Disk Dispersal and Planet Formation Time Scales

Lynne A. Hillenbrand

California Institute of Technology; Mail Code 105-24; Pasadena CA 91125; USA

E-mail: `lah@astro.caltech.edu`

Abstract. Well before the existence of exo-solar systems was confirmed, it was accepted knowledge that most – if not all – stars possess circumstellar material during the first one-to-several million years of their pre-main sequence lives, and thus that they commonly have the potential to form planets. Here I summarize current understanding regarding the evolution of proto-planetary dust and gas disks, emphasizing the diversity in evolutionary paths.

1. Introduction

From analysis of the chemical record as traced through meteoritic material, we can infer the detailed history of the formation and early evolution of our planetary system (e.g. Ehrenfreund, this volume). Since discovery of the first exo-solar system planet more than a decade ago, it has been understood that planetary systems around other stars could have properties very different from those characterizing the familiar Solar System. Further, the biases and systematics that are inherent in the many exo-solar system planet detection techniques, plus the current technological limitations, mean that the discovery of planetary systems resembling our own – in detail – remains for the future.

However, the great diversity in the measured orbital and internal properties among known "exo-planets" suggests that it would not be surprising were there similar diversity in the properties of the circumstellar disks out of which such planets form. Indeed there is a wide range in inferred disk size, disk mass, disk geometry/structure, and disk composition/chemistry, as touched upon by other authors in this volume (e.g. Henning, Natta, Dullemond, Aikawa). While the initial conditions for planet formation do appear diverse, typical early-stage properties are: $M_{disk} = 0.005$ $M_{\odot}$ (e.g. Osterloh & Beckwith 1995; Andrews & Williams 2005, 2007); $M_{disk}/M_{star} = $ 1-10%; $dM_{acc}/dt = 3\times 10^{-9}$ $M_{\odot}/yr$ (e.g. Gullbring et al. 1998; White & Basri 2003; Muzerolle et al. 2003); and $R_{disk} = $ 10-100 AU (e.g. Dutrey et al. 1996). We note that the dispersion can be orders of magnitude for some disk properties.

How does gas and dust that are initially well mixed and smoothly varying with radius and height turn into dynamically and compositionally diverse planetary systems? Here, we discuss the process of disk dissipation and *presumed* planet building, with particular attention to the current observational constraints on relevant time scales. We focus on stellar populations as a whole, rather than describing the many individual cases of disk evolution "in action," e.g. lines of evidence for grain growth which are covered by other authors in this volume. Theory has advanced in recent

years to the point of making specific predictions for the evolution of quantities that, in principle, can be observationally constrained: surface density with radius (the dissipation is inside/out in some models); total disk mass (predicted as nearly constant in some models); rate of disk accretion (ceases entirely in some models); gas-to-dust ratio (decreases from ~ 100 to $<1\%$); grain size distribution (expect increasing mean size); and chemical composition (set by response to x-ray, EUV, FUV, and optical photon heating from the star). While some of these measures are still beyond the realm of observational constraint, other tests having statistical significance are possible now. A potential "second parameter" effect is the local environment of the young star/disk system, and whether it is dynamically or radiatively important to the evolution of the disk (see Adams, this volume for discussion of cluster effects and Monin et al., 2007 for a review of stellar and substellar companion properties and their effects).

2. Planet Building

Observational probes of the planet formation process are directed towards understanding the evolution of circumstellar dust and gas properties. The basic processes on the dust side are those of decoupling from the gas, drift and mid-plane settling, coagulation and growth into larger grains, and consequent growth to macroscopic bodies termed "pebbles" then "planetesimals," which can continue to become "oligarchs", and eventually terrestrial sized planets. These processes may be traced by studying in large samples of disks e.g. spectral diagnostics of grain size, dust opacity vs wavelength, dust mass at optically thin wavelengths, disk structure as indicated by direct imaging or inflections in spectral energy distributions, etc. On the gas side, there is a maze of chemical evolution before and then during accretion of the gas – if giant planets are indeed formed – onto massive cores that were themselves accreted via the dust evolution processes just described. Tracers of gas disk evolution include probes of hot atomic gas accreting onto the star, numerous atomic and molecular gaseous species in more quiescent yet still warm regions of the disk, and measures of total gas mass via optically thin line emission.

