Initial Conditions of Planet Formation: 
Lifetimes of Primordial Disks

Eric E. Mamajek

Department of Physics & Astronomy, University of Rochester, Rochester, NY 14627-0171

Abstract. The statistical properties of circumstellar disks around young stars are important for constraining theoretical models for the formation and early evolution of planetary systems. In this brief review, I survey the literature related to ground-based and Spitzer-based infrared (IR) studies of young stellar clusters, with particular emphasis on tracing the evolution of primordial (“protoplanetary”) disks through spectroscopic and photometric diagnostics. The available data demonstrate that the fraction of young stars with optically thick primordial disks and/or those which show spectroscopic evidence for accretion appears to approximately follow an exponential decay with characteristic time $\sim 2.5$ Myr (half-life $\sim 1.7$ Myr). Large IR surveys of $\sim 2–5$ Myr-old stellar samples show that there is real cluster-by-cluster scatter in the observed disk fractions as a function of age. Recent Spitzer surveys have found convincing evidence that disk evolution varies by stellar mass and environment (binarity, proximity to massive stars, and cluster density). Perhaps most significantly for understanding the planeticity of stars, the disk fraction decay timescale appears to vary by stellar mass, ranging from $\sim 1$ Myr for $> 1.3 M_\odot$ stars to $\sim 3$ Myr for $< 0.08 M_\odot$ brown dwarfs. The exponential decay function may provide a useful empirical formalism for estimating very rough ages for YSO populations and for modeling the effects of disk-locking on the angular momentum of young stars.

Keywords: stars: pre-main sequence, planetary systems: protoplanetary disks, planetary systems: formation
PACS: 97.82.Jw, 97.10.Fy, 97.10.Gz

INTRODUCTION

For the 2nd Subaru International Conference on “Exoplanets and Disks: Their Formation and Diversity”, the goal of my introductory talk was to succinctly summarize some recent observational constraints on the parameters describing circumstellar disks relevant to planet formation. Rather than give short shrift to many subtopics within too few pages, I have elected to focus this manuscript on only one aspect of disk evolution: primordial disk lifetimes. For reviews on recent results on other aspects of circumstellar disk evolution, I refer the reader to the other reviews in this volume that were presented at the Kona meeting: especially those on disk geometry and coronagraphic polarimetry by M. Perrin, observations of debris disks by A. Moro-Martin, dynamical theory of planets, planetesimals, and dust by M. Wyatt, imaging debris disks by P. Kalas, modeling circumstellar disks by S. Wolf, spectroscopy of disks by M. Goto, characterizing gas and dust around main sequence stars by C. Chen, and dust growth in disks by H. Tanaka. For more exhaustive recent reviews on circumstellar disks around young stars, I refer the reader to the book by Hartmann [1], and the reviews by Beckwith et al. [2], Hillenbrand [3], Hillenbrand [4], Meyer et al. [5], Monin et al. [6], and Alexander [7].
Investigations of circumstellar disks and extrasolar planets have experienced explosive (and seemingly parallel) growth over the past two decades. Our knowledge of extrasolar planets has been driven mostly by enhanced techniques of optical spectroscopy (e.g. Doppler surveys), and more recently, photometry (e.g. transits, microlensing). Our knowledge regarding circumstellar disks orbiting young stars has been driven mostly by infrared and millimeter photometry and imaging, and more recently, spectroscopy (with obvious contributions to understanding accretion from optical spectroscopy). Protoplanetary disks set the initial conditions of planet formation, and to understand the diversity of planetary systems, we need to understand the physics, chemistry, and evolution of primordial disks.

