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INITIAL FREQUENCY, LIFETIME AND EVOLUTION OF YSO DISKS

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RESUMEN

Las imágenes infrarrojas de cúmulos profundamente inmersos en núcleos moleculares suministran una nueva información sobre la frecuencia a la que se encuentran los discos circunestelares de acrecimiento alrededor de estrellas muy jóvenes en el rango $0.1 < M_{\odot} < 1$. Para edades t << 10^6 años, la fracción de estrellas rodeadas de discos en ese rango de masas se aproxima al 100%. A través de fotometría infrarroja, se encuentra que las estrellas con masas M > 2 $M_{\odot}$ y edades t ~ 1–3 10^6 años, no muestran evidencias de un exceso infrarrojo suficiente que indique la presencia de discos circunestelares de acrecimiento. Sin embargo, para estrellas con M < 0.5 $M_{\odot}$, los discos de acrecimiento pueden perdurar más de 10^7 años. Con las nuevas técnicas, existen expectativas de llegar a conocer la evolución de los discos más allá de la fase de acrecimiento.

ABSTRACT

Infrared imaging of embedded clusters provides new information on the frequency with which circumstellar accretion disks are found around extremely young stars spanning the mass range $0.1 < M_{\odot} < 1$: at ages t << 1 Myr, the fraction of stars in this mass range surrounded by disks approaches 100%.

Infrared photometric surveys of optically-revealed young stellar clusters and associations provide important new constraints on the lifetimes of circumstellar disks surrounding stars of differing mass. By an age t ~ 1 Myr, stars with masses M > 2 $M_{\odot}$ show no evidence of infrared excesses of a magnitude consistent with the presence of circumstellar accretion disks. However, for stars with M < 0.5 $M_{\odot}$, accretion disks may persist for ages in excess of 10 Myr.

New techniques promise major advances in our ability to trace the evolution of disks beyond the accretion phase. ISO should have sufficient sensitivity in the mid- and far- infrared to detect (1) emission from the outer regions of disks in transition between massive (M >> 0.01 $M_{\odot}$), optically thick accretion disks and post-accretion structures; and (2) emission from "secondary" disks, analogous to that surrounding β Pictoris. The recent discovery of small (100 < r < 1000 AU) regions of ionized gas surrounding young, low mass stars located in clusters associated with O stars may provide another tool for identifying candidate post-accretion disks. Recent observations suggest that although these regions in most cases appear to be alternative "signposts" for accretion disks manifest as well through their infrared signatures, some appear to be associated with pre-main sequence stars which lack near-infrared excesses. Stars in this latter group may be surrounded by gas-dominated disks, in which nearly all solid material is in the form of bodies much larger than micron-size grains.

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

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1. INTRODUCTION

Our current paradigm holds that stars form within cold, rotating "cores" of dense molecular gas and dust embedded within much larger, lower density molecular clouds. When self-gravity overwhelms internal pressure forces, the core begins to collapse. Low angular momentum material collapses first, creating a central protostellar "seed," while higher angular momentum material rains in later, forming a flattened, optically-opaque infalling envelope of gas and dust which builds, and then feeds an accretion disk surrounding the central object (for example, Tereby, Shu, & Cassen 1984; Adams & Shu 1986; Shu, Adams, & Lizano 1987). Most (> 50%) of the star's ultimate mass is comprised of material transferred from the infalling envelope through the accretion disk, onto the surface of the protostellar "seed" (Kenyon 1995; Hartmann, Kenyon, & Hartigan 1993; Strom, Edwards, & Skrutskie 1993). During the final stages of stellar buildup, the envelope optical depth decreases, rendering the star and its surrounding accretion disk visible at optical wavelengths.

In the context of this paradigm, the youngest optically-visible pre-main sequence stars should show evidence of circumstellar accretion disks and perhaps of optically thin, remnant infalling envelopes. However, observations reveal that among optically-visible solar-type PMS stars ($M < 1\ M_{\odot}$) with ages $t < 1$ Myr, only ~50% exhibit the optical and infrared signatures diagnostic of accretion disks and remnant envelopes (e.g. Strom et al. 1989; Beckwith et al. 1989; Edwards, Ray, & Mundt 1993); among higher mass, optically-visible PMS stars of comparable age, the fraction is even lower (< 10%; Strom 1972; Hillenbrand et al. 1993; Strom 1994). Does the absence of accretion disk signatures for a significant number of the youngest, optically-visible PMS stars indicate a fundamental weakness in our understanding of how stars form and reach their ultimate masses, or does it instead suggest that in many cases the era of stellar buildup (through envelope infall and disk accretion) terminates well prior to the emergence of a newly-formed star from within its parent molecular cloud?

There are two observational approaches to answering this question. The first is to examine samples of pre-main sequence stars much younger than heretofore observed in order to establish whether the fraction of forming stars which show accretion disk signatures is higher at earlier evolutionary phases. The second is to study apparently "diskless" pre-main sequence stars more closely and/or with new techniques to establish whether these stars are surrounded by "fossil" disks, whose presence would strongly suggest the likelihood of an earlier disk accretion phase. Detecting and characterizing such fossil disks might also provide important new insight into the sequence and duration of critical stages leading to solar system formation.

In this review, our goals are:

- to establish the fraction of stars surrounded initially by accretion disks from infrared observations of extremely young clusters still deeply embedded within their parent molecular clouds;
- to determine the range in accretion disk lifetimes for stars of differing mass from observation of the fraction of optically-visible PMS stars which show disk signatures as a function of age;
- to seek evidence of "fossil" post-accretion disks, from (1) sensitive infrared searches for emission arising from small dust grains embedded within optically thin disks; and (2) searches for gas-dominated disks which show no evidence of dust emission arising from heated micron-size grains.

2. ACCRETION DISK SIGNATURES

Achieving the first two of our goals requires observational diagnostics which (1) can establish the presence of circumstellar accretion disks with minimal ambiguity; and (2) enable study of large samples young, pre-main sequence stars, including stars which are still embedded within their natal cores and/or parent molecular clouds.