The planet building processes all occur against the backdrop of viscous disk evolution (Hartmann et al. 1998; Takeuchi et al. 2005; Alexander & Armitage 2007), outflow via stellar/disk winds (Pudritz et al. 2007), ionization/photoevaporation (Hollenbach et al. 1994; Gorti & Hollenbach 2008), and radiative blowout of small grains once the disk becomes optically thin. Various time scales are involved, ranging from those relevant to radiative transfer and chemistry to those which scale with the dynamical time in the disk. Here, we discuss mostly the dust disk evolution, since observational constraints on gas disk evolution are more limited at present. Both remain hindered to some extent by observational sensitivity, despite significant advancement in recent years.

How long will known disks last? One relevant experiment is to consider the well-studied young stellar population of the Taurus-Auriga region for which all of the following are available: 1) detailed spectral energy distributions, including data from the Spitzer Space Telescope; 2) disk masses from millimeter measurements, and 3) mass accretion rates from inner disk to star, measured via either high dispersion spectroscopic measurements of "veiling" or lower dispersion direct detection of the Balmer continuum. A simple division of $M_{star}/(dM_{acc}/dt)$ yields a time scale – ranging from a few Myr to roughly a Gyr – for the accretion of material on to the central star. That these times are much longer, in the mean, than the inferred stellar ages indicates

that the accretion rates must have been much higher in the past in order to build up the stellar mass to its present value. This point has been made before in the literature, repeatedly.

The complementary division of $\mathrm{M}_{dust}/(\mathrm{dM}_{acc}/dt)$ also yields a time scale, that for the disk to dissipate under the assumption that all of the material currently residing in the disk eventually winds up on the star. The inferred times are factors of several longer than the stellar ages estimated at 1-2 Myr, suggesting that the disks will last well into the future. Given the simplistic assumptions regarding dust opacities used in estimating dust masses, they are likely underestimated, perhaps by an order of magnitude (e.g. Draine, 2006), and this would strengthen our argument regarding the potential for "long-lived" dust disks. When considered relative to typical theoretical time scales for planetary core formation and gas accretion, *all young disks with substantial dust and gas thus appear to have the potential to form planets* and can be considered proto-planetary.

How long does disk dissipation take, whether due to planetary formation or other processes? It has been known for some time (e.g. Skrutskie et al. 1990 working with IRAS, Nordh et al. 1996 with ISO) and confirmed with more recent data (e.g. Hartmann et al. 2005 and Furlan et al. 2006 with Spitzer) that 3-25 μm mid-infrared colors and SED slopes of young low mass stars (also known as T Tauri stars) in a single cluster segregate into two groups. They are interpreted as the stars with disks and the stars without disks. As the wavelength considered is decreased, blurring between the excess/disked and the non-excess/non-disked samples increases. Of note is that similar bifurcation in mid-infrared colors is seen not only among very young 1-2 Myr populations but also in somewhat older 5-10 Myr old populations such as the η Cha (Megeath et al. 2005) and TW Hya (Low et al. 2005) small associations. It is always present.

That there are no, or very few, objects of intermediate color or spectral slope found at mid-infrared and longer wavelengths among stellar populations of nominally the same age has been used to argue (e.g. Simon & Prato 1995; Wolk & Walter 1996) that the transition time from optically thick to optically thin disks is only a few hundred thousand years, i.e. that the disk dissipation process is quite rapid – once it starts. Bertout et al. 2007 and Hartigan et al. 1995, however, present evidence to the contrary that so-called "CTTS" and "WTTS", i.e. Classical accreting and Weak-/non-accreting T Tauri Stars, are distinguishable in their luminosity (*sic* age) distributions.