**PRIMORDIAL DISKS**

The existence of primordial disks around young stars was originally inferred through the spectroscopic evidence for accretion among classical T Tauri stars (<2 $M_\odot$ pre-main sequence stars) and evidence of circumstellar dust structures, later confirmed to be geometrically distributed as disks [see review by [1], and references therein]. Classical T Tauri stars have typical isochronal ages of <5 Myr, typical accretion rates of $\sim 10^{-7} - 10^{-9}$ $M_\odot$ yr$^{-1}$ [8], disk masses of $\sim 5 \times 10^{-3}$ $M_\odot$ ($\sim 0.5$ dex dispersion), and median disk/star mass ratios of $\sim 0.5\%$ [9]. Among the classical T Tauri star populations in star-forming regions are weak-line T Tauri stars – pre-MS stars lacking spectroscopic or photometric evidence for circumstellar dust. The disk masses inferred for weak-lined T Tauri stars from submillimeter observations are almost always <10$^{-3.5}$ $M_\odot$ [9]. Integration of the minimum-mass solar nebula model over the range of orbital radii for planets in our solar system leads to a disk mass of $\sim 10^{-2}$ $M_\odot$, [i.e. $\sim 2 \times$ the typical disk mass inferred for classical T Tauri stars; [10]], indicating that by the time low-mass stars evolve to the weak-line T Tauri phase their disk surface density is likely to be at least an order of magnitude too low to form planets like Jupiter and Saturn. By ages of $\sim 10$ Myr, samples of typical solar-type stars appear to have less than <tens of $M_{Earth}$ of gas within a few AU, and <few $M_{Earth}$ of circumstellar gas at orbital radii of $\sim 0-40$ AU [11]. Early in the protostar’s life, the disk (and protostar) are fed by infall from a vast molecular envelope associated with cloud cores. The molecular clouds forming embedded star clusters appear to disperse within $\sim 3$ Myr of star formation [12], effectively removing the source of dense gas feeding primordial circumstellar disks. The mechanisms for removing reservoirs of circumstellar gas are numerous, including viscous accretion radially inward toward the star (with some material subsequently ejected outward via jet), outward viscous decretion (through conservation of angular momentum), accretion into planets, photoevaporation by the central star, or even photoevaporation by a neighboring star [1, 7]. Given the numerous mechanisms for dispersing primordial disks, it is perhaps unsurprising that we find that typical disk lifetimes are similar to the brief timescale when the protostar is immersed in a sea of dense molecular gas.

While the longevity of the Sun’s protoplanetary disk is unknown, there are weak constraints. Detailed modeling of the geophysical, thermal, and rotational evolution of Saturn’s outermost large, regular satellite Iapetus by Castillo-Rogez et al. [13] requires
that Iapetus accreted most of its mass within ∼3.4–5.4 Myr\(^1\) after the formation of the solar system [defined by the formation of Ca-Al-rich inclusions 4,567.2 ± 0.6 Myr ago; \(^{15}\)]. This suggests that Saturn itself had accreted the majority of its mass [which is at least ∼67–80% hydrogen & helium; \(^{16}\)] from the Sun’s protoplanetary disk within ∼3.4–5.4 Myr. Variations of the ‘Nice model’ by Thommes et al. \(^{17, 18}\) can form the gas giants Jupiter and Saturn through core accretion, form Uranus and Neptune as ‘failed’ gas giants in the ∼5–10 AU zone, and scatter them to near their current orbital radii – all within 5 Myr – for models where the disk surface density is roughly an order of magnitude higher than the canonical Hayashi \(^{19}\) minimum-mass solar nebula. These results suggest that the formation of giant planets is at least plausible within the ∼10\(^6\)–7 yr lifetime of gas-rich protoplanetary disks, given the observed physical properties of observed primordial disks.