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 arising from viscously heated dust embedded within the disk (Edwards et al. 1993). Careful study of a selection of nearby, optically-visible solar-type YSOs suggests that stars which show significant excess near-infrared emission ($\lambda < 5\ \mu$) above photospheric levels typically exhibit all other accretion signatures. Hence, among optically-visible YSOs, *the presence or absence of a circumstellar accretion disk can be inferred with considerable confidence by determining whether a star shows a near-infrared excess or normal photospheric colors.*

For optically-visible YSOs, the presence of near-infrared excess emission can be determined from reddening-corrected broad-band photometric indices and an observed spectral type. Unfortunately, this procedure cannot be applied in the case of optically-invisible YSOs, where to date, accurate spectral types are available in only a few cases. Hence, although near-IR spectroscopic studies soon promise to provide spectral types for large

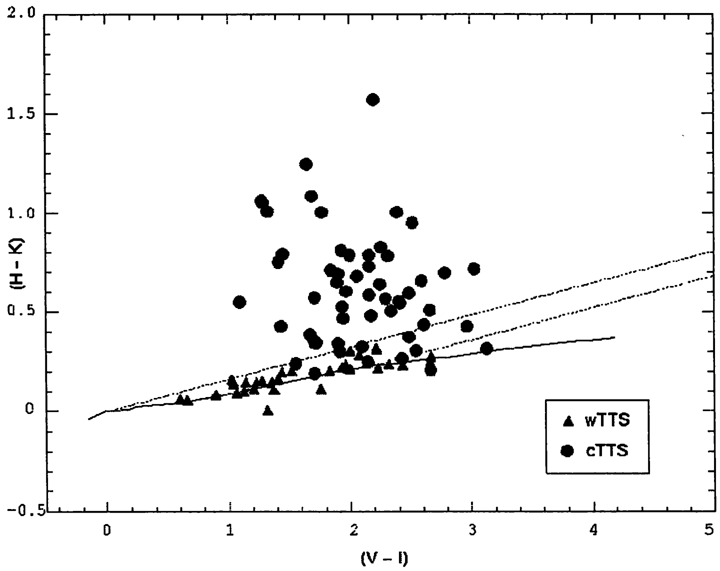

Fig. 1.— A (V-I)/(H-K) color-color diagram for a sample of classical (cTTS) and weak T Tauri (wTTS) stars in Taurus-Auriga. Superposed on the diagram is the relationship for unreddened dwarf stars along with interstellar reddening vectors (dotted lines) extending from the the locations of an A0 and M0 star. Among a sample of 50 cTTS with optical accretion signatures, 40 (80%) lie outside the interstellar reddening vectors and thus show unambiguous evidence (H-K indices exceeding reddened photospheric values) of near-infrared excess emission, presumably arising in the inner regions an optically thick circumstellar accretion disk. The wTTS, which show no optical accretion signatures also show no excess near-infrared emission.

numbers of embedded YSOs (see Casali & Eiroa 1995, Meyer 1995, for example), at present we must depend on photometric indices alone in order to diagnose near-infrared excess emission.

Color-color diagrams which combine a pair of indices – one dominated by photospheric emission, the other by infrared emission arising from a disk – provide the most useful tool for estimating the fraction of stars surrounded by accretion disks among a large population of young stellar objects. Two particularly efficacious color-color diagrams are shown in Figures 1 and 2. In both the (V-I)/(H-K) plane (useful in diagnosing accretion disks among stars just emerging from their natal cores; Figure 1) and the (J-H)/(H-K) plane (useful for diagnosing disks among optically-obscured YSOs; Figure 2) diagrams, a large fraction of those stars which show evidence of optical accretion signatures also show infrared excess emission large enough to enable to distinguish these objects from reddened main sequence and giant branch stars, and from PMS stars which lack accretion disks. However, not all stars which exhibit optical accretion signatures show infrared excesses in these diagrams. In particular, those stars surrounded by accretion disks that are viewed nearly equator-on, or have inner disk "holes" with dimension $r > 5\ R_*$ (Hillenbrand et al. 1995, poster session in these Proceedings) have infrared excesses small enough to place them within the interstellar reddening vectors, thus rendering them indistinguishable from diskless field or PMS stars. This difficulty can be avoided by making use of the (H-K)/(K-L) plane, in which all stars which show optical accretion signatures also show measurable infrared excesses. General use of this latter diagram as a disk diagnostic, however, awaits the general availability of large format InSb array detectors.

Table 1 summarizes the fraction of classical T Tauri stars (all of which show optical accretion signatures), which lie outside the reddening vectors in the indicated color-color plane, and thus have excess near-infrared emission consistent with that expected from optically-thick circumstellar accretion disks (e.g. Lada & Adams 1992). Disk fractions among fully or partially embedded populations of YSOs can be estimated from photometric observations by multiplying the observed percentage of stars which lie outside the reddening vectors in a given color-color plane by the reciprocal of the percentages listed in Table 1.

We caution that among optically-invisible YSOs, many of which may still be surrounded by infalling envelopes, the presence of a near-infrared excess in (H-K) or (K-L) could diagnose contributions not only from

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heated dust embedded within an accretion disk, but within the inner regions of an infalling envelope. However, (1) because *near*-infrared excess emission must arise from relatively warm dust located within 0.05 – 0.5 AU of the stellar surface; and (2) because such envelopes should not penetrate within the disk centrifugal radius ($10 < r < 100$ AU; Tereby, Shu, & Cassen 1984), it is likely that disk emission dominates. Observation of independent accretion indicators (e.g. infrared forbidden line and hydrogen line emission which provide diagnostics analogous to [O I] and Hα) for a large sample of optically-visible and later, embedded YSOs will be required in order to confirm the presumption that near-IR excess emission indeed provides a robust accretion disk diagnostic among optically-invisible stars.