The key to understanding the apparent diversity in the disk dissipation time scale may be found by considering whether the differences are due to those in the initial conditions from which the evolutionary process occurs, or to differences in the process itself or its duration. Notably, self-similar viscous disk evolution models (e.g. Hartmann et al. 1998) do not yield the rapid transition between strong and weak/no disks that is observed. Models invoking inside-out ionization/photoevaporation (e.g. Alexander & Armitage 2007) or rapid grain growth and planetesimal formation (e.g. Brauer, Dullemond, & Henning 2008) may.

3. Transitional Disks

A category of disks which has been identified for close to twenty years but has only recently become well-defined, is the so-called "transition" disk sample. These objects make up a very small fraction of the total disk population. The term "transitional"

is commonly used to describe several different categories of disks that are perhaps indicative of an "evolved" nature. There are those disks having less strong spectral energy distributions overall, relative to their counterparts. There are those disks having low dust content in the inner (<1-10 AU) regions based on no or weak near- and mid-infrared excesses, yet strong excess emission and quite diverse spectral energy distributions, at longer mid-infrared (e.g. Furlan et al. 2006; Watson et al. 2007) through sub-mm/mm wavelengths.

The latter objects have a range of inferred dust masses that is typical of the disked T Tauri population. However, inner disk gas content, where measurements are available, is low with gas surface densities <1-2 g/cm^2 and gas:dust ratios 250-1000 inferred at 0.5-1 AU (Saylk, Blake & Brown, 2007; Herczeg et al. 2007). This is consistent with the much lower-than-average accretion rates inferred from optical and ultra-violet diagnostics. According to the $M_{dust}/(dM_{acc}/dt)$ metric applied above, the "transition" disk sources are projected to be exceptionally long lived accretion systems if their future evolution is determined entirely by viscous dissipation. However, dust/gas removal may occur by other means, for example enhanced photoevaporation given that the inner disk is already cleared and the outer disk thus more directly illuminated by stellar photons.

The list of candidate "transition" disks is growing rapidly based on sensitive Spitzer data. In well-studied star forming regions, Spitzer has confirmed that many objects with only upper limits to their mid-infrared fluxes measured by IRAS, indeed have photospheric spectral energy distributions with an upturn at wavelengths longer than 5-20 μm. In other less well-studied regions, Spitzer by itself has characterized the entire strong/transitional/weak or non-disk population (e.g. Sicilia-Aguilar et al. 2006ab).

The relative paucity of "transitional" objects has long been used to argue that the phase from optically thick accretion to optically thin dust- and gas-poor disks is short-lived. One interesting question to ask is what are the ages of *the known* transitional systems, and how do they compare to those of the typical cluster or group member? We find that there is *no difference* in the mean, median, or distribution (via K-S test) of ages for the two populations in Taurus-Auriga. This finding is related to the apparent conundrum of CTTS and WTTS mixing in the Hertzsprung-Russell diagram (HRD), noted earlier.

It is thus the case that stars of apparently - if not nominally - the same age can have very different disks. This diversity is noted from consideration of bulk disk properties (presence/absence, total mass, size, accretion rate, etc.) as well as in the many details of dust grain size and composition that are available from surface layer spectroscopy or thermal emission from the near the mid-plane (see e.g. Natta, this volume).

4. Stellar Ages

This brings us to discussion of stellar ages. While there are a number of different empirically calibrated stellar age estimation techniques for stars between ∼100 Myr and ∼10 Gyr old (e.g. Mamajek & Hillenbrand 2008), for young stars, we are stuck essentially with the HRD as the only tool to determine stellar ages. I offer some cautionary words about what we can and what we should not believe about stellar ages inferred from individual measurements of $\log L/L_\odot$ and $\log T_{eff}$ for young stars.

