Origins 2002: The Heavy Element Trail from Galaxies to Habitable Worlds
ASP Conference Series, Vol. 2??, 2003
C.E. Woodward and E.P. Smith

Young Circumstellar Disks and Their Evolution: A Review

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Abstract. A detailed understanding of the physics of star and planet formation requires study of individual objects as well as statistical assessment of global properties and evolutionary trends. Observational investigations of circumstellar material surrounding young stars have matured to the point that both spectral energy distributions sampled over more than four decades in wavelength and spatially resolved images or interferometric visibilities at limited optical/infrared and sub-/millimeter wavelengths are becoming available, though for few individual objects at present. Data on star/disk systems combined with continuing surveys for exo-solar planets themselves will lead to constraints on the likelihood and frequency of solar system formation. An overarching goal of these pursuits is to connect what is observed elsewhere with the history of our own solar solar system, and hence enhance our appreciation of the uniqueness – or lack thereof – of the human circumstance.

1. Introduction

Several decades of theoretical and observational work has led to the following paradigm for star formation. Nearly free-fall collapse of an initially slowly rotating ($\Omega < 10^{-13}$ s^{-1}), cold ($T = 10 - 20K$), dense ($n \sim 10^5$ cm^{-3}) molecular cloud core leads to formation of a hydrostatic proto-star surrounded by a centrifugally supported circumstellar disk and remnant infalling envelope. The main infall/accretion phase during which most of the stellar mass is acquired is heavily obscured ($A_V > 10^3$ mag) and relatively short ($< 10^5$ yr; Shu et al. 1987; Boss & Hartmann 2001). A self-luminous source emerges from within the shroud of its parent molecular core and becomes visible ($A_V <$ 5-10 mag) at near-infrared and optical wavelengths as a pre-main sequence star contracting along a Hayashi track (in the most likely case of a low-mass object) in the HR diagram (see, e.g. Palla, 2001 for a review). The system evolves through the final stages of infall and then disk accretion, which can last up to $\sim 10^7$ yr in some cases (Muzerolle et al. 2000; Alencar & Batalha 2002). Competition between inward accretion and the simultaneously operating process of outflow along the magnetic/rotation axis affects both the mass and the angular momentum of the forming star, as well as the amount of raw material left in the disk for possible formation of planetary systems. The disks dissipate on times scales as short as $<10^6$ years, in some cases, and as long as $>10^7$ years, in a minority of cases, due to a combination of accretion onto the central star, ablation by the star's radiation field or wind, and/or assembly of smaller particles into larger bodies.

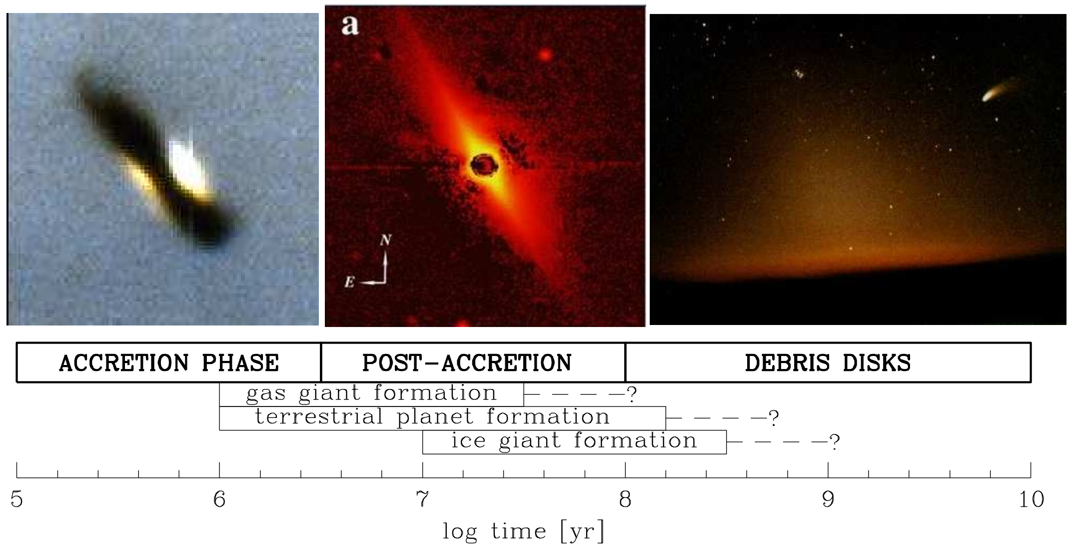

Figure 1. Images of disks at various evolutionary stages scaled to a timeline showing our general understanding of the basic phenomena. Data are courtesy of J. Stauffer and B. Patten (left panel, Ori 114-426 optically thick "silhouette disk" as seen with HST/WFPC), Kalas & Jewitt 1995 (middle panel, β Pic as seen in ground-based coronographic imaging), and P. Kalas (right panel, our own zodiacal dust disk along with a comet, as photographed from Calar Alto).

For solar-type stars, the ultimate result in at least 10% and perhaps as many as 50% of cases is a mature solar system.

Over the past 5-7 years we have witnessed 1) dramatic confirmation through direct imaging of many aspects of this picture, which was established previously using indirect arguments, and 2) the enlightening discovery of fully formed exo-solar planets and planetary systems. The remainder of this introduction outlines the existing observational evidence and theoretical support that underpins our still largely schematic understanding of planet formation as a concomitant to star formation, illustrated in Figure 1. We then discuss in some detail current constraints on the time scales for circumstellar disk dissipation. Mannings, Boss, & Russell (2000) provide an extensive set of reviews on many topics relevant to the ideas expressed herein; see also Podosek & Cassen (1994) for a briefer look at theory, observations, and solar system constraints on planet formation timescales.