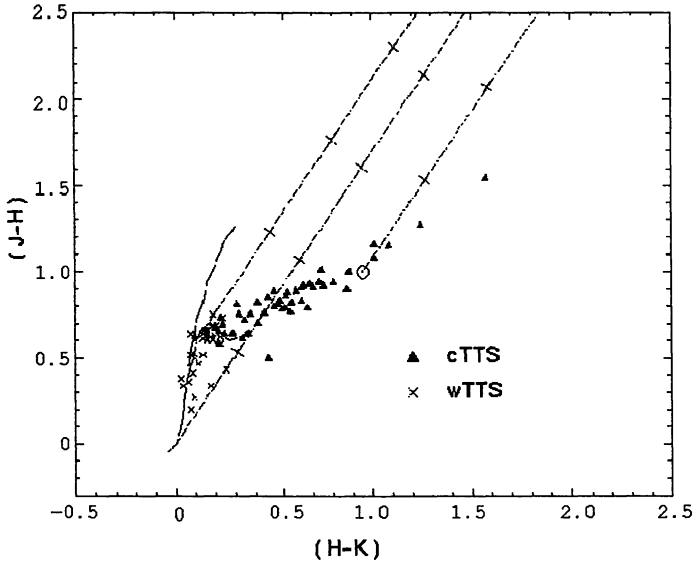

Fig. 2.— A (J-H)/(H-K) color-color diagram for a sample of cTTS and wTTS stars in Taurus-Auriga. Superposed on the diagram are the relationships for unreddened dwarf and giant stars along with interstellar reddening vectors (leftmost pair of dashed lines) extending from the extrema of the dwarf relationship. Also superposed on the diagram (rightmost dashed line) is a vector extending from the most extreme color (open circle) predicted for a flat, optically thick, accretion-dominated disk. Stars lying to the right of this line must have additional sources of excess near-infrared emission. Among a sample of 48 cTTS with primary optical accretion signatures, 30 (63%) lie outside the interstellar reddening vectors and thus show unambiguous evidence (H-K indices exceeding reddened photospheric values) of near-infrared excess emission, presumably arising in the inner regions ($r < 0.1$ AU) of an optically thick circumstellar accretion disk. The wTTS, which show no evidence of optical accretion signatures also show no evidence of excess near-infrared emission.

Table 1

Fraction of Disks Identified in Various Color-Color Planes

Plane	Percent Identified
(J-H)/(H-K)	63%
(V-I)/(H-K)	80%
(H-K)/(K-L)	100%

3. ACCRETION DISK FREQUENCIES AMONG EXTREMELY YOUNG YSOs

As noted in the Introduction, published estimates of disk frequencies have thus far been based on observations of optically-visible samples of young stellar objects whose ages typically span the range 1 to 3 Myr. Our goal here is to estimate disk frequencies at much earlier evolutionary phases. To do this, we have carried out deep near-infrared imaging (JHK) surveys for three relatively nearby star-forming regions which contain optically-obscured aggregates of young stellar objects: (1) aggregates located within 3 dense molecular cores in the Ophiuchus star-forming complex (Strom, Kepner, & Strom 1995); (2) the infrared cluster associated with NGC 2024 in the Orion B cloud (Lada 1992; Meyer 1995); and (3) the infrared cluster centered on the molecular outflow sources in the Mon R2 association (Dougados et al. 1995). Our approach implicitly assumes that because most YSOs in these three regions are optically-obscured, they are on average younger than those located in star-forming regions whose population is dominated by optically-visible objects. While plausible, this assumption must be verified by determining ages for a representative sample of embedded YSOs from their location in the (L, T_{eff}) plane; this step awaits accurate spectral types from near-infrared spectra.

We present in Figures 3, 4 and 5 respectively, the (J-H)/(H-K) diagrams for the Ophiuchus cores, NGC 2024, and Mon R2.

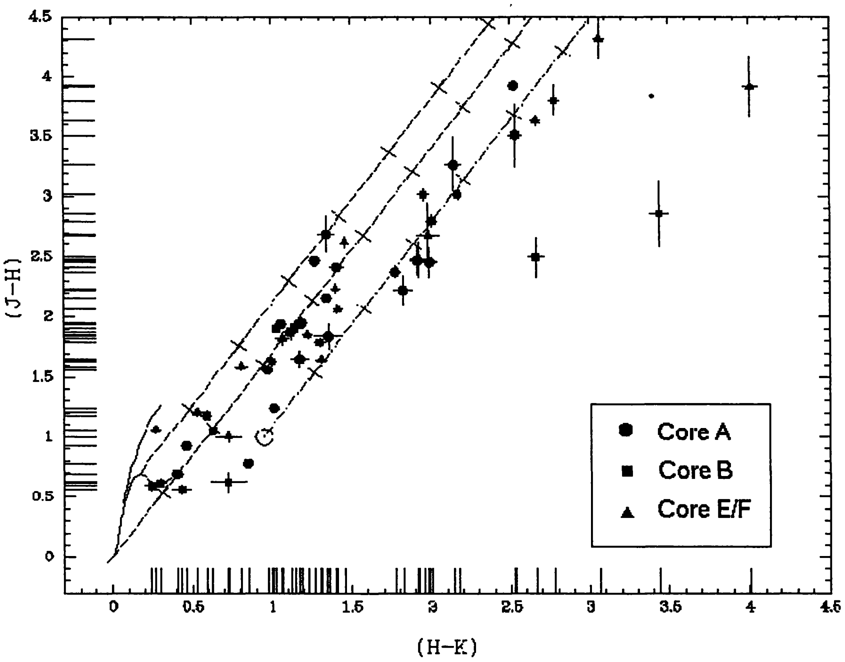

Fig. 3.— A (J-H)/(H-K) diagram in which we indicate the location of YSOs contained within the stellar aggregates associated with molecular cores A, B, and E/F in in the Ophiuchus star-forming complex (Strom et al. 1995). The two left-most dashed lines represent reddening vectors extending from the extrema of the domain occupied by unreddened dwarf stars. The right-most dashed line extends from a point corresponding to the most extreme color expected for a flat, optically thick accretion-dominated disk.