First, there are systematic concerns. For example, several 5-10% precise values of

the distance to the Orion Nebula Cluster have become available very recently (Hirota et al. 2007, Jeffries 2007; Sandstrom et al. 2007; Menten et al. 2008), indicating that all previous interpretations of the HRD for this cluster have suffered from systematic overestimate of the stellar luminosities and hence underestimate of the stellar ages. Another systematic effect is that of unresolved binarity, the implications of which on stellar luminosity estimates given the apparent trends with primary mass in component mass ratios and separation distributions, remains poorly characterized empirically – even for very well studied clusters.

A further concern of systematic nature is that pre-main sequence evolutionary tracks vary substantially between theory groups. Comparison among available tracks reveals a trend in inferred stellar age that is relatively flat (reflecting consistency between the various sets of evolutionary tracks) for earlier type F and G stars, but increasing to about 0.75 dex age differences (indicating strong variation among theory groups) for later type K and M young stars, as demonstrated in Hillenbrand, Bauermeister & White 2008. In addition to model-to-model systematics, it seems that *all* currently available sets of tracks under-predict stellar masses by 30-50% (Hillenbrand & White 2004) while simultaneously under-predicting low mass stellar ages by 30-100% and over-predicting high mass stellar ages by 20-100%, (Hillenbrand, Bauermeister & White 2009). Finally, from comparison of presumably co-eval populations in pre-main sequence clusters, it is concluded that the higher mass stars systematically appear older than the lower mass stars in the same cluster, regardless of adopted tracks or mean cluster age. Although observers are generally grateful to have the opportunity to impose theoretical interpretation on their data, the ensemble findings suggest that detailed work in stellar astrophysical theory is still needed, as is guidance from dynamical mass measurements across the pre-main sequence.

Second, there are random errors having to do with the accuracy of observationally determined quantities. These errors act to broaden luminosity dispersion, which is often (quite erroneously) interpreted as evidence for true age dispersion. Sources of random error include both astrophysical noise such as photometric variability, stellar/disk "activity," and observational noise such as pure Poisson error in the measurements along with conditions such as source crowding or high background and other non-photospheric emission specific to certain young regions.

How much confidence can we place in stellar ages and hence inferred evolution of other physical variables based upon them? At present, a conservative estimate is that ages are accurate to factors of no better than ∼2-3, including both systematic and random uncertainties. Prudence thus dictates caution regarding the inference of e.g. star formation histories in molecular clouds and cloud-free stellar associations, as well as in assessment of evolutionary time scales for e.g. circumstellar disks or stellar angular momentum.

Beyond absolute calibration of mean ages, we must ask whether all stars in a particular stellar cluster or association have the same age, or if there is evidence for age dispersion among cluster members (e.g. Tout, Livo, Bonnell, 1999). We (e.g. Hillenbrand, Bauermeister, White 2008) have been running monte carlo simulations to test whether observed luminosity distributions are consistent with error distributions or, perhaps, indicative of true age spreads. The evidence at this point suggests that the vast majority of cluster stars are consistent within the errors with having the same age i.e. there are no discernible age spreads representing the bulk of young stellar populations. Admittedly, there *are* some stars out on the tails of the luminosity distributions that seem hard to explain unless they are individually suffering some

large unidentified source of error (e.g. Slesnick, Hillenbrand, & Carpenter, 2008). St34 in Taurus, which appears on the old side, or PDS66 in Upper Sco which appears on the young side, are well-known examples of such objects which remain enigmatic at present.

5. Current Understanding of Disk Dissipation

Returning now to the question of the time scale for disk dispersal and planet formation, we proceed by assembling: 1) a set of stars which are known members of young associations or clusters, 2) optical and/or near-infrared information which allows us to locate them in the theoretical HR diagram, and 3) a quantitative disk diagnostic. Associations and clusters are useful bins because they provide statistical robustness, they offer samples having a range of stellar and substellar masses, and they provide stars having the same formation environment, metallicity, and stellar age (probably). The optical and near-infrared photometric/spectroscopic data assembly is fairly "bread-and-butter" at this point in astronomical history, requiring only time/effort and a careful assessment of errors. For the last need of a disk diagnostic, we could choose an optical depth indicator such as monochromatic infrared excess at one or more wavelengths wavelengths, a proxy of total disk mass, or an inferred disk accretion rate. For reasons of relative abundance and uniformity, we opt here to make use of infrared excess as our diagnostic.

