The Formation of Star and Planetary Systems: New Results from *Spitzer*

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**Abstract.** Protoplanetary disks are thought to be the birthplaces of planetary systems. The formation and the subsequent evolution of protoplanetary disks are regulated by the star formation process, which begins with the collapse of a cloud core to form a central protostar surrounded by a disk and an overlying envelope. In the protostellar phase, most of the envelope material is transferred onto the star through the disk during episodic, high accretion events. The initial conditions for planet formation in protoplanetary disks are likely set by the details of these processes. In this contribution, I will review some of the new observational results from *Spitzer* on protostellar evolution and the structure and evolution of protoplanetary disks surrounding young stars in nearby star forming regions. The implications of these results for planet formation and eventual disk dissipation are discussed.

1. Introduction

Stars are formed in the dense and cold cloud cores within molecular clouds. In the current paradigm for star formation, the gravitational collapse of a slowly rotating cloud core leads to the formation of a central protostar surrounded by a rotating disk and an overlying envelope from which the material rains down onto the disk (Shu et al. 1987; McKee & Ostriker 2007). High angular momentum material in the envelope first collapses into a disk before getting accreted onto the central protostar. In the early embedded stages, the system drives powerful bipolar jets/outflows, the origin of which is not entirely understood. As the system evolves, the envelope dissipates either by draining onto the disk or is cleared out by stellar winds and outflows, leaving behind a young pre-main sequence star surrounded by a disk. Planetary systems are formed out of such protoplanetary disks which are the natural byproducts of star formation process.

In the widely accepted ‘core accretion’ model, the planet formation process begins with the subμm-sized grains in protoplanetary disks sticking together to grow into larger mm- and cm-sized particles (e.g. Weidenschilling 1980). As they grow, the larger grains sink down to the disk mid-plane; sedimentation of the dust can cause significant changes in the vertical structure of the disk (D’Alessio et al. 2006). Along with the grain growth, mineralization of the initially amorphous dust grains also takes place in protoplanetary disks (e.g. Watson et al. 2009). The larger grains that have settled to the disk mid-plane further grow into km-sized planetesimals, which through collisional growth, eventually form protoplanets (e.g. Weidenschilling 2008). Once these ‘planetary embryos’ have become sufficiently massive (∼10 M⊕), they accrete gas from the disks to form
giant planets (e.g. Pollack et al. 1996). A Jupiter-like gas giant formed in the disk can gravitationally alter the disk structure by forming radial gaps and holes in them (Rice et al. 2003; Quillen et al. 2004). The disks eventually dissipate either by planet formation processes clearing the disks and/or by various other disk dispersal processes such as accretion onto the central star, photoevaporation and magneto-rotational instability (MRI) induced disk clearing (e.g. Alexander et al. 2006; Chiang & Murray-Clay 2007).

2. Protostellar Evolution

The various evolutionary stages that young stars go through have traditionally been classified on the basis of their observed spectral energy distributions (SEDs). The continuum spectral index, $\alpha \equiv \frac{d \log (\lambda F_\lambda)}{d \log (\lambda)}$, evaluated between 2 and 20 $\mu$m has been used for this classification (Wilking 1989; Greene et al. 1994). Under this scheme, objects with a rising infrared continuum ($\alpha \geq 0.3$) are classified as Class I sources and objects with flat infrared continuum ($-0.3 \leq \alpha < 0.3$) as ‘Flat spectrum sources’; Class II objects have infrared continuum slope $-1.6 \leq \alpha \leq -0.3$ and Class III sources show marginal infrared excess with $\alpha < -1.6$. These empirical SED classes roughly correspond to the different physical stages in the theoretical model: the Class I sources have a collapsing envelope surrounding the protostar-disk system; the Class II sources have dissipated most of their envelope and are characterized by a pre-main sequence star surrounded by a disk; the disk dissipation is well underway in Class III sources. An additional class, Class 0, was introduced later to represent objects in an evolutionary stage prior to that of Class I, where the mass in the envelope is substantially higher than that of the central protostar (Andre et al. 1993; Andre & Montmerle 1994). Traditional SED classes, however, may not always represent the actual physical evolutionary stages as described above, particularly in regions of high extinction: a highly extinguished Class II object could easily be misclassified as a Flat spectrum or a Class I source (McClure et al. 2010; Evans et al. 2009).