Table 2
Disk Fractions Inferred for Embedded Clusters

Cluster	fraction outside reddening vector	inferred disk percentage	mass range
Ophiuchus	34/49	100%	0.1 – 3.0 $M_\odot$
NGC 2024	41/60	100%	0.2 – 3.0 $M_\odot$
Mon R2	50/80	100%	0.1 – 0.5 $M_\odot$
Mon R2	21/38	88%	0.5 – 1.0 $M_\odot$
Mon R2	10/25	64%	1.0 – 2.5 $M_\odot$

We list in Table 2 the observed percentages of stars located rightward of the reddening vectors in the (J-H)/(H-K) plane, the inferred disk frequencies (using the correction factors from Table 1), and the approximate range of stellar masses spanned by the sample. The latter are derived from reddening-corrected J-band luminosities and the methods outlined in Strom et al. (1995) and Meyer (1995). *For all three embedded clusters, the inferred disk frequency among the stars represented in these samples approaches 100%.*

The results for the Mon R2 cluster summarized in Table 2 suggest (based on small number statistics) that the fraction of stars which exhibit near-infrared excesses may decrease with increasing parent star mass. If this

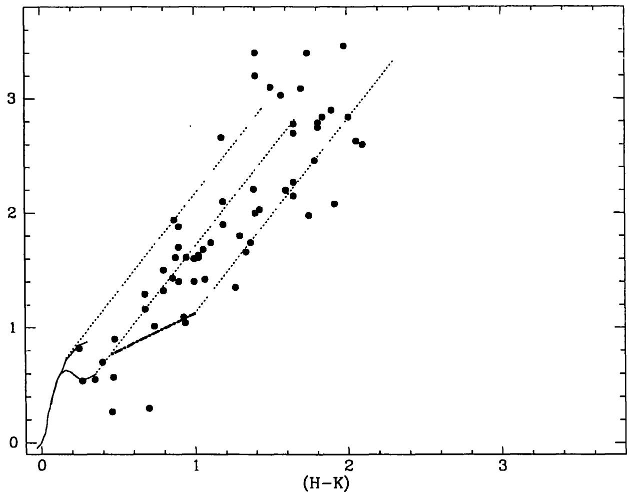

Fig. 4.— A (J-H)/(H-K) diagram for the embedded stellar cluster associated with NGC 2024.

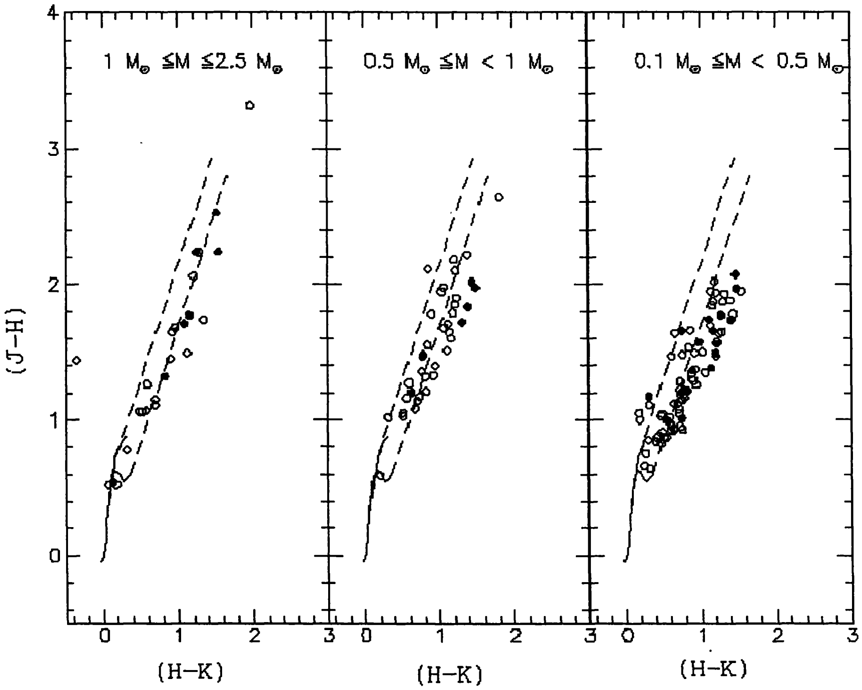

Fig. 5.— A set of three (J-H)/(H-K) diagrams for the embedded stellar cluster associated with Mon R2. The individual panels include measurements for stars inferred to fall in the indicated mass ranges.

impression is correct, and if the ages of the low and high mass stars are identical, then the duration of the envelope infall/disk accretion phase must be shorter among higher mass stars.

A systematic relationship between disk/envelope lifetime could provide an essential clue to identifying the differences in core initial conditions which give rise to stars of different mass (Shu, Adams, & Lizano 1987; Myers & Fuller 1993). In view of the importance of confirming the trend suggested in Table 2, we examined (Strom & Hillenbrand, unpublished) the distribution of infrared excesses among a proper motion selected sample of young PMS stars located within a 2pc region centered on the Orion Nebula Cluster (Jones & Walker 1988;

McNamara et al. 1989; van Altena et al. 1988). In Figure 6 we present an HR diagram for the sample in which the plotted points are coded to distinguish between stars which show infrared excesses indicative of accretion disks or infalling envelopes, and those which lack such excesses. Our data show that among stars with ages $t <$ 3 Myr, ~30% of the PMS stars in the mass range $1.0 < M/M_\odot < 2.0$ exhibit disk signatures, while *none* of the more massive stars in the sample show evidence of excess near-infrared emission diagnostic of accretion disks and/or infalling envelopes. These data thus confirm that the disk accretion/envelope infall phase appears to be shorter for stars of higher mass (see also Strom 1972; Warner, Strom, & Strom 1979; Hillenbrand et al. 1993).

4. ACCRETION DISK LIFETIMES AMONG OLDER PMS STARS

The results of the previous section provide convincing evidence that (1) during their initial formation stages, all stars in the mass range $0.1 < M/M_\odot < 3$ are surrounded by circumstellar accretion disks; and (2) the disk accretion phase is completed by an age $t < 1$ Myr among higher mass stars, but can persist for much longer among solar-type PMS stars. However, neither the data presented in section 3, nor that available in the literature provides a sound basis for constraining the *maximum* lifetimes for accretion disks around solar-type stars. What evidence there is (e.g. Strom, Edwards, & Skrutskie 1993) suggests a large *range* in disk lifetimes among stars with masses $\dot{M} < 1\ M_\odot$; in some cases, stars as young as 0.5 Myr lack disks, while in others accretion disks persist to ages at least as great as 3 Myr. It is of great importance to establish the frequency distribution of disk lifetimes as a function of age among solar-type stars both (1) to provide limits on the range of times available for building planetesimals (e.g. Weidenschilling & Cuzzi 1993), and (2) to understand the distribution of initial angular momenta among these stars (Edwards et al. 1993; Bouvier et al. 1993; Bouvier 1994; Strom 1994; Edwards 1995).