Dust grains radiate over a broad range of wavelengths depending on their temperature and size. We can measure excess emission above a stellar photosphere due to absorbing and thermally re-emitting dust in the circumstellar environment. Such excess (infrared) emission can be measured via empirical colors, or more appropriately and more accurately, from colors corrected for a theoretically or empirically determined stellar photospheric contribution. To gain a complete picture of the disk dissipation process, we want to measure the excess amplitudes over a wide range of wavelengths, ideally, and of course over a range of ages.

Independent of the wavelength studied or the mean age of the sample, there is ample evidence for a range of infrared excess properties observed among young pre-main sequence stars. For example, color excess distributions (e.g. 8-24 μm and 3.6-8 μm from Spitzer, or K-L and H-K from the ground) span a wide range of values at the youngest ages. Towards older ages, however, the distributions narrow, and eventually reflect just the error distribution. Hernandez et al. 2007, for example, show the frequency distribution of near- to mid-infrared spectral energy distribution slopes in several clusters <5 Myr of age. The distributions are double-peaked, indicative of the well-known bimodal behavior between "disked" and "non-disked" stars referred to above. Figure 1, employing a different analysis technique, shows reddening-corrected near-infrared color excesses over photospheric values, which are broadly distributed rather than double-peaked, and likely indicative of the range in accretion properties exhibited by young stars. From overall consideration of star forming regions having nominally different ages, a trend of decreasing dust disk (mean) frequency towards older (mean) ages is observed. But the devil is in the details.

5.1. Disk Dissipation Trends with Stellar Radius

Short infrared wavelengths trace hot dust and thus near-infrared excesses (JHK bands) sample material at ∼0.03-0.1 AU. Longer wavelengths trace cooler dust
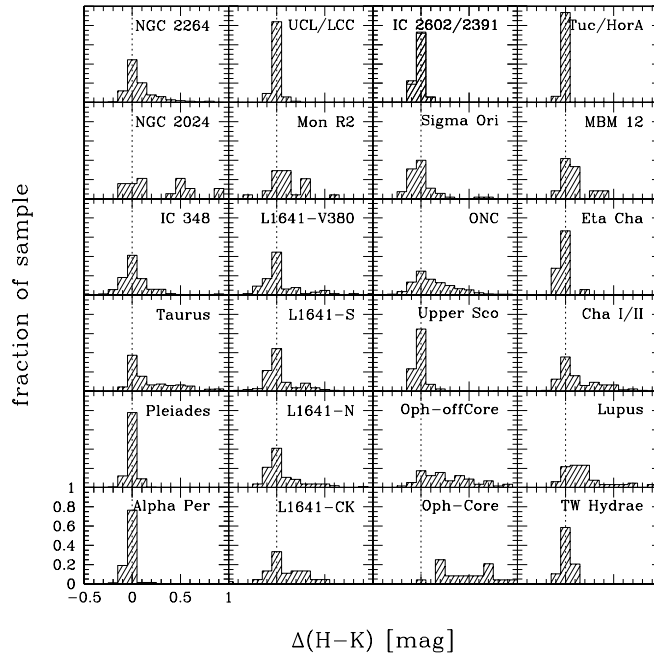
Figure 1. Normalized frequency distribution of near infrared excesses indicative (when positive) of hot circumstellar dust associated with accretion processes in <1-100 Myr old stars superposed (when negative) on the underlying error distribution. The younger clusters show a range of near-infrared excess amplitudes (including zero excess) while the older clusters are more strongly peaked at near-zero excess.