The number of objects in various SED classes have been used to estimate the relative lifetimes of the evolutionary stages (e.g. Wilking 1989; Greene et al. 1994; Kenyon & Hartmann 1995). Such studies carried out before the Spitzer era yielded an average lifetime of $\lesssim 0.1$ Myr for the Class 0 phase (Andre et al. 1993) and $0.1 - 0.2$ Myr for Class I phase (Greene et al. 1994; Kenyon & Hartmann 1995). Many of these studies suffered from small number statistics and possible differences in the earlier evolutionary classes between clouds. The large Spitzer survey of five nearby molecular clouds by the c2d team have significantly improved the data statistics (Evans et al. 2009; Enoch et al. 2009). The lifetimes of the protostellar evolutionary classes are estimated from the number counts of objects in various SED classes, under the assumptions of continuous star formation and a mean lifetime of 2 Myr for the Class II objects. The mean lifetime for the Class I phase was found to be $0.4 - 0.6$ Myr with an additional 0.4 Myr for the Flat SED phase (Evans et al. 2009). The average lifetime derived for the Class 0 phase is $0.1 - 0.2$ Myr. These lifetimes are significantly longer than most of the earlier estimates in the literature (Evans et al. 2009).
2.1. The ‘Luminosity Problem’

Most of the stellar mass is built during the embedded protostellar phase which lasts for $\sim 0.5$ Myr (Evans et al. 2009). A steady accretion rate of $1.0 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ would then be required to build a 0.5 $M_\odot$ star, which corresponds to an accretion luminosity of $L_{acc} = 6 L_\odot$. However, the observed median bolometric luminosity of most of the Class I protostars in the nearby clouds is $\lesssim 1 L_\odot$ (Kenyon et al. 1990; Motte & André 2001), significantly smaller than the expected accretion luminosity. Moreover, the observed luminosity is an upper limit for $L_{bol}$: only a small fraction of $L_{bol}$ is attributable to accretion (Muzerolle et al. 1998; White & Hillenbrand 2004). This ‘luminosity problem’ of protostars, first recognized by Kenyon et al. (1990), is essentially an accretion rate problem: the observed accretion rates in Class I protostars are significantly smaller than those required to build a star during the embedded protostellar phase.

The Spitzer observations of protostars in the nearby clouds confirm the ‘luminosity problem’ (Evans et al. 2009; Enoch et al. 2009). The observed $L_{bol}$ of most Class I sources are significantly lower than those predicted by the standard infall models with steady accretion (Evans et al. 2009; Dunham et al. 2009). The $L_{bol}$ distribution shows a dispersion of several orders of magnitude, with a few objects displaying higher $L_{bol}$ values than predicted by the models. Furthermore, Spitzer observations do not show any clear evidence for an early phase of rapid mass accretion, suggesting that most of the stellar mass is built during the Class I phase (Evans et al. 2009). The observed distribution of $L_{bol}$ of the Class I protostars in nearby clouds is better explained by protostellar evolutionary models with episodic mass accretion, rather than those with steady accretion (Dunham et al. 2009). All the available evidence seem to indicate that the accretion onto the protostar during the embedded phase is non-steady and time variable. This was first proposed by Kenyon et al. (1990), who suggested that the accretion during the embedded phase must be episodic with prolonged periods of very low accretion. Most the of the stellar mass is built during the high accretion events.

It has been suggested that the high accretion stage of the protostellar phase corresponds to the FU Ori objects (Kenyon et al. 1990; Hartmann 1998). FU Ori systems exhibit sudden increases in brightness ($\Delta V \sim 5$ mag) and remain luminous or decay slowly over decades (Herbig 1977; Hartmann & Kenyon 1996). The FU Ori outbursts are believed to be caused by the rapid increase in the accretion rates which can be as high as $10^{-4} M_\odot$ yr$^{-1}$ during the outburst (Hartmann & Kenyon 1996). In the low accretion state of the protostars, the material falling in from the envelope onto the disk at a much higher rate, piles up in the outer disk. The accumulation of the material makes the disks unstable; the onset of thermal or gravitational instabilities in the disk then transfers the bulk of the disk material onto the central star at high accretion rates, which is observed as the brief high luminosity FU Ori outburst (Hartmann & Kenyon 1996; Hartmann 1998).