1.1. Pre-Collapse: The Structure of Molecular Cloud Cores

Before initiation of star formation, molecular gas organizes itself on large scales (10s-100s of pc; $>10^4$-10^5 $M_\odot$) into clouds, sheets, and filaments, and on smaller scales (<0.1-1 pc; <10-10^3 $M_\odot$), into individual protostellar and proto-cluster cores. The structure of pre-collapse molecular cores has been inferred from observations of marginally resolved thermal emission at far-infrared through millimeter wavelengths. These data can be fit with power-law density distributions $\rho(r) \propto r^{-\alpha}$ with α closer to 0.5-1 (flatter profiles) in the inner regions and 2-4 (steeper) in the outer regions (Ward-Thompson et al. 1999, 1994; Andre et al. 1996). Tafalla et al. (2002) adopt the hybrid functional form $\rho(r) = \rho_o/(1 + (r/r_o)^\alpha)$. Disagreement remains, however, concerning the need for deviation from the isothermal prediction, $\alpha = 2$ (Shirley et al. 2002, 2000; Evans et al. 2001), and whether there is any consistency with the free-fall prediction, $\alpha = 1.5$. Recently, Alves et al. (2001), Harvey et al. (2001), and Racca et al. (2002) have probed the structure of high column density material at even higher spatial resolution using optical/infrared photometry of background stars to measure surface density profiles of several Bok globules. The observations are well-described by more sophisticated (compared to simple power-law functions) Bonner-Ebert spheres. A number of near-critical, that is, on the verge of or just having begun collapse, cloud cores have been identified.

Evidence for transition from molecular cores to proto-stars comes from observations of characteristically asymmetric line profiles in CO, CS, and other high density traces (see reviews by Myers et al. 2000 and Evans 1999) which demonstrate the earliest stages of gravitational collapse and infall. Indeed, one source studied in this manner, B335, was also found to be an unstable Bonner-Ebert sphere using the extincted starlight techniques just discussed. The typical size of the region inferrred to participate in the infall is <0.1 pc.

1.2. Early Stages: Spherical Infall and Disk Accretion.

Following the main collapse phase, a proto-star emerges. Proto-stars are usually defined according to criteria regarding the the fractional infrared through sub-/millimeter luminosity, the wavelength of peak emission in the spectral energy distribution, the spectral index, or ideally the mass in the central object compared to mass in the infalling envelope (see, e.g. Andre et al. 2000). One of their observational signposts are strong molecular outflows thought to be driven by highly collimated jets. Hundreds of protostellar objects have been cataloged within a few kpc of the Sun. Modelling of the nearest of these, in molecular clouds ~150 pc distant, has shown that their spectral energy distributions are generally well-matched at long wavelengths by simple radiative transfer of released gravitational energy through spherically symmetric infalling circumstellar envelopes. At short wavelengths (2-3 μm), however, there is suggestion based on flux excesses above the model predictions (Kenyon et al. 1993a) as well as spatial and polarization information (Kenyon et al. 1993b and references therein), that the optical depths to the central sources are far less than the pure-spherical infall picture predicts. An extended but flattened dust geometry is suggested, and confirmed by imaging (e.g. millimeter, Ohashi et al. 1996; HST/WFPC, Stapelfeldt et al. 1999; HST/NICMOS, Cotera et al. 2001, Padgett et al. 1999) which shows disk-like dust lanes separating bipolar cometary-shaped nebulae. The simultaneous consideration of the spectral energy distribution and spatially resolved images at several wavelengths (Padgett et al. 2003) enables detailed modelling which leads to physical parameter estimation. The composite observations of these protostellar systems are best explained if there are inner cavities in the infalling envelopes, which allow short-wavelength photons from some combination of the central object, the inner accretion disk, and the base of the jet/outflow region emitted towards the poles of the dust envelope to scatter and escape into the line-of-sight of the observer. Although some of these scattered light images have been obtained with HST and Keck, the majority of protostars in the nearest molecular clouds are fainter than I=25 and will require NGST/CELT for detailed study in the optical/infrared as well as SOFIA/ALMA for mid-infrared/sub-millimeter work at high spatial resolution.

After the envelope has fully settled into the existing disk, the central star becomes an optically visible T-Tauri (lower masses) or Herbig Ae/Be (higher masses) object. Due to the short time scales involved, observation of the accretion disk phase around even higher mass early-B and O-type stars is rare. Global disk heating is provided from two main sources: dissipation of viscous energy due to accretion, and radiant heating of the disk surface by the central stellar object. Additional heating processes such as chromospheric flaring events and x-ray ionization and flaring, may also be important. Observable signatures at this stage include mid-infrared to sub-/millimeter emission from dust at a range of temperatures, near-infrared emission from hot dust and gas in the inner disk, and a variety of optical and ultraviolet emission lines (as well as continuum excess) due to accretion of material from the inner disk directly onto the star. The strongest evidence for accretion comes from observation at high spectral resolution of the hot, blue excess above the expected photospheric spectrum, and detailed modelling of atomic emission line profiles. "Typical" low-mass ($\sim$0.5 $M_\odot$) young (1-3 Myr) stars in the well-studied Taurus-Auriga molecular cloud have accretion rates spanning a wide range, from $\sim$$10^{-9}$-$10^{-7}$ $M_\odot yr^{-1}$ (e.g. Valenti et al. 1993, Hartigan et al. 1995, Gullbring et al. 1998, White & Ghez 2001) with modest evidence for a direct correlation with stellar mass (e.g. Hillenbrand et al. 1992; Rebull et al. 2002, 2000; White & Basri 2003).