In order to address this problem observationally, it is necessary to examine a sample of PMS stars (1) known to be complete (or completely representative) for a given range of masses and ages; and (2) which span

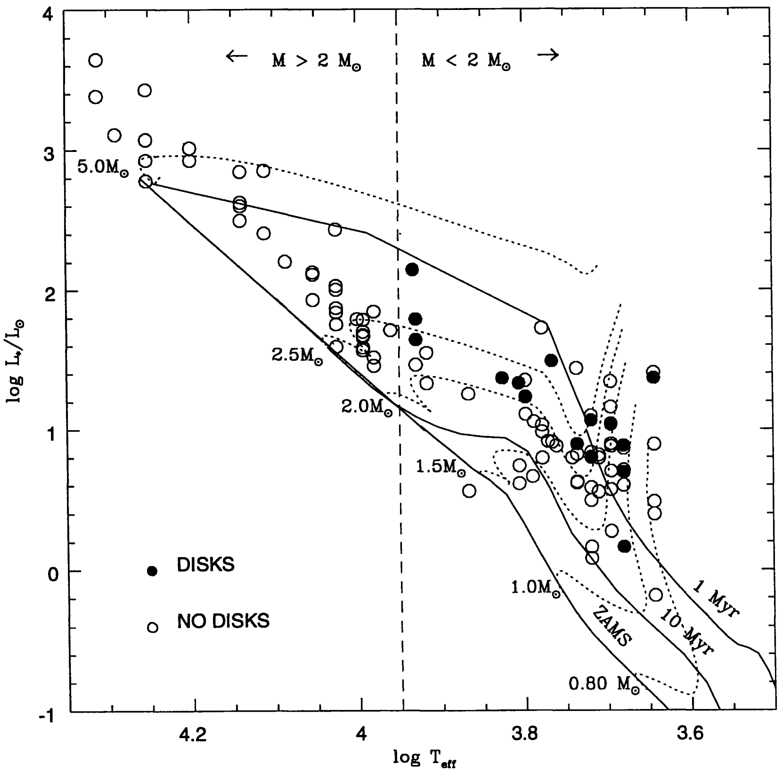

Fig. 6.— An HR diagram for a proper motion-selected sample of stars located within 2pc of the center of the Orion Nebula Cluster. Filled symbols indicate stars with (H-K) excesses consistent with the presence of circumstellar accretion disks; open symbols indicate stars with measure (H-K) values consistent with photospheric colors. Superposed on the (L, T_{eff}) plane are the tracks recently published by D'Antona & Mazzitelli (1994) using the Canuto—Mazzitelli prescription for convective energy transport.

a wide range of ages. Unfortunately, nearby star-forming regions such as Taurus-Auriga are not ideally suited to such studies because the range of ages represented among the stellar population projected on the molecular cloud complex is rather narrow (virtually all stars have ages t < 3 Myr; Gómez et al. 1992). Members of previous generations of stars, if any, have long since wandered far from the current cloud boundaries.

However, YSOs associated with giant molecular clouds (e.g. Orion A and B) and OB associations (e.g. Orion OB1; NGC 2264) span a much wider range of ages. Hence, detailed study of such regions appears more likely to yield definitive limits on maximum disk lifetimes. Some preliminary results are available from the dissertation work currently underway by L. Allen at the University of Massachusetts (Allen 1995) which provides a comprehensive study of ages, masses and disk frequencies among a representative sample of PMS stars in the L1641 cloud (located within the Orion A complex). Figure 7a presents a composite HR diagram for two regions (each of dimension $\sim 2\times2$ pc) located in the northern half of L1641, while Figure 7b provides a plot depicting the fraction of stars which exhibit accretion disk signatures as a function of age, and spanning the mass range $0.1 < M/M_\odot < 1.0$. We conclude from these Figures that among solar-type PMS stars (1) the fraction of stars surrounded by accretion disks decreases with age; and (2) *in some cases, accretion disks persist for ages in excess of 10 Myr.*

It is essential to add a cautionary note regarding the reliability of PMS ages, particularly for (1) all stars whose location in the HRD imply ages of t < 3 Myr when compared with conventional PMS evolutionary tracks which do not take into account the accretion history of PMS stars; and (2) for older stars still surrounded by accretion disks, and for which the mass accretion rate through the disk produces accretion luminosity comparable to that generated by processes internal to the star. Early explorations suggest that the effects of accretion on the evolutionary path of a star can be dramatic (e.g. Stahler 1988; Palla & Stahler 1992). Hence, until a comprehensive set of tracks for different disk accretion rates is available, absolute ages for PMS stars should be treated with considerable skepticism. However, the *trends* discussed in these last two sections (disk lifetimes vs. mass; fraction of solar-type stars surrounded by disks as a function of "age") should not be affected significantly by uncertainties in PMS ages.

5. THE SEARCH FOR "FOSSIL" DISKS

Near-infrared ($\lambda < 5\mu$) measurements are sufficiently sensitive to detect as little as $\sim 10^{-20}$ gm (the mass of an asteroid) of micron-size circumstellar dust surrounding solar-type and higher mass young stars, provided