2.2. Envelope-Disk Accretion in Protostars

The envelope infall signatures in Class 0/Class I protostars have been observed in the molecular lines in the submm and mm wavelengths (Ohashi 2004). However,
Figure 1. High-resolution Spitzer-IRS spectra (black line) of (a) NGC 1333 IRAS 4B (Watson et al. 2010) and (b) IRAS 13036-7644 (Manoj et al. 2010b). Except the [S I] and [Si II] lines, which originate from outflows, all the other lines seen in the spectra are from pure rotational transitions of water and OH. In both the panels, the observed spectra are compared to a simple plane-parallel LVG model (gray line,) showing water and OH lines, which originate in an envelope-disk accretion shock (see Watson et al. 2007).

these observations typically trace spatial scales of $\sim 0.01$ pc and densities of $10^5 - 10^6$ cm$^{-3}$ and thus probe large scale infall motions in the envelopes (e.g. Di Francesco et al. 2001). Direct observational evidence for the material falling onto the embedded disks in a protostar has been lacking until recently. The freely falling envelope material which acquires supersonic terminal infall velocities is thought to be decelerated within the accretion shocks at the disk surface (Ulrich 1976; Cassen & Moosman 1981; Neufeld & Hollenbach 1994). One of the most important Spitzer discoveries in protostellar studies has been the detection of the arrival of infalling envelope material on the disk in an envelope-disk accretion shock, through the mid-infrared emission lines of water and OH lines observed in protostars viewed face-on with the Infrared Spectrograph (IRS). This was first detected in NGC 1333-IRAS 4B, which shows a rich emission-line spectrum of water and OH (Watson et al. 2007) (see Figure 1). The relative intensities of the water lines indicate their origin in extremely dense ($10^{10} - 10^{12}$ cm$^{-3}$) and warm ($\sim 170$ K) gas. Detailed modeling shows that the gas is heated by a low velocity ($\sim 2$ km s$^{-1}$) envelope-disk accretion shock, caused by the envelope material landing on the disk in an annulus of 40 – 60 AU. The rate at which the envelope material is falling on the disk, obtained from the total water line luminosity under the assumption of water line emission being the major coolant, is found to be $0.7 \times 10^{-4}$ M$_\odot$ yr$^{-1}$, quite similar to the envelope infall rates estimated from molecular line observations (for details see Watson et al. 2007).

Watson et al. (2010) carried out a survey of 85 face-on Class 0/Class I protostars within 500 pc, with the Spitzer IRS high resolution modules to look for signatures of envelope-disk accretion and outflows in them. They detected water and OH lines in roughly half of their sample. An example of this, the high resolution mid-IR spectrum of IRAS 13036-7644, which is a bright Class 0 source in the small cloud DC303.8-14.2 towards Chamaeleon II, is shown in Figure 1 (Manoj et al. 2010b). The modeling of the spectra of the protostars, which show mid-IR emission lines of water and OH, indicates that the condi-
Figure 2. The envelope-disk accretion rate, estimated from the water and OH lines in the mid-IR spectra, of 18 protostars plotted against the protostellar accretion plus outflow rate. The dashed line represents infall rate equal to the protostellar accretion plus outflow rate. IRAS 4B and IRAS 13036-7644, whose spectra are shown in Figure 1, are labeled. Most protostars observed, show significantly higher envelope infall rates compared to the protostellar accretion and outflow rates, indicating that the material is accumulating in their disks.