1.3. Middle Stages: Termination of Accretion and Planet Building

As was true for the protostellar stage, much excitement over the past several years has come from direct imaging of later disk evolutionary phases. In the Orion nebula, for example, O'Dell et al. (1993) and McCaughrean & O'Dell (1996) presented stunning images of so-called silhouette disks which provided visual evidence of flattened disk-like geometry associated with young stars for the first time shortward of millimeter wavelengths. Optical/infrared imaging of scattered light and thermally emitting disks surrounding optically visible stars has been provided by HST (e.g. Schneider et al. 2000; Krist et al. 2000; Weinberger et al. 2002; Grady et al. 2001) and ground-based AO (e.g. Roddier et al. 1996, Close et al. 1998). Resolved structure has also been found in interferometric studies (e.g. Akeson et al. 2000; Tuthill et al. 2001; Millan-Gabet et al. 2001; Hinz et al. 2001; Eisner et al. 2003). These images/visibilities provide information on orientation and on disk size vs. wavelength which, in combination with spectral energy distributions, has led to a new class of models for Herbig Ae/Be stars in particular (Dullemond et al. 2003).

For infalling protostellar envelopes as well as for active accretion and more passive "reprocessing" disks, modelling of optical through millimeter spectral energy distributions using radiative transfer techniques is hindered by the many degeneracies between: dust composition, grain size distribution, radial/vertical structure and scale heights, and overall geometry including system inclination. Longer wavelengths measure cooler temperatures which generally correspond to larger radii, though spectral energy distribution details will depend on the specifics of the radiative transfer, including scattering. An active debate at present concerns the three-dimensional geometry of such disks, in particular the existence and size of inner disk magnetospheric holes, the degree of outer disk flaring (α in the expression $(h/R)^\alpha$ where h is the vertical height and R is the corresponding disk radius), the evidence for settling of material within the disk vertically to the mid-plane which may be a critical early step in planet formation, and the opening of gaps in disks as a consequence of planet formation. Increase in surface brightness sensitivity through high contrast direct imaging and interferometric techniques should resolve large-scale three-dimensional structure or place clear limits on the degree of disk flaring. Observations of holes, gaps, truncations, warps, and non-axisymmetric structure, all plausibly induced by planet-disk interactions (e.g. Calvet et al. 2002, Wolf et al. 2002, Ozernoy et al. 2001), may offer the first direct evidence of ongoing or recent planet formation.

1.4. Late Stages: Debris Disks

Beyond the "primordial" disk stage discussed so far, in which the disks are still undergoing initial dissipation of the material out of which they and their central star formed, is the "secondary" or so-called debris disk stage in which second-generation dust is produced in collisions between planetesimals that are themselves stirred by gravitational interactions with larger planets, and by comets. A working definition of a debris disk (in the absence of gas) is one in which the survival time of the dust – given drag into the star via the Poynting-Robertson effect and/or radiation blowout – is much shorter ($\sim 10^5$ yr is a typical number) than the stellar age. Our own zodiacal dust is an example in which the asteroid belt and Edgeworth-Kuiper Belt are the source regions for the parent bodies which produce dust (e.g. Stern 1996) due to perturbation of the smaller bodies in these belts by our gas giant planets, primarily Jupiter and Neptune.

Debris disks can be distinguished from primordial disks in the following ways: They are low mass ($<$0.01 $M_\oplus$) and gas poor ($<$10%), the dust is located mainly at large radii and hence cold, the system dynamics are dominated by radiation pressure /collisions, and most significantly, the grains are in the process of being destroyed. Primordial disks on the other hand, are more massive (0.01 - 0.1 $M_\odot$) consisting of both dust and gas, have material distributed over a large radial range with a corresponding range of temperatures from warm to cold, have system dynamics dominated by a more massive gas component perhaps in keplerian rotation, and finally, are undergoing a dominant process of grain sticking/growth. It can be quite difficult to distinguish between these two scenarios (primordial and secondary) for any given observed system, especially at younger ages, say in the 3-30 Myr range.

Debris disks were discovered by IRAS (Aumann et al. 1984) via their thermal emission and later spatially resolved in short-wavelength scattered light and long-wavelength thermal emission from the ground (e.g. Smith & Terrile 1984; Holland et al. 1998) and from space (e.g. Weinberger et al. 1999, Heap et al. 2000; Heinrichsen et al. 1998). The few debris disks which have been resolved appear asymmetric, radially and/or azimuthally, and exhibit morphologies consistent with those predicted from the dynamical response of the disk to an embedded planet or planets (e.g. Wyatt et al. 1999; Liou & Zook 1999; Moro-Martin & Malhotra 2002). The exo-solar debris disks (see Lagrange et al. 2000 and Backman & Paresce 1993 for reviews) along with studies of the zodiacal dust and asteroid+Kuiper belts in our own solar system (see Luu & Jewitt 2002 for a review) have suggested a close relationship between late-stage debris disks and the presence of planetary systems.

Giant planets are now known to orbit within $\sim$3 AU of $\sim$6% of solar-type stars in the solar neighborhood (Marcy et al. 2000), with increasing evidence for commonality of multiple planet systems (Fischer et al., this volume; Marcy et al. 2003 website). The bulk properties of the planets discovered to date are *dis*-similar to those in our own solar system, in that semi-major axes typically are much smaller and eccentricities typically much higher; nevertheless, several near-analogs of Jupiter and/or Saturn have been found already with more surely on the horizon. The mere existence of exo-solar planets has substantially increased interest in the connection between the disks commonly seen around young stars, and solar systems such as our own.