**PRIMORDIAL DISK LIFETIMES**

Photometric and spectroscopic observations appear to be telling us that the circumstellar disks of young stars undergo radically divergent evolutionary paths at a very young age. Early ∼3-4 \(\mu\)m surveys suggested \(^{20}\), and recent Spitzer surveys of nearby young stellar groups have confirmed \(^{21, 22}\), that primordial accretion disks around lower-mass stars tend to last longer than around higher-mass stars. However within a given mass range, there appears to be quite a dispersion in disk lifetimes. Shorter disk lifetimes have been demonstrated for stars which are higher in mass [e.g. \(^{22}\)], in multiple systems [e.g. \(^{23, 24}\)], and which are in the immediate vicinity (<0.5 pc) of O-type stars [e.g. \(^{25, 26}\)], or are in denser stellar clusters [e.g. \(^{27}\)]. Hence there appear to be multiple variables affecting primordial disk lifetimes. Although the well-cited disk survey of Haisch et al. \(^{28}\) pointed towards a maximum disk lifetime of 6 Myr, we now know of many convincing examples of older accretors: multiple examples in the ∼6–10 Myr-old η Cha, TW Hya, and 25 Ori groups, the accretor PDS 66 in Lower Cen Crux (stellar age ≃7–17 Myr), and the unusual binary StH\(\alpha\) α34 (∼8–25 Myr) \(^{4}\).

A modern version of the “Haisch-Lada\(^2\) plot” (disk fraction vs. sample age) is shown in Fig. 1. While the observational definitions of what constitutes a star with a probable primordial accretion disk can vary slightly from study to study, this plot represents a best effort to summarize the situation with the data available. As demonstrated by Haisch et al. \(^{29}\) from the sample of known T Tauri stars in Taurus \(^{43}\), 3-4 \(\mu\)m excesses trace spectroscopically identified classical T Tauri stars ∼100% of the time, while ∼2 \(\mu\)m excesses trace classical T Tauri stars only ∼70% of the time. Similarly, Silverstone et al. \(^{44}\) detected 3.6 \(\mu\)m excess emission solely around previously known classical T Tauri stars among a large sample of FGK-type stars with ages ∼3 Myr to ∼3 Gyr. With these findings in mind, I consider stars to be accretors whether they are (1) spectroscopically identified as classical T Tauri stars (through a H\(\alpha\) emission criterion), and/or (2) through L-band or Spitzer 3.6 \(\mu\)m excess, and/or (3) their emission beyond 3.6 \(\mu\)m was classified

---

\(^{1}\) Although originally quoted as 2.5–5 Myr, the timescale was recently updated by the same group \(^{14}\) using revised heat production values for \(^{26}\)Al decay.
FIGURE 1. Age of stellar sample vs. fraction of stars with primordial disks (the “Haisch-Lada” plot) either through Hα emission or infrared excess diagnostics. The best fit exponential decay curve is plotted with timescale $\tau_{\text{disk}} = 2.5$ Myr. Disk fraction data are plotted for (in age order) NGC 2024 [0.3 Myr; 29], NGC 1333 [1 Myr; 30], Taurus [1.5 Myr; 31], Orion Nebula Cluster [1.5 Myr; 28], NGC 7129 [2 Myr; 32], NGC 2068/21 [2 Myr; 33], Cha I [2.6 Myr; 34, 27], IC 348 [2.5 Myr; 21], σ Ori [3 Myr; 35], NGC 2264 [3.2 Myr; 28], Tr 37 [4.2 Myr; 36], Ori OB1b [4 Myr; 35], Upper Sco [5 Myr; 22], NGC 2366 [5 Myr; 37], γ Vel [5 Myr; 38], λ Ori [5 Myr; 39], η Cha [6 Myr; 40], TW Hya [8 Myr; 31], 25 Ori [8 Myr; 35, 38], NGC 7160 [11.8 Myr; 36], β Pic [12 Myr; 41], UCL/LCC [16 Myr; 42].

by the authors as being likely due to primordial disk due to the SED shape or strength of the IR excess. The nature of some disks is unclear. Lada et al. [21] and others have identified stars with weak IR excesses whose nature as stars with either accretion disks of lower optical depth or simply warm dusty debris disks is at present ambiguous. Given the rarity of “transition disks” (disks with large inner holes), their inclusion or exclusion is usually within the disk fraction uncertainties, and will have negligible impact on this analysis. The fraction of stars in the transition phase has been noted to be very high in a young sample [e.g. ~1 Myr CrA; 46]. I have not yet attempted to disentangle the effects of stellar mass in Fig. 1, so the reader should simply interpret the disk fractions as being most representative of the low-mass population of stars ($< 2$ M⊙) as they dominate the stellar samples. I have omitted results for more distant clusters whose disk fraction

---

2 A glossary for common terminology for young stellar objects with disks (the “diskionary”) was recently compiled by Evans et al. [45].
statistics were completely dominated by high mass stars (>1–2 M⊙).