The envelope-disk accretion shock in them are similar to that found for IRAS4B. With the new diagnostic of envelope-disk accretion rate made available by Spitzer, it is now possible to compare the various flows in a protostellar system. In Figure 2 the envelope-disk infall rate of the observed protostars is compared to the protostellar accretion plus outflow rate. The envelope-disk infall rate is estimated from the total luminosity of the water lines observed (see Watson et al. 2007). The protostellar accretion rate is computed from $L_{bol}$, assuming $\frac{R_*}{M_*} = \frac{10 R_*}{M_\odot}$, following the prescription of Evans et al. (2009) and Enoch et al. (2009). The outflow rate is computed from the luminosity of [Si II] line at 34.8 \(\mu\)m in the IRS spectra. The [Si II] line is a good proxy for the [O I] 63.2 \(\mu\)m line which measures the outflow rates, as it is a dominant coolant for densities of $10^3 - 10^4$ cm$^{-3}$ and outflow speeds of 30 − 150 km s$^{-1}$ (Hollenbach & McKee 1989). It is clear from Figure 2 that the envelope infall rates derived from water and OH lines for most protostars are at least an order of magnitude higher than the protostellar accretion and the outflow rate. This indicates that material is piling up in the disk and is not efficiently accreted onto the star or carried out by the outflow. This could eventually lead to FU Ori-like outburst which is caused when the material that is accumulated in the disk is accreted onto the central protostar in a massive accretion event. Thus, the flow imbalance in protostars,
measured from their mid-IR spectra, is consistent with, and argues strongly for episodic accretion in protostars.

3. Structure and Evolution of Protoplanetary Disks

The embedded phase in the protostellar evolution ends after most of the envelope mass has been transferred to the central star through the disk. A pre-main sequence star surrounded by an accretion disk is left behind. In such Class II objects, the emission from protoplanetary disks dominates the SED longward of 2 µm. The thermal emission from the dust grains in the disks, heated by the stellar radiation, is responsible for the excess emission in these young stars. The optically thin emission from the dust grains in the surface layers of the disk produces the silicate emission features centered at 10 and 20 µm seen in the mid-IR spectra. The optically thick emission from the deeper layers and the disk midplane dominates the mid-IR continuum. The detailed shape of the mid-IR continuum is related to the disk geometry and could be used to probe the vertical and radial structure of the disks (D’Alessio et al. 2006). The silicate emission features inform us on the size, shape and composition of dust grains in the disks (e.g. Bouwman et al. 2001). Spitzer observations in the mid-IR, probe the planet forming regions (∼1 – 10 AU) of protoplanetary disks (Dullemond et al. 2007; D’Alessio et al. 2006) and thus provide powerful diagnostics for the structure and evolution and the dust mineralogy of these disks.

Most solar-mass stars younger than ∼1 Myr appear to harbor disks around them; by ∼3 – 5 Myr most of them shed their disks (Haisch et al. 2001; Hillenbrand 2005; Hernández et al. 2008). Clues to the planet formation and disk dissipation processes must therefore be sought in 1 – 2 Myr protoplanetary disks where disk evolution in ‘action’ could be studied. Below, I summarize the results from the large Spitzer IRS survey of protoplanetary disks in the nearby 1 – 2 Myr old star forming regions of Taurus, Chamaeleon I (Cha I) and Ophiuchus carried out by the IRS_disks team (PI: Dan M. Watson).

