contain material in quantity at least *sufficient* to build a solar system ($M_{disk} > 0.01\ M_{\odot}$; Beckwith et al. 1990; Hillenbrand et al. 1992; Weintraub, Sandell, & Duncan 1989). When near-infrared excesses are no longer measurable, the observed mm-continuum fluxes suggest the absence of heated micron-sized dust at a level $M_{disk} << 0.01\ M_{\odot}$.

Near-infrared surveys of both solar-type and high mass young stars are sufficiently sensitive to detect as little as $\sim 10^{-20}$ gm (the mass of an asteroid!) of micron-size circumstellar dust provided that such dust distributed throughout in the inner (r < 0.1 AU) of a circumstellar disk where it can be heated to temperatures T ~ 1000 K. The absence of significant excess infrared emission at ages t > 0.1 Myr for stars with $M > 3\ M_{\odot}$, and at ages t > 10 Myr for lower mass stars argues that either (1) on these timescales, micron size grains have been thoroughly "cleaned" from circumstellar disks which originally contained $M_{disk} > 0.01\ M_{\odot}$; or (2) that such grains have been assembled into larger bodies, thus reducing the effective radiating area of solid material and consquently the excess infrared radiation.

Evidence that larger bodies may in fact have been built in disks is provided by observations of β Pictoris and a large number of analogous intermediate mass stars. This A-type main sequence star has an estimated age t $\sim$ 100 Myr, and yet shows evidence of both (1) a measurable infrared excess, consistent with an asteroid mass of micron-size dust distributed over a disk of dimension 1 000 AU, and (2) a disk-like structure manifest in scattered visible light (e.g., Backman & Gillett 1988). The presence of a disk surrounding a star of this age requires that the micron-size dust be replenished. Lacking a source of such dust, micron-size grains will spiral inward through the disk in response to the Poynting-Robertson effect, and reach the surface of the star on timescale t $<< 10^5$ yr. The most likely mechanism for replenishing the population of micron-size grains is collisions between larger bodies, analogous to the collisions which are believed to have occurred during the period of "maximum bombardment" responsible for the cratering manifest on the Lunar surface and on other bodies throughout the solar system.

The mass of β Pic is $\sim 2\ M_{\odot}$. From the statistics summarized in § 4.2, its circumstellar accretion disk could not have survived for much more than 1 Myr. Hence, agglomeration of micron-size grains to form entities of size much larger than 1 micron must have taken place on a timescale t $<$ 1 Myr. Hence, the chain of events that ultimately leads to formation of larger grains and possibly planetesimals, must have been initiated no more than 1 Myr from the time that β Pic began to collapse within its natal core. The fact that intermediate mass stars such as β Pic can apparently assemble micron-size grains into larger bodies on relatively short timescales suggests that in stars like the sun, where the pace of disk evolution is more modest, formation of large bodies should not have been a challenge to nature.

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