2. Potential for Planet Formation in Young Circumstellar Disks

Let us now backtrack to the middle stages (adolescence, if you will) to discuss in more detail the expectations and observational evidence concerning primordial disk dissipation. The basic schematic from proto-stars to planets as outlined in the introduction is well accepted, though the details of evolution, including relevant time scales, are still quite poorly constrained. There is now overwhelming observational evidence that young circumstellar dust and gas disks exist. Questions then arising – many of which likely can not be answered this decade – include: How, and on what time scales, does the gas and dust found near ubiquitously around young solar-type stars evolve? Do disks last long enough to form planets? When, where, and how frequently do planets form in circumstellar disks? How do forming planetary systems evolve dynamically? Are there variations in solar system birth and evolution with mass or other properties of the parent star, or with local circumstellar environment? What is the range in diversity of stable planetary system architectures? How unique is our own solar system? How frequent are habitable planets?

2.1. Bulk Properties Consistent with Pre-Planetary Solar Nebula

We consider first the likelihood that young dust and gas disks are in fact proto-planetary. The raw material of planetary embryos, earth-like rocks, and jupiter-like gas giants is abundant. Whether any individual disk *will* form planets is of course unknowable. But that, in the mean, they are at least *capable* of forming planetary systems similar to our is almost a certainty, as evidenced from observed disk sizes, masses, and composition/chemistry.

Disks around young stars were spatially resolved for the first time at millimeter wavelengths (e.g. Sargent & Beckwith 1987) which measure cold gas and dust in the outer disk regions. Unequal axial ratios, combined with implied dust masses large enough that the central stars should not be optically visible if the dust geometry is spherical, stood as the strongest evidence for close to a decade that these are in fact disks and hence potential proto-planetary systems. Continued interferometric work (e.g. Lay et al. 1994, Dutrey et al. 1996, Duvert et al. 2000; Kitamura et al. 2003) suggests that disk diameters – *in instances where spatially resolved images are in fact obtained* – range from 70-700 AU and are even as large as 2000 AU in some cases. These size estimates are consistent with those inferred from the optical/near-infrared scattered light images discussed above, and in the typical case are comparable to or larger than our solar system. Surface density profiles, e.g. simple power-laws with $\Sigma(r) \propto r^{-p}$ or viscous disk "similarity solutions" with with $\Sigma(r) \propto r^{-p} e^{-r^{(2-p)}}$ have suggested a wide range in the value of p (0-1.5 for the power-law case). Furthermore, kinematic models of spatially resolved CO emission suggest Keplerian rotation (e.g. Koerner et al. 1993; Mannings et al. 1997; Simon et al. 2000; Koerner & Sargent 2003).

Disk masses are derived from optically thin millimeter flux and an adopted opacity-wavelength relationship which leads to uncertainties of factors of 5-10. Under common assumptions, however, calculated dust masses range from $10^{-4.5}$ to 10^{-3} $M_{\odot}$ (e.g. Beckwith et al. 1990). Making the further assumption that the dust:gas ratio by mass is unaltered from the canonical interstellar value of 1:100, total disk masses average around 0.02 $M_{\odot}$, or about the Minimum Mass Solar Nebula (Kusaka et al. 1970; Weidenschilling 1977) which is the reconstitution of present-day solar system mass and composition to solar consistency. It should be stressed that, as was true for the spatially resolved emission, *detection at all of millimeter flux* is made amidst an increasingly large number of upper limits, and so the true "mean mass" is even lower than quoted above.

The composition of both young primordial and older debris disks has been shown to resemble that of solar system comets. Ground-based 10 and 20 μm work on brighter sources (e.g. Hanner et al. 1995, 1998; Sitko et al. 1999) and ISO 2-30 μm spectroscopy (e.g. Meeus et al. 2001; Bouwman et al. 2001) have revealed an impressive suite of solid state (and PAH) dust features. Mineralogical details of the dust are modelled on a case-by-case basis due to cosmic variance, but the mean composition appears to be ~70-80% amorphous magnesium-rich olivines, ~1-10% crystalline forsterite, ~10-15% carbons, ~3-5% irons, and other trace components such as silicas. In particular, crystallinity is advocated in ~10% of sources. Studies of gas chemistry (see review by van Dishoeck & Blake 1998; also Aikawa et al. 2002) probe evidence for the building blocks of life. In the disk, temperature increases from the mid-plane outward while density decreases outward, leading to a strong dependence of fractionization on radius and height in the disk.

In summary, the observed sizes, masses, and dust/gas chemical composition of young disks are all consistent with solar nebula estimates. The mean disk properties are, however, still biased by detection limits and selection effects.

2.2. Expected Evolutionary Time Scales

We draw upon the "ground truth" provided by our own solar system, and also look to theory for guidance regarding the expected time scales for disk evolution.

At present there are three basic classes of models for planet formation. In the accretion model (e.g. Pollack 1996; Lissauer 1993; Weidenschilling & Cuzzi

1993), a multi-stage accumulation process involving dust settling and sticking leads to slow and then run-away accretion of solids over 1-10 Myr, followed by slow and then run-away accumulation of gas over the next 10-100 Myr. The time scales are highly dependent on parameters such as the initial disk surface density; hence the range of disk lifetimes is not a firm predictable though gas disk lifetimes are expected to be longer than dust disk lifetimes. A hybrid between these pure accretion models and the pure fragmentation models discussed next is the theory (e.g. Youdin & Shu 2002; Goldreich & Ward 1973) that initial small particle sticking and settling to near the disk midplane is followed by gravitational instability leading to planetary core contraction, which may lead to further solid and gas accumulation. Planet formation time scales in this scenario are expected to be shorter than in the pure accretion models. Pure fragmentation models (e.g. Boss 1998; Bodenheimer 1985) by contrast, advocate that giant planet formation is a relatively rapid (<<1 Myr), direct effect in massive, gravitationally unstable gas disks. This theory predicts short disk lifetimes and possibly even early-stage radial velocity signatures of planetary-mass perturbers in the spectra of parent stars. Finally, the capture theory of planet origins (e.g. Woolfson & Oxley 2000) is still discussed. In the mainstream theories of planet formation, possible co-existence of newly formed planets and the accretion disk also leads to considerations of orbital migration (e.g. Lin et al. 2000; Trilling et al. 1998), in which final orbital parameters, in particular the semi-major axis and eccentricity, are different from those that obtain close to the epoch of planet formation.