3.1. Dust Sedimentation in Disks

The first step towards planet formation is the growth of subµm-sized grains in protoplanetary disks via coagulation. As the grains grow larger, they sink towards the disk mid-plane; both the grain growth and sedimentation deplete the amount of small dust grains in the disk surface layers. This reduces the opacity offered by the disk surface layers to the stellar radiation and as a result the amount of energy absorbed by the surface layers decreases. Consequently, the degree of flaring of the disk decreases, making the disks flatter: higher the degree of sedimentation, flatter are the disks (D’Alessio et al. 2006; Dullemond et al. 2007). The changes in the disk geometry is readily reflected in the mid-IR SEDs. Self-consistent accretion disks models, which incorporate the effects of dust settling, show that the shape of the mid-IR continuum is a good measure of the degree of dust settling (D’Alessio et al. 2006). In particular, the SED slope between 13 and 31 µm has been used to characterize the vertical distribution of the dust in the disks (D’Alessio et al. 2006; Furlan et al. 2006; Watson et al. 2009).
A careful comparison of the observed mid-IR continuum slope of young protoplanetary disks in Taurus, Cha I and Ophiuchus with that predicted by the models shows that significant dust settling has occurred in $1 - 2$ Myr old protoplanetary disks. The dust-to-gas mass ratio in the surface layers of most of these disks is found to be lower by factors of 100 to 1000 compared to the standard ISM value, indicating a high degree of sedimentation in these disks (Furlan et al. 2006; McClure et al. 2010; Manoj et al. 2010a). Further, the degree of sedimentation and the frequency of sedimented disks in the $\sim 1$ Myr old Taurus, the $\sim 2$ Myr old Cha I and the $\lesssim 1$ Myr Ophiuchus star forming regions are found to be similar (Furlan et al. 2009; McClure et al. 2010; Manoj et al. 2010a). This is demonstrated in Figure 3, where the distribution of the continuum spectral slope evaluated between 13 and 31 µm from the Spitzer IRS spectra of the young stars in these three regions are compared. The range and frequency of the distribution of the observed $n_{13-31}$ index in quite similar in all the three regions. This suggests that significant dust settling occurs in protoplanetary disks by $\lesssim 1$ Myr. A comparative study of the median mid-IR SEDs of these three regions also confirms that overall, the vertical structure of the disks in these three regions are very similar (Furlan et al. 2009).

3.2. Grain Growth and Crystallization

The silicate emission features observed in the mid-IR spectra of young stars have been used to infer the dust properties in protoplanetary disks. Silicate emission feature produced by the subµm-sized amorphous grains in the disks tend to be narrow and peaked. Grain growth and crystallization makes the silicate emission profile broad and structured (e.g. Bouwman et al. 2001). Detailed analysis of the shape and strength of silicate features in the Spitzer IRS spectra of a large sample of Class II objects in the Taurus region, show evidence for significant grain growth and crystallization in those disks (Watson et al. 2009). More quantitative spectral decomposition modeling of the IRS spectra shows a
wide range in the degree of grain growth and crystallization in young disks (e.g. Sargent et al. 2009; Juhász et al. 2009). In general, the degree of dust processing (grain growth and crystallization) is found to correlate well with the degree of dust sedimentation in disks: less sedimented disks show evidence for relatively less processed dust whereas flat and highly sedimented disks appear to have highly processed grains (Watson et al. 2009; Sargent et al. 2009; McClure et al. 2010). However, no strong correlations have been found between various stellar parameters and the degree of dust processing (Watson et al. 2009).

3.3. Transitional Disks

One of the important contributions of Spitzer in the area of disk evolution has been the identification and characterization of a large number of disks with significantly altered radial structures. Such disks have been called ‘transitional disks’ to suggest that they are possibly in an evolutionary stage in between that of an optically thick disk and an optically thin disk (Skrutskie et al. 1990). Their SEDs are characterized by a significant deficit of flux at wavelengths $\lesssim 10 \mu m$ compared to that of the optically thick, full disks, along with a sharply rising continuum and excess emission comparable to, or higher than, that of a typical Class II disk at mid- and far-infrared wavelengths (Calvet et al. 2005; Espaillat et al. 2007a; Kim et al. 2009; Furlan et al. 2009) (see Figure 4). Detailed modeling of their SEDs shows that transitional disks have inner holes or gaps in the radial dust opacity distribution that are surrounded by an optically thick outer disk with a ‘wall’ at its inner edge. Emission from this ‘wall’, where the abrupt transition from the inner optically thin region to outer optically thick disk takes place, is responsible for the sharply rising continuum longward of $13 \mu m$ observed in these objects (Calvet et al. 2005; Espaillat et al. 2007b, 2008). Several transitional disks have now been identified from Spitzer photometric and spectroscopic surveys of nearby young clusters (Furlan et al. 2009; Kim et al. 2009; Muzerolle et al. 2010). Most transitional disks are Classical T Tauri stars (CTTs) meaning that they are active accretors; however, their accretion rates are slightly lower than the median accretion rate of other Class II disks in the region (Najita et al. 2007).