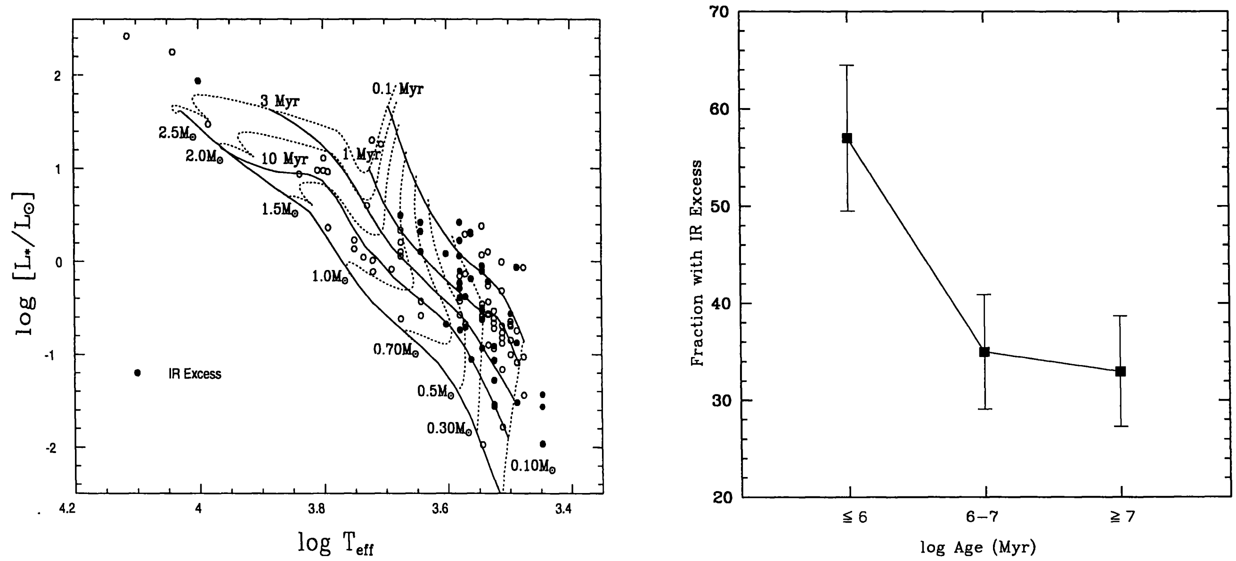

Fig. 7.— (a) The left-hand panel presents an HR diagram derived by Allen (1995) for a representative sample of stars in the northern part of the L1641 molecular cloud. The superposed tracks are again from D'Antona & Mazzitelli (1994) (see Fig. 6). Filled symbols indicate the locations of those stars which have (H-K) excesses consistent with the presence of accretion disks; open symbols represent stars which have (H-K) indices consistent with photospheric colors. (b) The right-hand panel summarizes the fraction of stars as a function of age in the mass range $0.1 < M/M_\odot < 1.0$ which exhibit accretion disk signatures.

that such dust is distributed throughout in the inner (r < 0.1 AU) of a circumstellar disk where it can be heated to temperatures T ~ 1000 K (Skrutskie et al. 1990; Strom, Edwards, & Skrutskie 1993; Dutkevitch 1995).

Hence, the results of section 3 (which suggest that virtually all stars in the mass range $0.1 < M/M_\odot < 3$ are initially surrounded by optically thick accretion disks), combined with the apparent absence of measurable excess infrared emission at ages t > 1 Myr for stars with $M > 2\ M_\odot$, 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 $M_{disk} > 0.01\ M_\odot$ (Beckwith et al. 1990); or (2) that such grains have been assembled into larger bodies, thus reducing the effective radiating area of solid material and consequently the excess infrared radiation.

Evidence that larger bodies may in fact have been built at least in some disks is provided by observations of β Pictoris and a large number of analogous intermediate mass and solar-type stars. This A-type main sequence star has an estimated age t ~ 100 Myr, and yet shows evidence of both (1) a measurable infrared excess ($\lambda > 10\mu$) consistent with an asteroid mass of micron-size dust distributed over a disk of dimension 1000 AU, and (2) a disk-like structure manifest in scattered visible light (e.g. Backman & Paresce 1993). 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 (of at least planetesimal size) analogous to the collisions which are believed to have occurred during the epoch of "maximum bombardment" responsible for the cratering manifest on the Lunar surface and on other bodies throughout the solar system.

The absence of large numbers of PMS stars with detectable excess infrared emission arising from optically thin disks, suggests a very short "transition time" between the massive, optically thick accretion disks which surround stars initially, and "fossil" disks, which perhaps contain planetesimals, but lack more than an asteroid mass of micron-sized grains. Strom et al. (1989) and Skrutskie et al. (1990) discuss 3 stars (DI Tau, V819 Tau, SAO76411A) out of a sample of 83 PMS stars in Taurus-Auriga which may be in an evolutionary stage intermediate between the accretion and post-accretion disk phases. While these three stars show no evidence of either measurable near-infrared excess emission diagnostic of heated grains in the inner disk, or of accretion of material onto the stellar surface (no strong Balmer line emission, spectral veiling or forbidden line emission), they nevertheless exhibit large mid- and far- infrared excess emission, comparable to that expected for flat, optically-thick disks. Based on these observations, Strom, Edwards, & Skrutskie (1993) speculate that the end of the disk accretion phase may be followed ($\Delta t < 0.3$ Myr) by an epoch of rapid planetesimal building in the inner disk. Assembly of larger bodies in the outer disk regions may require longer timescales (thus explaining the apparent presence of micron-size dust at disk radii r > 0.5 AU despite the absence of dust in the inner disk regions).

In Figure 8, we plot the spectral energy distribution of one of these "transition cases" V819 Tau. Superposed on the plot is a line indicating the location of the composite star plus disk spectrum for a flat reprocessing disk

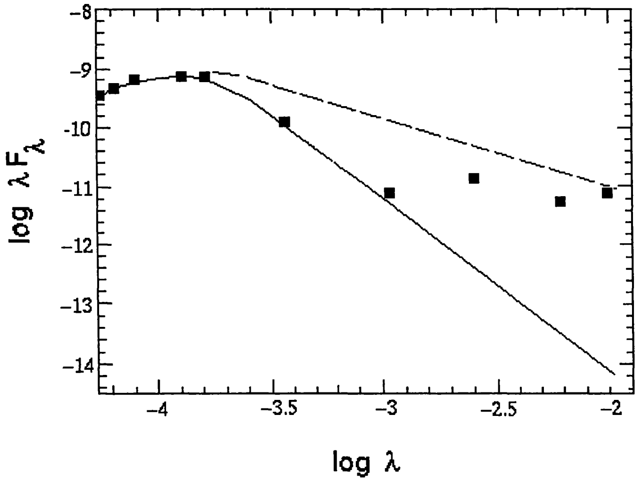

Fig. 8.— The observed spectral energy distribution for V819 Tau. The wavelength scale is in units of log (cm). Superposed on this diagram (dashed line) is the spectrum expected were V819 Tau surrounded by a flat, optically thick disk extending inward to the stellar surface and viewed at an inclination of 60 degrees.

viewed at an inclination of 60 degrees. The observed lack of significant excess emission at $\lambda < 10\ \mu$ suggests the presence of an "inner hole" in which the dust optical depth, $\tau << 1$ in regions $r < 0.2$ AU. At radii $r > 0.5$ AU, the disk appears to be optically thick, since the observed infrared fluxes at $\lambda > 25\mu$ fall near that predicted for a flat, optically disk.