In our own solar system, meteoritic evidence concerning survival time of the solar nebula suggests "several Myr" as the relevant evolutionary time scale. Studies, especially those concerning extinct radionuclides, support this time span for initial accretion, differentiation, and core formation (see e.g. review by Wadhwa & Russell 2000). It should be emphasized that although dispersal of the solar *nebula* may occur quickly, the total duration over which inner planet formation was completed in fact approached 50-100 Myr.

As we will describe, these limited constraints from theory and from our own solar system are consistent with the equally vague precision with which disk lifetimes can be inferred from observations of potential planetary systems now in the making.

2.3. Measures of Disk Evolution

Resolved disk images as discussed in the introduction certainly have led to a wider appreciation of the convincing case for proto-planetary disks; however, the reality is that few such images exist at present. We still rely for the most part on "indirect" measurements such as broadband photometry and spectral energy distributions, as well as high resolution optical and near-infrared spectroscopy to study disks and disk accretion. Young circumstellar disks can be depleted of material via several mechanisms. These include: accretion of their dusty and gaseous material onto the central star, "excretion" of material into an outflow generated close to the star in some models (Shu et al. 1994; Hirose et al. 1997) and further out in the disk in others (Konigl & Pudritz 2000), ablation by the stellar ultraviolet radiation field or mechanical wind (Shu et al. 1993) and finally, decrease of opacity due – in the standard model – to growth proceeding from insterstellar-like dust grains to rocky planetesimals. The potential influence of the environment in which normal disk evolution proceeds should not be ignored. Location in a high stellar density region or in proximity to a massive star may also accelerate disk evolution (see review by Hollenbach et al. 2000).

What can we hope to measure as primordial dust and gas disks evolve through the planet building epoch into secondary/debris disks? Possible diagnostics as a function of age include:

- evolution of disk geometry in direct imaging data
- evolution of the spectral energy distribution
- decay in measured disk accretion rates
- increase in mean grain size and evidence for chemical evolution
- decrease in dust mass
- decrease in gas mass
- late stage dust regeneration signifying transition to a debris disk.

Some, albeit in most cases limited, evidence for at least modest evolution from primordial disk conditions exists in all of these areas. In what follows we focus on evolution of spectral energy distributions. In order to establish trends, robust statistics are needed from the youngest ages characteristic of star-forming regions still associated with molecular gas (<1-2 Myr), through the entire period of gas giant and terrestrial planet formation (∼100 Myr for our own solar system), as depicted in Figure 1.

3. Disk Evolution in Young Stellar Clusters and Field Stars

Young star clusters have a number of attributes that are attractive for statistical studies of circumstellar properties, namely the relatively uniform distance, age, and chemical composition of their members. Clusters can therefore provide the samples required to compare properties such as mean and dispersion in disk lifetimes as a function of stellar mass (within a cluster) and as a function of stellar age or chemical composition (between clusters). Known targets for this kind of work can be segregated into the following coarse age groups: <1 Myr (partially embedded star forming regions), 1-3 Myr (optically revealed stellar populations still associated with molecular gas), 10-15 Myr (association members in gas-poor "fossil" star-forming regions; N.B. this is a particularly sparsely-populated age range at present), 55 Myr, 90 Myr, and 120 Myr (the ages of nearest open clusters). Stars in the 5-50 Myr age range are extremely hard to identify since they stand out from much older field star populations only with detailed observations (not, e.g., in wide-field photometric surveys). They may be revealed through such signatures of youth as common proper motion with young groups, enhanced Li I absorption, Ca II H&K core emission, and x-ray activity. In fact, finding stars in this age range should be relatively easy due to our circumstance in the Galaxy near a ring of moderately recent star formation ("Gould's Belt"); yet current samples of 5-50 Myr old stars number only in the tens.

We now summarize the evidence for disk evolution over <1-100 Myr time scales using available cluster, association, and field star samples. As a caveat we note that the poor precision of stellar ages is still a major contributor to the uncertainty in derived time scales.

3.1. Inner Accretion Disks

It has been adequately demonstrated in the literature that there is an empirical connection between near-infrared (1-3 μm) flux excess and spectroscopic signatures of accretion directly onto the star, as well as a connection between accretion and outflow (e.g. Hartigan et al. 1995). We therefore utilize measured emission above expected photospheric values in the near-infrared to infer presence of an accretion disk. These wavelengths are sensitive to hot dust and gas in the inner disk, <0.05-0.1 AU, where the geometry of the emitting region may in fact be quite complex (see e.g. Mahdavi & Kenyon 1998).