Ages and age uncertainties are taken from the published studies, however minimum age uncertainties of ±1 Myr or ±30% (whichever is greater) were adopted if uncertainties were not quoted. The usual caveats exist for the ages plotted in Fig. 1. There are significant differences in the ages estimated using different evolutionary tracks, and even as a function of mass for a single set of tracks [47], and none of the tracks have consistently matched predictions of masses with dynamically-constrained masses over the stellar mass spectrum.

Fig. 1 demonstrates that any statements regarding the lifetimes of primordial disks need to be statistical in nature. Statements to the effect that “all disks disappear” by ∼3 or ∼6 Myr are oversimplified assessments. I have decided to be provocative and plot an exponential function to fit the data. An exponential is convenient as it has a value of one at age zero (assuming that all stars are born with disks), trends towards zero as age increases (all primordial accretion disks eventually disappear), and one only needs to fit one parameter (the e-folding timescale τ_disk). When simultaneously minimizing the residuals in the disk fraction and age (Fig. 1), I arrive at a best fit timescale of τ_disk = 2.5 Myr. Unfortunately the best fit has reduced χ^2 ≃ 2.5, suggesting that either (1) the uncertainties in the assessed disk fractions and ages are significantly underestimated (by factor of √2.5 ≃ 1.6), and/or (2) there are significant cluster-to-cluster differences in disk fraction decay time, and/or (3) an exponential function is simply inadequate for fitting the trend. As cluster-to-cluster variations have been demonstrated – especially at age ∼5 Myr [22, 25, 27, 48], and cluster ages are especially uncertain, I suspect that these two factors are the primary causes of the high χ^2 of the best fit. Removing individual clusters from the fit varies τ_disk by <10%, which is probably a reasonable estimate of the precision in τ_disk given our current knowledge of the ages of these star-forming regions.

Recent Spitzer surveys have quoted disk fractions as a function of stellar mass in cluster samples. We can now look at these data in a different way, and combine the various results and quote a single metric (τ_disk) to more concisely summarize the observed trend and allow comparison between non-coeval samples. The exponential decay formalism is convenient for calculating e-folding times for various subsamples where we have sparse data available. If disk fraction evolves as an exponential decay, and a cluster of a given age is observed to have a disk fraction that is assumed to lie on that decay curve, one can estimate the primordial disk decay timescale from that subsample:

\[ \tau_{\text{disk}} = -\tau / \ln(f_{\text{disk}}) \]  

Where τ is the age of the sample, and f_disk is the observed disk fraction. Using this technique, I will estimate preliminary values of τ_disk for stellar subsamples segregated by stellar mass.

What is the characteristic timescale for the primordial disks around brown dwarfs? Results from early surveys identifying 3-4 µm excesses among small samples of substellar objects hinted that half of all disks were likely dispersed within ∼1–3 Myr [49, 50]. More recent disk fractions for larger samples of substellar objects have been quoted in a series of papers by Luhman and collaborators, notably for IC 348 [τ = 2.5 Myr; f_disk = 42%; 51], Cha I [τ ≃ 2.5 Myr; f_disk = 50%; 51], and σ Ori [τ = 3 Myr; f_disk ≃ 60%; 51].
To this set, I include the disk fraction of substellar objects in Upper Sco ($\tau = 5$ Myr) from Mohanty et al. [50], which ranged from $\sim 5$–20% depending on whether the accretors were defined via spectroscopic or photometric techniques (we assume $12.5 \pm 7.5\%$). Note that the individual $f_{\text{disk}}$ values have uncertainties of $\sim 7$–20%, which translate into significant errors in $\tau_{\text{disk}}$, especially for small $f_{\text{disk}}$. Using equation [1], these disk fractions and ages translate into decay timescales of $\tau_{\text{disk}} \simeq 2.9, 2.9, 5.9, \text{ and } 2.4$ Myr, for IC 348, Cha I, $\sigma$ Ori, and Upper Sco, respectively. These results suggest that the typical primordial disk decay timescale for brown dwarfs is approximately $\tau_{\text{disk}} \simeq 3$ Myr – i.e. marginally longer than for stellar samples ($\sim 2.5$ Myr).