with mid-infrared excesses (LMNQ bands or Spitzer IRAC camera) probing ∼0.2-10 AU and far-infrared and sub-mm/mm wavelengths typically ∼10-100 AU. Stellar temperature/luminosity are also influential in setting these ranges; the above numbers are relevant for a young "solar-type" star. It should not be forgotten that there are significant radiative transfer effects introduced on top of this simple picture due to radial and vertical disk structure as well as grain properties. Regardless, in the innermost disk regions, a lack of 1-2 μm excess observable from the ground implies $< 10^{-5}M_\odot$ ($< 3.5M_{Earth}$) in dust at the relevant temperature of ∼1000K. In the mid-disk range, lack of 8 and 24 μm excess with Spitzer implies $< 1M_{Earth}$ in ∼100 K dust. In the outer disk, where the prevalent upper limits to sub-mm and mm excesses are less restrictive, only $< 10^{-4}M_\odot$ ($< 35M_{Earth}$) in 30-50K dust is implied by a non-detection.

In the near infrared, measuring typically sub-micron grains, we believe that the excesses are tied directly to the accretion of material from the inner disk to the star. Indeed, the general decay of near-infrared excess with advancing stellar age over 1-10 Myr is well-reproduced by a similar decay in the frequency of Hα emission for the same stars (Dahm, 2005; see also Mohanty et al. 2005, Jayawardhana et al. 2006). These arguments are buttressed by older evidence in the literature for a 1:1 correlation among members of Taurus-Auriga between thermal emission from disks and gas emission from accretion (Edwards et al. 1994). Characteristic time scales are a few Myr (see Hillenbrand, 2005 for more in depth discussion) and functional fits to the accretion diagnostics of the form $time^{-1}$, $time^{-2}$, or e^{-time} may be appropriate.

In the mid-infrared, measuring typically micron-sized grains, evidence is rapidly building from Spitzer (Silverstone et al. 2006, Lada et al. 2006, Sicilia-Aguilar et al. 2006, Carpenter et al. 2006, Megeath et al. 2005, Dahm & Hillenbrand 2007) but was also apparent from the ground (Mamajek et al. 2004) that a similar though perhaps slightly longer decay time can be inferred. In the sub-millimeter and millimeter, measuring potentially large grains up to tens or hundreds of microns in size, although no trends are available yet, there is a clear cliff of detectability that appears intimately tied to disk presence at shorter wavelengths. The data are consistent with *all* CTTS having disks with mass $> 10^{-4} M_\odot$ and <10% of WTTS having substantial sub-mm disks (Andrews & Williams 2005).

There are, of course, some caveats to the above. One limitation is observational sensitivity, meaning that the weakest or lowest mass disks are not detectable. This is generally due either to raw observational sensitivity limits, or to lack of calibration precision which effectively destroys capability to detect excesses within that uncertainty level. A second limitation is in the physical interpretation of employed disk diagnostics, i.e. how well we understand the physics leading to the excess flux and how we correlate wavelength of the excess with temperature/location of the emitting disk material. A final uncertainty, as discussed in detail above, relates to the accuracies of stellar ages.

How do we interpret the current trends in disk dissipation vs wavelength (*sic*, disk radius)? We still – and will for some time – lack an unambiguous mapping between observed spectral energy distributions and physical disks. However, coming back to the so-called "transitional disks," it is notable that the observations indicate morphologies suggestive of the dust becoming optically thin first at shorter wavelengths and only later at longer wavelengths. This apparent ordering could be due to processes associated with physical disk draining (e.g. via accretion onto the central star, through launching into a wind, or by photoevaporative processes that perhaps progress from the inner disk to the outer disk) *or* to transformation of disk material (e.g. the growth of small interstellar-like particles into grains larger than $\lambda/2\pi$ which are then not generally detectable at wavelength λ).