To calculate the color excess due to the disk, one must derive and subtract from the observed color the contributions from foreground/circumstellar extinction and from the stellar photosphere in order to arrive at an intrinsic excess, e.g. $\Delta(H-K) = (H-K)_{observed} - (H-K)_{reddening} - (H-K)_{photosphere}$. The information required for assessing Δ(H-K) includes a spectral type (for intrinsic stellar color and bolometric correction determination), optical photometry (for dereddening and locating stars on the HR diagram, assuming known distance), and infrared photometry (for measurement of disk "strength"). The value of the infrared excess is affected by stellar properties (mass, radius) and disk properties (accretion rate, inclination, geometry); see Meyer et al. 1997 and Hillenbrand et al. 1998 for detailed discussion. Masses and ages are inferred via comparison to models of pre-main sequence evolutionary tracks, which themselves carry uncertainties of 20-100% between authors over certain mass and age ranges (see comprehensive discussion in Baraffe et al. 2002).

Observationally, our best effort at measuring the evolution of inner circumstellar accretion disks is represented in Figure 2, produced from a sample of ∼3000 stars located ∼50-800 pc from the Sun with sufficient information for calculation of $\Delta(H-K)$. There are several important points made by these plots. First, although individual stars (left panel of Figure) in nearby star forming regions can appear to have ages <1 Myr, not a single cluster or association (right panel of Figure) has median age significantly <1 Myr. This is in part a selection effect since the requirements for inclusion in our sample generally preclude the presence of proto-stars and transitional objects. Second, even at the earliest evolutionary stages at which stars can be located in the HR diagram, the optically thick inner disk fraction does not approach unity. This may be influenced by the same selection effect, though indicates strongly that *some* disk evolution does happen very early on for *some* stars, before they become optically visible. Third, beyond 1 Myr of age, where samples are more representative of stellar populations as a whole (if not close to complete for most of the regions represented), there is a steady decline with time in the fraction of stars showing near-infrared excess emission (i.e. optically thick inner disks), as well as large scatter at any given age. The conversion of this Figure into a frequency distribution of accretion disk lifetimes is discussed in Hillenbrand, Meyer, & Carpenter (2003). Fourth, the median lifetime of inner optically thick accretion disks based on assessment of modern data may be as short as 2-3 Myr. Comparison of the left and right panels of Figure 2 leads us to the conclusion

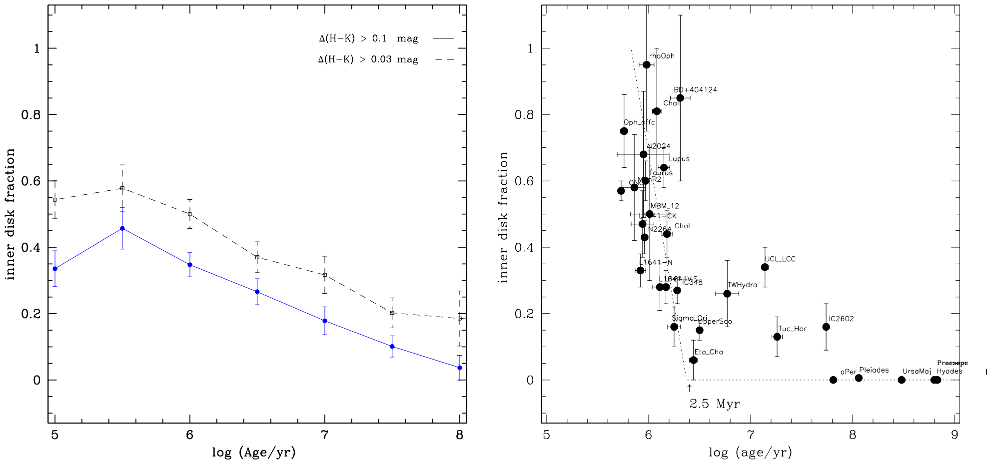

Figure 2. *Inner accretion disk fraction vs. stellar age* inferred from H-K excess measurements for ∼3000 stars. In the left panel, each star contributes individually to the age bin found from its location on the HR diagram. The dashed line uses a cut of Δ(H-K) $>$ 0.03 mag to define a disk while the solid line uses the more conservative Δ(H-K) $>$ 0.1 mag. Note that non-gaussian errors tend to scatter stars into older age bins, thus inflating the disk fraction at older ages. In the right panel, clusters are treated as single units of age corresponding to the median age found from the HR diagram. Here, an intermediate cut of Δ(H-K) $>$ 0.05 mag is used to define a disk.

that there is undoubtedly scatter of individual young stars into older age bins, which affects the appearance of the left panel substantially more than that of the right panel. The left panel may thus be considered an upper limit to the disk fraction, especially at older ages.

Other discussions of inner disk lifetimes have used different techniques and more limited samples of stars (e.g. Walter et al. 1988, Strom et al. 1989, Skrutskie et al. 1990, Beckwith et al. 1990, Strom 1995; Haisch et al. 2001). However, the general conclusions regarding inner disk lifetimes in the 3-10 Myr age range are, broadly speaking, similar to our findings of <2-3 Myr. In addition, Muzerolle et al. (2000) demonstrate an indirect correlation of *accretion rates* with age, with at least several stars showing measurable accretion signatures beyond 10 Myr. So although most disks appear to evolve relatively rapidly, a small percentage may retain proto-planeary nebular material for factors of 5-10 longer than does the average disk.

3.2. Outer Disks

Mid-infrared wavelengths, ∼10-90 μm, probe disk radii ∼1-5 AU, equivalent to the outer terrestrial and inner gas giant planetary zones of our solar system. To date, observational sensitivity has been the primary hindrance to measurement of outer circumstellar disk evolution. Data from the IRAS and ISO satellites, when presented in the same form as Figure 2 (e.g. Meyer & Beckwith 2000; Roberto et al. 1999), show similar morphology with ∼10 Myr needed for depletion of 90% of optically thick outer disks. The implication is that outer disk dissipation times are only slightly longer than, or perhaps even consistent with, inner disk dissipation times, and hence that disk evolution is both rapid and relatively independent of radius. Spangler et al. (2001) and Habing et al. (2001), however, argue for a much longer time scale, on the order of hundreds of Myr. There may be some confusion in these studies between primordial and debris disks as a single, continuous evolutionary path is not expected. As the dust transitions from optically thick to optically thin, spectroscopy becomes an especially important tool for tracing the mass in terms of grain size distribution and composition. Imminence of SIRTF, which is sensitive to *nearby stellar photospheres between 3.5 and at least 24 μm* will enable statistical studies of primordial and debris disk evolution on several AU scales.