What is the characteristic decay timescale for primordial disks around high mass stars? The small disk fractions, and low numbers of high mass stars in stellar groups, make this surprisingly difficult to quantify. Hernández et al. [52] conducted a systematic survey of the nearest OB associations to quantify the fraction of Herbig Ae/Be stars ($> 2 M_\odot$). Their results found $f_{\text{disk}} \leq 5\%$ for all of their samples (3-15 Myr), and for their two youngest samples: $f_{\text{disk}} = 5.1 \pm 2.0\%$ in Ori OB1bc (3.5 $\pm$ 3 Myr) and $f_{\text{disk}} = 4.3 \pm 1.8\%$ in Tr 37. Using Spitzer to survey the $\sim 2.5$ Myr-old IC 348 group, Lada et al. [21] found a disk fraction of $11 \pm 6\%$ among $> 1.3 M_\odot$ stars. The Hernández et al. [35] survey of the $\sim 3$ Myr-old $\sigma$ Ori clusters does not provide spectral types or masses, but interpolation of their Fig. 11 and Table 3 suggests a disk fraction of $> 1.3 M_\odot$ stars of $\sim 10\%$, consistent with Lada et al.’s findings for IC 348. [22] found no evidence for primordial disks around a sample of 92 BAFG-type ($> 1.3 M_\odot$) members of $\sim 5$ Myr-old Upper Sco (consistent with $f_{\text{disk}} < 4\%; 95\%$ confidence), however 7/21 ($\sim 35\%; \text{ K0–K6}$) of $\sim 1-1.3 M_\odot$ stars have primordial disks! The results from these three Spitzer surveys are consistent with $\tau_{\text{disk}} \simeq 1.2$ Myr for $> 1.3 M_\odot$ stars. These results are also broadly consistent with the frequency of $> 2 M_\odot$ Herbig Ae/Be stars in nearby associations [52].

It is possible that $\tau_{\text{disk}}$ could be used as a very coarse age estimator for multi-wavelength investigations of distant star-forming regions imaged both in the infrared and in X-rays where there is an estimate of the young stellar population both with primordial disks (class O/I/II objects) and without (class III objects). The mean age of the population would then be approximately $\tau \simeq -\ln f_{\text{disk}} \times \tau_{\text{disk}}$ where $f_{\text{disk}} = N_{\text{disk}} / (N_{\text{disk}} + N_{\text{no disk}})$ and $\tau_{\text{disk}} \sim 2.5$ Myr. This estimate would only provide the coarsest of ages (as we now have evidence that disk lifetimes are dependent on stellar mass and environment), however, in the quest for useful stellar age estimators, even the bluntest of diagnostics can be helpful.

In summary, it is clear from Spitzer surveys that the lifetime of primordial disks is not only a function of age, but stellar mass, multiplicity, and proximity to O-type stars. Disk fraction appears to vary roughly as an exponential decay, with typical timescale $\tau_{\text{disk}} \simeq 2.5$ Myr. This constant appears to vary from $\sim 1.2$ Myr for $> 1.3 M_\odot$ stars to $\sim 3$ Myr for brown dwarfs. Although numerous mechanisms have been posited for depleting circumstellar disks, we need more observations to better constrain the disk evolution as a function of these stellar parameters (and for other untested parameters, e.g. metallicity), and more theoretical work to model these depletion mechanisms. It is clear that there are ample future opportunities for observations with the Subaru telescope to improve our understanding of the formation and early evolution of planetary systems.
ACKNOWLEDGMENTS

I thank the SOC for the Subaru conference for inviting me to give this review talk, and I thank Michael Meyer and Dan Watson for contributing slides. Thanks also go to Alex Shvonski and Mark Pecaut for commenting on an early draft.