The search for additional candidate "transition disks" in nearby star-forming regions will benefit from a number of planned ISO programs directed at measuring mid- and far- infrared fluxes for large samples of PMS and young main sequence stars which lack measurable near-IR excess emission. These observations should also have the sensitivity required to detect younger analogs of β Pictoris – PMS and young main sequence stars which have developed "secondary disks" populated by small grains produced as a byproduct of planetesimal collisions. These observations, combined with mm-continuum observations aimed at detecting and determining dust masses in the outer disk regions, promise a far more detailed picture of the evolution of the dust component of disks following the end of the disk accretion phase, and thus a profound advance in our understanding of the sequence and timescales of events leading to the assembly of solar systems.

To date, all large-scale surveys aimed at diagnosing the presence of circumstellar disks associated with young stellar objects rely on observations of infrared emission produced by heated dust. However, dust represents only a trace component of disks, 99% of whose mass is initially in the form of gas. The ability to detect the gaseous components of disks is nevertheless essential if we are to develop a complete picture of disk evolution. For example, virtually all theories put forth to explain the formation of the Giant Planets in our Solar System require (1) assembly of solid cores of mass $\sim 10\ M_{\oplus}$; followed by (2) accretion of gas from a ***gas-rich disk***. Is it possible to develop techniques capable of detecting disk gas? If so, can we find evidence gas-rich, solid-poor disks which might be in an evolutionary phase intermediate between the epoch of solid body assembly and the era of Giant Planet building?

Recent high resolution HST and VLA observations, combined with near-infrared ground-based imaging suggest a definite "yes"to the first question, and a more tentative "yes" to the second. Wide Field/Planetary Camera observations of a region directly surrounding the Trapezium cluster through filters admitting [O III] λ 5007 Å, [N II] λ 6584 Å, and Hα resulted in the discovery of gaseous emission regions ("proplyds") of dimension comparable to that expected for accretion disks ($100 < r < 1000$ AU) associated with $\sim$50 PMS stars (O'Dell, Wen, & Hu 1993; O'Dell & Wen 1994). Many of these sources had been detected previously

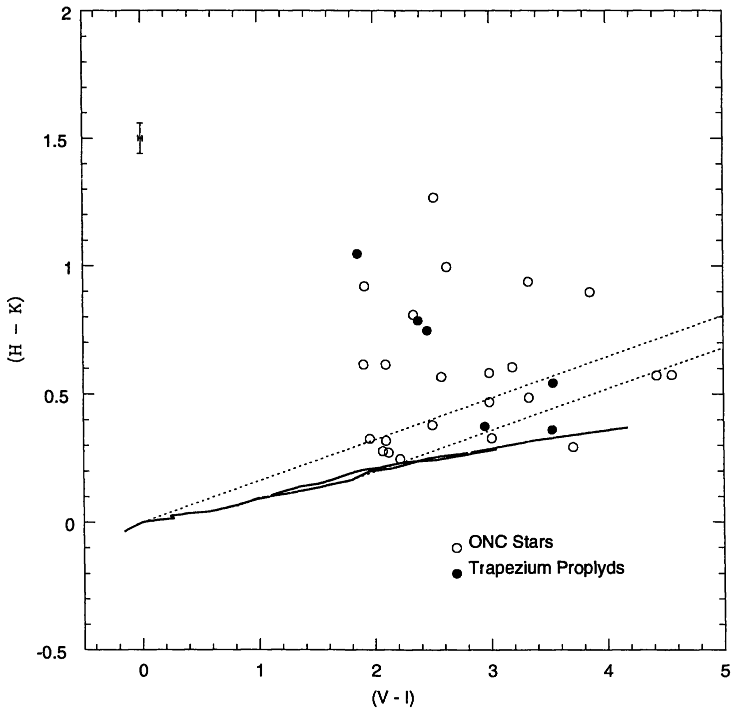

Fig. 9.— A (V-I)/(H-K) diagram for stars in the Trapezium Cluster. The filled circles represent the location of 6 of the "proplyds" recently discussed by O'Dell et al. (1994)

from VLA observations of radio continuum emission at cm-wavelengths (Churchwell et al. 1987). Both O'Dell et al. (1993) and Churchwell et al. (1987) suggest that the observed emission arises either (1) "outer skins" of the disks ionized by Lyman continuum radiation arising from the Trapezium O-stars; (2) ionized material driven from the disk surfaces; or (3) ionized material contained in a circumstellar envelope. The significance of these observations of small-scale emission regions associated with young stars lies in their ability to directly detect *gas* associated with circumstellar structures with no reference to the presence (or absence) of excess near-infrared emission. Infrared imaging of the Trapezium cluster (McCaughren & Stauffer 1994; McCaughren, unpublished; Makidon et al. 1995) suggests that many, but not all of the proplyds are associated with YSOs which exhibit near-infrared excess emission of a magnitude consistent with origin in a circumstellar accretion disk. In Figure 9, we present a (V-I)/(H-K) diagram for (1) a sample of 6 proplyds; and (2) a larger sample of Trapezium cluster stars which show no evidence of resolved optical or radio emission. The optical data are from the HST study of Prosser et al. (1994) while the infrared data are from infrared data obtained at Kitt Peak (with SQIID) and at the MDM observatory (using a NICMOS camera). Note that three of the proplyds clearly have (H-K) excess emission which places them in the region occupied by classical T Tauri stars. The remaining proplyds have colors (H-K) excess emission consistent with that expected for reddened stars which lack disks. The higher resolution infrared images currently being analyzed by McCaughren suggest that "most" of the proplyds in his larger sample show (H-K) and (K-L) excesses consistent with emission arising in circumstellar accretion disk. However, at least one proplyd (Jones/Walker 588; Jones and Walker 1988) lacks both the (H-K) and (K-L) excess expected for an optically thick disk; this star is one of the three proplyds whose location in the (V-I)/(H-K) plane is consistent with photospheric colors (no disk).