Millimeter wavelength emission probes the outer (~50-100 AU) cold disk regions and is also optically thin. Most millimeter observations have been directed towards stars younger than $\sim 10^7$ year, but because of the distance of these populations, generally place only upper limits on dust masses beyond the optically thick disk phase (e.g. Duvert et al. 2000). Dust mass surveys of older (10^7 - 10^9 year), closer, candidate debris disk stars (e.g. Zuckerman & Becklin 1993, Jewitt 1994, Carpenter et al. 2003) also reveal mostly upper limits due to current sensitivity limits, though also several detections with dust masses as low as 10^{-8} $M_\odot$ (still a factor of $\sim 10^2$-10^3 above our own zodiacal dust disk).

3.3. Length of Transition from Optically Thick to Optically Thin

Once the process of disk dissipation starts, how long does it take for an individual object to transition from optically thick to optically thin? As argued by Skutskie et al. (1990) and Wolk & Walter (1996) based on the perceived lack of "transition" objects, the process of evolution from optically thick to thin takes only a few hundred thousand years or less. Similarly, Nordh et al. (1996) show 7-15 μm flux ratios in Chamaeleon that are scattered around *either* the colors expected from flat/flared disks, *or* around photospheric colors, with essentially no objects located in between these clusterings. When does a particular system go from being primordial (dominated by growth of smaller bodies into larger ones) to debris (dominated by destruction of larger bodies into smaller ones which are then removed from the system via Poynting-Robertson drag + stellar wind effects)? Figure 3, for example, shows the spectral energy distribution of a moderately young (~30 Myr old) star which may be in the process of depleting its primordial dust disk, or which may have begun regenerating a dust disk. More detailed study, particularly dust spectroscopy, is needed in order to begin answering these kinds of questions.

There *is* evidence for the growth of grains in young disks to sizes larger than are expected based on our knowledge of interstellar dust. Typically these arguments have been made from measurement of the frequency dependence of opacity in the expression $\tau_\nu(r) = \kappa_\nu \times \Sigma(r)$ where $\kappa_\nu \propto \nu^\beta$ and the $\beta = 2$ appropriate for interstellar dust often yields in measurements of optically thin sub-/millimeter spectral energy distributions to $\beta = 0 - 1$ (see Miyake & Nakagawa, 1993). Calvet et al. (2002) discuss this and other evidence for grain growth in the specific case of TW Hydra. Expected consequences on spectra

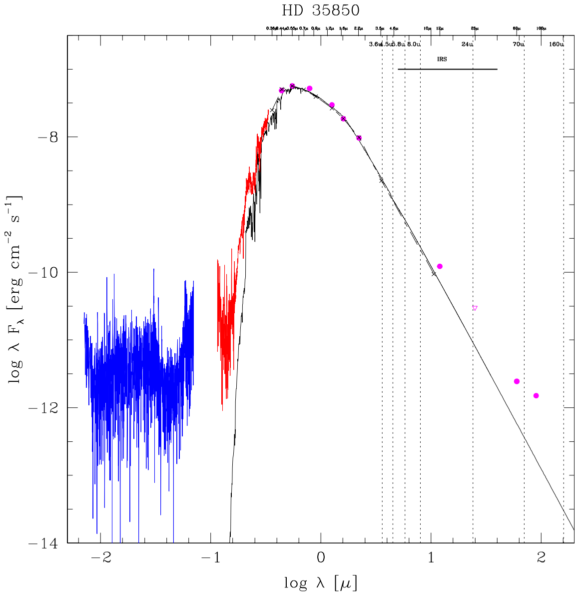

Figure 3. Observed spectral energy distribution of HD 35850 (F8 V star at 27 pc) from extreme-ultraviolet (EUVE; IUE) through optical/infrared (Hipparcos; 2MASS) to far-infrared (IRAS; ISO) wavelengths, compared to a Kurucz model atmosphere. This star is thought to be between 10 and 100 Myr old and has either a late-stage primordial disk or an early-stage debris disk. Vertical dotted lines indicate effective wavelengths of SIRTF filters.

and overall spectral energy distributions are presented in a parameter study of disk geometry and grain properties by D'Alessio et al. (2001).

4. Other Parameters Affecting Disk Evolution: Companions

As mentioned earlier, the orbital radii and eccentricities of those exo-solar planets discovered to date bear little resemblance to our own solar system's planets. If the architecture of our solar system is indeed rare or even unique, it may be that variables other than disk mass, size, and composition may be important. Environment, e.g. location in a clustered vs. in an isolated star formation region could potentially influence the disk, as already discussed. Stellar properties imparted from the cloud core or set during the collapse phase and early evolution of the disk, such as mass, metallicity, and specific angular momentum may play some role as well. For the remainder of this section we focus on multiplicity and the possible influence of stellar/substellar companions on disk evolution.