Indeed, an open question is whether disk material dissipates at all radii simultaneously, or whether inner disks disappear first, as holes develop on a viscous evolution, dynamical, or photoevaporative time scale, and propagate outwards. The expected times are in all cases comparable to the dynamical time scale - days in the inner disk and $\sim 10^5$ years in the outer disk. Although fast, these are perhaps not fast enough to produce the "CTTS/WTTS switch" that is observed. One way of describing empirically the evolutionary process may be via measurement of the slope of the infrared excess as it departs the stellar photosphere, vs the wavelength at which the departure occurs (e.g. Cieza et al. 2007). It is proposed that grain growth implies clearing over a large range of wavelengths near-simultaneously, while dynamical or photoevaporative effects would proceed from the interior of the disk outward. It is suggested that these scenarios would have different tracks in such a diagram.

5.2. Disk Dissipation Trends with Stellar Mass

Another very clear trend from Spitzer data is the mass dependence of circumstellar disk dissipation. Carpenter et al. 2006 and Dahm & Hillenbrand 2007 show evidence in two different clusters of nominal age 5 Myr that the disks remain around only the lowest mass (K and M) stars. This is the first definitive evidence of the long espoused

notion that higher mass stars may lose their disks more rapidly. The finding is as one might infer from some combination of the larger radiation fields and the higher inferred mass accretion rates (Calvet et al. 2005, Garcia Lopez et al. 2006) for more massive stars, and is consistent with an interpretation that the mass dependent dissipation trend is driven by initial conditions (Alexander & Armitage 2005). Further, the disks remaining in these two clusters (Upper Sco and NGC 2362), as well as others (such as λ Ori, σ Ori, and Orion OB1) in even more recent literature, are weakened in strength or amplitude of the measured excess, relative to the larger excess values observed towards stars in younger regions of similar mass.

How do we interpret the current trends in disk dissipation vs stellar age, as a function of stellar mass? Clearly, the fact that we can even use terminology such as "disk fraction" suggests that at any given age, some stars have disks while others do not. In other words, there is dispersion - indeed, diversity – in the time scale for disk dispersal. This is true even among objects with apparently identical properties otherwise (stellar mass, metallicity, star formation environment). Further, the mass dependence of both accretion properties and thermal dust emission processes is clear, and also accompanied by dispersion. An open question is whether the observed trends should be interpreted as dispersion in initial disk properties, dispersion in the onset of some common disk evolutionary switch, or dispersion among individual objects in the relative importance of the various possible disk dissipation mechanisms.

6. Quantifying Diversity

The wide dispersion in observed spectral energy distributions is especially prevalent at ages of <1-3 Myr and perhaps indicative of dust disk geometry to first order and of radiative transfer effects in detail. By ∼5 Myr the diversity settles down, with observed disks predominantly "weak" and by ∼10 Myr most disks are undetectable or nonexistent, with only a very few stars having "strong" disks. What we really want to know, however, is not the evolution of observational parameters – e.g. disk fraction, infrared excess amplitude, SED slope, λ_{onset}, optical veiling, emission line fluxes etc – such as we have discussed or alluded to thus far, or even the evolution of corresponding physical parameters – disk radial and vertical structure, total dust mass, grain size distribution, $(\mathrm{d}M_{accretion}/\mathrm{dt})$, gas mass etc.. Rather, we aim to understand a higher level question: the frequency distribution of the lifetime of dust (as well as gaseous) material above a certain mass, as a function of disk radius. How many such disks last only 0.1 Myr years, how many 1 Myr, how many 5 Myr, 10 Myr, 20 Myr?

This is approached, in principle, via building the distribution of disk lifetimes as a function of wavelength. Ideally we want to go even further and understand the mean and dispersion in the evolution of physical quantities e.g. the disk surface density distribution, $\Sigma(r)$. Are such distributions gaussian or do they exhibit long tails? Does planet formation occur throughout the distribution, or only within the long tails? Is the circumstellar evolutionary process different for stars of different mass, or for binary vs single stars?