The presence of holes and gaps in transitional disks, inferred from their observed SEDs, suggests that significant disk evolution has occurred in these disks. Various disk evolutionary mechanisms have been proposed to explain the origin of inner holes/gaps in transitional disks: substantial grain growth, planet formation, photoevaporation and MRI-induced inner disk clearing are some of them (Dullemond & Dominik 2005; Marsh & Mahoney 1992; Quillen et al. 2004; Alexander et al. 2006; Chiang & Murray-Clay 2007). It has been suggested that the Jovian mass planets opening up gaps and holes in the disks can explain most of the observed characteristics of a large sample of transitional disks (Kim et al. 2009; Najita et al. 2007; Rice et al. 2003; Calvet et al. 2005; Espaillat et al. 2007b).

In close binary systems (few AU separation) stellar companions can clear inner holes in the circumbinary disks (Artymowicz & Lubow 1994); the observed SEDs of such systems would appear transitional-disk-like, as has been demonstrated in the case of CoKu Tau/4 (Ireland & Kraus 2008). However, as argued by Muzerolle et al. (2010), not all close binaries show evidence for significant
inner holes. Objects which show these SED characteristics are likely to be in transition.

**Evolved Disks**  The large photometric and spectroscopic surveys with *Spitzer* have also identified another class of disks whose excess emission is significantly lower than that of the Class II median for that region. These disks differ from the transitional disks discussed above in that their excess flux, even at longer wavelengths, is considerably lower than that of the Class II median. Also, they do not have a rising continuum longward of 13 \( \mu \)m indicating that the outer disk probably is not as optically thick as that of Class II disks and the ‘wall’ emission is not significant. This class of disks has been identified by various names in the literature: ‘evolved disks’, ‘anemic disks’, ‘homologously depleted disks’ (Lada et al. 2006; Hernández et al. 2007b; Currie et al. 2009; Luhman et al. 2009). The SED of an evolved disk is compared to that of a ‘transitional disk’ in Figure 4.

Another crucial difference between classical transitional disks which have inner holes/gaps and the evolved disks is that the most evolved disks are Weak-line T Tauri stars (WTTs). They have stopped accreting or are accreting at very low rates (Muzerolle et al. 2010; Manoj et al. 2010a). It is not clear if evolved disks fit into an evolutionary sequence in which the optically thick disk develops inner gaps and holes and eventually dissipates inside out. It is possible that they represent a different evolutionary path for the primordial optically thick disks where the disk dissipation does not proceed inside out. In this sense, evolved disks have also been taken to be in a transitional phase between a primordial optically thick disks and optically thin debris disks (Lada et al. 2006; Currie et al. 2009; Muzerolle et al. 2010). However, it is unclear what mechanisms can dissipate primordial disks simultaneously at all radii.

### 3.4  Disk Lifetimes

Ground based surveys which used the near-IR excess and emission lines diagnostics to probe the innermost parts (\( \ll 1 \) AU) of the disks have shown that the median lifetime of accretion disks around young stars is only a few...
Myr (Haisch et al. 2001; Hillenbrand 2005; Hernández et al. 2005; Manoj et al. 2006). *Spitzer* observations in the mid-IR, which probe the planet forming regions in the disk ($\lesssim 10$ AU), have confirmed this. The *Spitzer* studies of disk fraction in clusters show that most disks dissipate in about $3 - 5$ Myr (e.g. Hernández et al. 2008; Mamajek 2009). A small fraction of disks appear to last longer: the well known examples of long-lived accretion disks include members of η Cha (6 Myr), TW Hya (8 Myr) and 25 Ori (8 Myr) groups, PDS 66 (7 – 17 Myr) and St Ηα 34 (8 – 25 Myr) (Mamajek 2009, and references therein). Disk dissipation timescale is also found to depend on the central stellar mass: disk lifetimes are shorter for intermediate mass (spectral type late B to F) stars (Carpenter et al. 2006; Lada et al. 2006; Hernández et al. 2007a; Currie et al. 2009) and marginally longer for brown dwarfs compared to that for solar-mass (spectral type K to early M) stars (Luhman et al. 2005; Mamajek 2009).