It is possible that the proplyds which lack definitive excesses in the (V-I)/(H-K) plane are in fact surrounded by disks, but are either (1) viewed nearly equator-on; or (2) have inner holes of dimension $r > 5\ R_*$ (see section 2). However, the absence of excess emission even at 3.5μ (L) for JW 588 would require an inner hole of dimension $r > 20\ R_*$, much larger than expected on the basis of current models which attribute small ($r \sim$ 2-5 R_*) holes to "interruption" of an accretion disk by a stellar magnetosphere (see Königl 1995; Shu 1995; Edwards 1995). It is therefore possible that the proplyds, selected solely because they show evidence of circumstellar *gas* emission, may contain among their members objects which lack significant quantities of dust in their inner disks. Further observations of a larger sample of proplyds, perhaps extending out to the limit of InSb detectors ($\lambda \sim 5\mu$), will be critical to determining whether these objects represent gas-rich objects in which planetesimal building has begun, at least in the inner disk, but in which the bulk of disk gas has yet to be assembled into Giant planets or dissipated.

6. SUMMARY

Our basic results can be summarized as follows:

- at ages $t << 1$ Myr, the frequency with which circumstellar accretion disks are found approaches 100% for YSOs spanning the mass range $0.1 < M/M_\odot < 3$.
- the duration of the envelope infall/disk accretion phase appears to decrease systematically with increasing stellar mass.
- the duration of the disk accretion phase for stars with $M < 0.5\ M_\odot$ spans a wide range of ages from $t < 1$ Myr to $t > 10$ Myr.
- the discovery of "proplyds" may provide a means for identifying stars which are surrounded by gas-dominated disks in which the solid material (at least in the inner disk regions, $r < 0.5$ AU) is either absent or in the form of bodies much larger than micron-size grains.

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REFERENCES

Adams, F. C., & Shu, F. H. 1986, ApJ, 308, 836
Adams, F. C., Lada, C., & Shu, F. H. 1987, ApJ, 312, 788
Allen, L. 1995, unpublished PhD Dissertation, University of Massachusetts

Backman, D. E., & Paresce, F. 1993, in Protostars and Planets III, ed. E. Levy & M. Matthews (University of Arizona Press)

Beckwith, S., Sargent, A., Chini, R., & Güsten, R. 1990, AJ, 99, 924

Bouvier, J., Cabrit, S., Fernández, M., Martín, E. L., & Matthews, J. M. 1993, A&A, 272, 176

Bouvier, J. 1994, in Cool Stars, Stellar Systems and the Sun, ed. J. P. Caillault, ASP Conf. Ser., 64

Churchwell, E., Wood, D. O. S., Felli, M., & Massi, M. 1987, ApJ, 321, 516

Dougados, C., Carpenter, J., Meyer, M., & Strom, S. E. 1995, in preparation

Dutkevitch, 1995, unpublished PhD Thesis, University of Massachusetts, Amherst

Edwards, S., Strom, S., Hartigan, P., Strom, K., Hillenbrand, L., Herbst, W. Attridge, J., Merrill, M., Probst, R., & Gately, I. 1993, AJ, 106, 372

Edwards, S. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 309

Casali, M. M., & Eiroa, C. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 303

Gómez, M., Jones, B. F., Hartmann, L., Kenyon, S. J., Stauffer, J. R., Hewett, R., & Reid, I. N. 1992, AJ, 104, 762

Hartmann, L., Kenyon, S. J., & Hartigan, P. 1993, in Protostars and Planets III, ed. E. Levy & M. Matthews (University of Arizona Press)

Hillenbrand, L. A., Massey, P., Strom, S. E., & Merrill, K. M. 1993, AJ, 106, 1906

Jones, B. F., & Walker, M. F. 1998, AJ, 95, 1755

Kenyon, S. J. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 237

Lada, C. J., & Adams, F. C. 1992, ApJ, 393, 278

Lada, E. A. 1992, ApJ, 393, L25

Makidon, R., Strom, S. E., Meyer, M., & Hillenbrand, L. A. 1995, in preparation

McCaughrean, M. J., & Stauffer, J. R. 1994, AJ, 108, 1382

McNamara, B. J., Hack, W. J., Olson, R. W., Mathieu, R. D. 1989, AJ, 97, 1427

Myers, P., & Fuller, G. A. 1993, ApJ, 402, 635

Meyer, M. 1995, unpublished PhD Dissertation, University of Massachusetts

O'Dell, C. R., Wen, Z., & Hu, X. 1993, ApJ, 410, 696

O'Dell, C. R., & Wen, Z. 1994, ApJ, 436, 194

Palla, F., & Stahler, S. W. 1992, ApJ, 392, 667

Prosser, C. F., Stauffer, J. R., Hartmann, L. W., Soderblom, D. R., Jones, B. F., Werner, M. W., & McCaughrean, M. J. 1994, ApJ, 421, 517

Skrutskie, M. F., Dutkevitch, D., Strom, S. E., Edwards, S., Strom, K. M. & Shure, M. A. 1990, AJ, 99, 1187

Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23

Stahler, S. 1988, ApJ, 322, 804

Strom, S.E. 1972, PASP, 84, 745

Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451

Strom, K. M., Kepner, J., & Strom, S. E. 1995, ApJ, in press

Strom, S. E. 1994, in Cool Stars, Stellar Systems and the Sun, ed. J. P. Caillault, ASP Conf. Ser., 64

Tereby, S., Shu, F.H., & Cassen, P. 1984, ApJ, 286, 529

van Altena, W. F., Lee, J. T., Lee, J., Lu, P. K., & Upgren, A. R. 1988, AJ, 95, 1744

Warner, J. W., Strom, S. E., & Strom, K. M. 1977, ApJ, 213, 427

Weidenschilling, S. J., & Cuzzi, J. N. 1993, in Protostars and Planets III, ed. E. Levy & M. Matthews (University of Arizona Press)