7. Gas!

We are unlikely to be able to discern in great detail what has happened to the ubiquitous early-stage circumstellar dust, via studies of the dust itself. Instead, we might turn to studies of the gas, which dominates the mass and therefore the disk

dynamics. In the grain growth scenario for planet formation, the gas is likely to remain beyond the dust disk lifetime and be available for continued disk accretion/outflow. Conversely, in a disk clearing scenario accompanying planet formation, the gas likely disappears via the same or a similar mechanism to that causing the dust removal. As in so many other areas of disk evolution, the less observationally constrained gas is key to our astrophysical understanding. Some of these same points have been made recently by Najita et al. 2007.

What of current gas constraints? Emission in H_2 and CO has been detected from the ground (Weintraub et al. 2000; Bary et al. 2002, 2003; Bitner et al. 2007; Salyk et al. 2007; Ramsay Howat & Greaves, 2007) and measures warm-to-hot gas in disk surface layers or inner disk regions. With Spitzer, [Ne II] at 12.8 μm has been observed (Pascucci et al. 2007; Lahuis et al. 2007) and may actually measure the photo-evaporative flow (Herczeg et al. 2007). Spitzer has also detected OH, H_2O and simple organic molecules (Salyk et al. 2008, Carr & Najita 2008). Non-detections currently imply less than a few percent of $M_{Jupiter}$ remaining at the current age of the star, though samples are limited. Further gas studies, e.g. with the forthcoming Herschel, are needed. Of note is that the ages inferred for several of the very few systems with detected and measured gas content are relatively old – 5-10 Myr!

8. Closing in on the Future

One point to emphasize, in particular, regarding circumstellar disk evolution is that whatever happens to the early stage gas and dust disks, happens fast. An increasingly important limit to our understanding is thus the large uncertainty in stellar ages which leads to large uncertainty in disk evolution times, since $\Delta\tau_{evolution} < \delta\tau_{age}$. In other words, the phenomenon occurs on time scales comparable to or less than a stellar age resolution element. Not so much later in the disk evolution process, as primordial disks are dissipating, it is likely that debris disks are arising. For these, now gas-poor disks, in contrast to the gas-rich primordial disk situation, $\Delta\tau_{evolution} > \delta\tau_{age}$. In other words, the phenomenon occurs on somewhat longer time scales than the uncertainties in stellar ages. Also needed for progress on disk evolution is semantic agreement on, and a common definition for, "age," especially concerning a meaningful time zero point.

Better understanding is needed of the transition from "primordial" disks – in which the mean grain size is increasing with time as sub-micron material agglomerates to eventually form planets – and "debris" disks – in which the mean grain size is decreasing with time as micron to cm-sized and larger material is destroyed in the planet-induced stirring of planetesimals and resulting collisional cascade, and followed by radiative blowout or inward drag. Because the youngest examples of debris disks overlap in age with the oldest known (accreting, even!) primordial disks, we are going to have to be somewhat careful in parsing the data in the 3-15 Myr age range where vestiges of both types of disk are likely present.

As an example, Carpenter et al. 2006 may be seeing in their 5 Myr old sample evidence for debris disks surrounding some of the earlier type (A-F) stars and unevolved primordial disks surrounding the later type (K-M) stars. It has also been argued by Metchev et al. 2005 in the case of the $\sim$ 12 Myr old M-type star AU Mic, that while the inner regions of the spatially resolved disk are collisionally evolved debris, the outer regions are most likely pristine material that is still part of the remnant primordial disk. The formation of debris disks, commonly accepted

as evidence of formed planetesimals and even planets, can easily be confused with long-lived primordial disks. In the absence or neglect of relevant information, extreme caution and probably cleverness in the interpretation of observational data is needed. Gas studies are extremely promising in this regard.

Finally, we note that the relationship between disk evolution and planet formation is becoming increasingly clear. We are currently in a stage of great luxury – based on the substantial progress over the past several years – in being able refine the questions we can both fathom and afford to ask of increasingly predictive theory and increasingly detailed observations.

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