The observed low frequency ($\lesssim 10\%$) of transitional disks in young clusters, has long been taken as evidence for a relatively short-lived (less than a few hundred thousand year) transitional phase, during which an optically thick disk turns into an optically thin disk (Skrutskie et al. 1990; Wolk & Walter 1996; Prato & Simon 1997). The primordial disks last for a few Myr, but disk dissipation, once initiated, occurs rapidly, on timescales $\ll 1$ Myr. This is sometimes referred to as the ‘two-timescale’ behavior of disk dissipation (Alexander et al. 2006). The *Spitzer* studies have significantly improved the statistics of well characterized transitional disks in nearby young clusters. Some studies have reported a relatively high fraction ($40 – 50\%$) of transitional and evolved disks in a few young clusters (Sicilia-Aguilar et al. 2008; Currie et al. 2009). Based on this, it has been argued that the lifetimes of transitional disks are comparable to that of primordial disks and that the disk dissipation is not as rapid as previously thought (Currie et al. 2009; Currie & Kenyon 2009). However, in some of these studies, flat well-settled disks and primordial disks around late M type stars have been misidentified as transitional or evolved disks, thereby increasing their apparent frequency (see Luhman et al. 2009; Furlan et al. 2009; Ercolano et al. 2009). The frequency of transitional and evolved disks has also been found to have an age dependence: a few percent at $1 - 2$ Myr rising to $10 – 20\%$ at $3 – 10$ Myr (Muzerolle et al. 2010). While this trend may be real, the higher frequency of disks in transition in older clusters may not necessarily imply a longer transition timescale. It is more likely that star formation has stopped in older ($\geq 3$ Myr) clusters, and as a result, there is no steady supply of primordial disks, which shoots up the ratio of the number of transitional disks to primordial disks. When the different star formation histories of $2 – 10$ Myr clusters are properly taken into account, the transitional phase appear to last only for about $10 – 15\%$ of the median primordial disk lifetime ($\sim 3$ Myr) (Luhman et al. 2009).

## 4. Dispersion in Disk Evolution

The evolution of protoplanetary disks has now been studied using various observational diagnostics, including the disk properties measured in the mid-IR wavelengths by *Spitzer*. The disk evolutionary indicators such as disk fraction in a cluster, disk optical depth, accretion rate, disk masses, degree of dust
sedimentation and grain processing in the disk, on average, show a discernible evolutionary trend with age which is broadly consistent with the theoretical expectations (e.g. Hernández et al. 2008; Furlan et al. 2009; Hartmann 1998; Carpenter et al. 2005). However, the observed disk properties also show a large dispersion. The disk fraction in clusters, in general, decreases with age, but in every age bin there is a large scatter (Hillenbrand 2005, 2008; Mamajek 2009). While most disks dissipate in about 3 – 5 Myr, a significant fraction (20 – 30%) of stars appear to lose their disks as early as ∼ 1 Myr (see Hernández et al. 2008; Mamajek 2009). A small fraction of stars retain their disks at ages ≥ 5 Myr. Even in a given 1 – 2 Myr old cluster, disk optical depths (measured as the IR slope and/or IR excess) show a large dispersion. While most disks show evidence for significant dust settling and are relatively flat, a few disks with a high degree of flaring show no evidence for dust sedimentation (D’Alessio et al. 2006; Furlan et al. 2006; Watson et al. 2009; McClure et al. 2010; Manoj et al. 2010a). Transitional disks have developed radial holes/gaps in them while the evolved disks are about to become optically thin at all radii (Kim et al. 2009; Furlan et al. 2009; McClure et al. 2010; Manoj et al. 2010a). The measured accretion rates of young stars in a cluster also show a large dispersion: there are high accretors (accreting at rates of ∼ 10^{-7} M_⊙ yr^{-1}) and non-accretors among systems with similar central star properties (Hartmann et al. 1998). Disk masses of otherwise identical systems in the same cluster are different by a few orders of magnitude (Andrews & Williams 2005). The degree of grain growth and crystallization inferred for T Tauri disks in a cluster span a wide range (Watson et al. 2009; Sargent et al. 2009; Olofsson et al. 2009).