Although our Sun is not a member of a multiple star system, a significant fraction (30-80%) of all stars do appear to be born in binaries, triples, or higher order multiples (see review by Mathieu et al. 2000). For solar-type systems in the solar neighborhood, the distribution of orbital periods is gaussian in log and peaks at 180 days (Duquennoy & Mayor 1991) or 30 AU – within our current solar system. An intriguing study of binarity by Patience et al. (2002) showed a much lower peak in the semi-major axis distribution for stars which are members of clusters (4 AU) than for less densely spaced young stars (40 AU, similar to the DM91 field star distribution) and also a lower overall companion frequency (just 10%). They surmise that the solar neighborhood field star distribution could be comprised of star-forming regions that were ~70% clusters and ~30% low density regions, i.e. that *most* stars form with companions within 2-8 AU.

What is the role of multiples in disk evolution and are there implications for planet formation? Potentially planet-building circumstellar disks do exist around young multiples (e.g. the GG Tau "prototype") as well as singles. And planets do form in widely separated binary systems (e.g. Cochran et al. 1997; Lowrance et al. 2002). Little is known, however, about the planet-forming potential of stars with high-mass brown dwarf and stellar companions ($m_2/m_1 >$ 0.05) near the peaks of the semi-major axis distributions, that is, with separations of only a few to several tens of AU.

Lubow & Artymowicz (2000) calculate that circumstellar disks around individual binary components will be truncated at radii in the range 0.2-0.5 times the orbital separation, while any circumbinary disk surrounding the primary+secondary system will have an inner radius of 2-3 times the orbital separation. Although disks associated with binary systems are predicted to be truncated, they may still have sufficient surface density to form planets. Lower mass (though not necessarily truncated) disks for 1-100 AU binaries are indeed suggested by observation (Jensen et al., 1996).

Several surveys capable of probing into the low-mass brown dwarf regime have already been conducted, enabled by improvements in high-contrast imaging technology, but still limited in impact by uncertainties involving physical association vs. chance projection. Farihi et al. (2002) discuss an ongoing investigation of companions to white dwarfs, a survey which thusfar has revealed only GD 165B (Becklin & Zuckerman 1993). Schroeder et al. (2000) used HST/WFPC to survey stars within 13 pc, finding no previously unidentified companions. Lowrance (2001) investigates a sample of nearby GKM stars with HST/NICMOS, and finds several sub-stellar companions, while McCarthy (2001) uses coronographic techniques to study somewhat younger GKM stars, with a yield of no confirmed sub-stellar objects. Oppenheimer et al. (2001) conducted a volume-limited survey of similarly mixed mass and age stars finding only Gl 229B (Nakajima et al. 1995). Generalizing the results of the above investigations, sensitivities extend to masses of a few to tens of Jupiter masses over separations of a few tens to a few hundreds of AU. Wider companions (>1000 AU) to FGKM stars are summarized by Gizis et al. (2001) and closer companions (<3-5 AU) are probed by doppler monitoring planet search programs. Overall, the frequency of brown dwarf and planetary (<1-80 $M_{Jupiter}$) companions appears to increase with orbital separation, rising from <0.3% at <3 AU, to <3% on tens of AU scales, to <10% by thousands of AU.

Our own recently initiated survey can extend previous work in several directions. Taking advantage of the fact that, at young ages, the faintest of companions detectable with modern equipment are in fact giant planets, Metchev & Hillenbrand (2002) describe adaptive optics coronographic work that is sensitive to companion masses as low as 3-10 $M_{Jupiter}$ for the younger and closer portion of their sample. The parent stars are F8-K0 solar analogs (0.8-1.2 $M_\odot$), and the survey explores a broad age range from 3 Myr to 3 Gyr. Complementing this work is an ongoing precision velocity program (Marcy et al.) that will reveal giant-planet and any larger masses closer in to the central star than can be seen in direct or corongraphic imaging. The target stars are members of the Meyer et al. (2002) SIRTF/Legacy program for which dust disk information will soon be available, enabling a complementary discussion of the effect of companions (stellar, brown dwarf, and planetary) and disks.

5. Summary of Young Circumstellar Disks and Their Evolution

Direct imaging has finally convinced even the most stubborn skeptics that circumstellar dust and gas *disks* do exist around young stars. Detailed information on composition, size, mass, and even some hints regarding surface density distributions are available in a limited number of cases. However, we still need to rely on traditional photometric and spectroscopic techniques for the statistics required to understand disk dissipation time scales. At present, there is evidence for decreasing trends with age in: disk fraction, mean disk accretion rate, and mean disk mass. There are also signs in young disks of evolution from interstellar grain parameters. What may be most interesting however, is the large dispersion about the mean for any given age, in all of these trends.

By establishing over the next decade the decay with time of primordial dust via near- and mid-infrared excess around stars of different mass, we will have taken the first step in understanding the possibilities for planetary formation. Studies to determine the time scales for dust disk dissipation should be followed by those aiming to similarly quantify time scales for gas disk dissipation. Fully constraining the time period over which raw materials needed for planetary formation are available means, ultimately, following the evolution of disk surface density as a function of radius from the central star. The outstanding problem in planning for this kind of statistically robust future is that we do not have adequate samples of stars in the 5-50 Myr age range, a critical time in planet formation and early solar system evolution.

In the near-future, SIRTF and SOFIA will provide an abundance of detail on continuum spectral energy distributions and dust mineralogy, as well as hints regarding gas (H_2) content. Further afield, NGST and CELT will study gas disk evolution with the same rigor we are about to study dust disk evolution. ALMA will provide images with the spatial resolution required for investigation of radial and azimuthal disk structure before and during the planet-building phase. Early investigations (such as those currently proceeding) of the influence of stellar and sub-stellar companions on disk characteristics will be supplanted by those using improved ground- and space-based high contrast imaging and interferometric (e.g. Keck-I and SIM) technology. Exo-solar planet statistics continue to assemble.

The connection between disks and planets is increasingly obvious.

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