Is the observed dispersion in disk properties in a cluster, caused by the age spread within the cluster? It is unclear if the dispersion in the measured luminosity distribution of members of a cluster or association indicate a true age spread or observational or other random errors. Some authors have suggested that the WTTS and transitional disks are older than CTTS in a cluster (Bertout et al. 2007; Fang et al. 2009) while others find no evidence for such an age difference (Kenyon & Hartmann 1995; Herbig 1998; Hartmann 2001; Herbig & Dahm 2002; Dahm & Simon 2005). True age spreads are likely to be much smaller than the apparent age spreads inferred from the luminosity dispersion (Hartmann 2001; Hillenbrand et al. 2008). Recent Monte carlo simulations suggest that bulk of the cluster members are consistent within errors as having the same age with the exception of a few outliers (Hillenbrand 2008; Hillenbrand et al. 2008; Hillenbrand 2009). It appears that the observed dispersion in disk properties in a cluster cannot be entirely due to the age spread. The stars of apparently same ages can have different disks. Disk evolution probably is not a function of age alone. Other possible factors contributing to the observed dispersion in disk properties are stellar multiplicity (see Bouwman et al. 2006; Cieza et al. 2009) and effect of immediate environment such as cluster density (Luhman et al. 2008) and proximity to an O-type star (Balog et al. 2006; Hernández et al. 2008; Mercer et al. 2009). However, it is unclear if these effects can fully explain the observed dispersion in disk evolution. Current evidence seems to suggest that systems with similar stellar mass, age, multiplicity status and environment can have different disk properties (e.g. Watson et al. 2009; Furlan et al. 2009; McClure et al. 2010; Manoj et al. 2010a).
How else do we understand the observed dispersion in disk evolution in otherwise identical systems? If all the disks started out the same - i.e. if the initial conditions like disk mass, surface density and radius are the same - then is the observed dispersion a result of different disk dissipation mechanisms, with different characteristic timescales being dominant in different disks? Or is it that these mechanisms start operating at different times in different disks? Could it be that the disk dissipation and planet formation processes are stochastic in nature? Indeed, planet formation simulations show that disks with similar initial properties can result in very different final configurations (Thommes et al. 2008).

However, if the initial configurations of protoplanetary disks are different, they would look different at any instant of time, even if they all go through the same temporal evolutionary sequence. Some of the self-consistent simulations of planet formation in protoplanetary disks show that the outcome of the process strongly depends on the initial conditions of the disks such as disk mass and the viscosity parameter $\alpha$, among others. Disks with an initial mass of $0.1 \text{ M}_\odot$ and low $\alpha$ ($\sim 0.001$) tend to form giant planets early, which migrate extensively and clear out the disks faster. On the other hand, low mass disks ($\lesssim 0.01 \text{ M}_\odot$) with high $\alpha$ ($\sim 0.01$) are too slow to form planets and last longer (Thommes et al. 2008). In this picture, some of the long-lived disks such as TW Hya, PDS 66 and St 34 could represent disks which have failed to form planets (see Hartmann et al. 2005), the controversial detection of a hot Jupiter around TW Hya notwithstanding (Setiawan et al. 2008; Huéldamo et al. 2008). Thus, the later evolution and the appearance of a few Myr old protoplanetary disks are affected and shaped by their initial conditions. It is quite possible that the observed dispersion in the properties of disks in a cluster is just a reflection of the dispersion in the initial properties of these disks.

The initial conditions during the formation of protoplanetary disks is set by the star formation process. If episodic accretion is the norm during the embedded phase of the protostellar evolution, then the disks undergo a series of high accretion events. The frequency and magnitude of these events must clearly have an effect on the subsequent evolution and the observed properties of protoplanetary disks. The observed dispersion in the disk evolution could then partly be understood as the star formation process determining the initial disk configuration before the onset of planet formation.

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