REFERENCES

1. L. Hartmann, *Accretion Processes in Star Formation*, Accretion processes in star formation / Lee Hartmann. Cambridge, UK ; New York : Cambridge University Press, 1998. (Cambridge astrophysics series ; 32) ISBN 0521435072., 1998.
2. S. V. W. Beckwith, T. Henning, and Y. Nakagawa, *Protostars and Planets IV* pp. 533–+ (2000), [arXiv:astro-ph/9902241](https://arxiv.org/abs/astro-ph/9902241).
3. L. A. Hillenbrand, *ArXiv Astrophysics e-prints* (2002), [arXiv:astro-ph/0210520](https://arxiv.org/abs/astro-ph/0210520).
4. L. A. Hillenbrand, *ArXiv Astrophysics e-prints* (2005), [arXiv:astro-ph/0511083](https://arxiv.org/abs/astro-ph/0511083).
5. M. R. Meyer, D. E. Backman, A. J. Weinberger, and M. C. Wyatt, “Evolution of Circumstellar Disks Around Normal Stars: Placing Our Solar System in Context,” in *Protostars and Planets V*, edited by B. Reipurth, D. Jewitt, and K. Keil, 2007, pp. 573–588.
6. J.-L. Monin, C. J. Clarke, L. Prato, and C. McCabe, “Disk Evolution in Young Binaries: From Observations to Theory,” in *Protostars and Planets V*, edited by B. Reipurth, D. Jewitt, and K. Keil, 2007, pp. 395–409.
7. R. Alexander, *New Astronomy Review* 52, 60–77 (2008), [0712.0388](https://arxiv.org/abs/0712.0388).
8. E. Gullbring, L. Hartmann, C. Briceno, and N. Calvet, *ApJ* 492, 323–+ (1998).
9. S. M. Andrews, and J. P. Williams, *ApJ* 631, 1134–1160 (2005), [arXiv:astro-ph/0506187](https://arxiv.org/abs/astro-ph/0506187).
10. S. J. Desch, *ApJ* 671, 878–893 (2007).
11. I. Pascucci, U. Gorti, D. Hollenbach, J. Najita, M. R. Meyer, J. M. Carpenter, L. A. Hillenbrand, G. J. Herczeg, D. L. Padgett, E. E. Mamajek, M. D. Silverstone, W. M. Schlingman, J. S. Kim, E. B. Stobie, J. Bouwman, S. Wolf, J. Rodmann, D. C. Hines, J. Lunine, and R. Malhotra, *ApJ* 651, 1177–1193 (2006), [arXiv:astro-ph/0606669](https://arxiv.org/abs/astro-ph/0606669).
12. L. Hartmann, J. Ballesteros-Paredes, and E. A. Bergin, *ApJ* 562, 852–868 (2001), [arXiv:astro-ph/0108023](https://arxiv.org/abs/astro-ph/0108023).
13. J. C. Castillo-Rogez, D. L. Matson, C. Sotin, T. V. Johnson, J. I. Lunine, and P. C. Thomas, *Icarus* 190, 179–202 (2007).
14. D. L. Matson, J. C. Castillo-Rogez, T. V. Johnson, N. Turner, M. H. Lee, and J. I. Lunine, “26Al Decay: Heat Production and Revised Age for Iapetus,” in *Lunar and Planetary Institute Science Conference Abstracts*, 2009, vol. 40 of *Lunar and Planetary Institute Science Conference Abstracts*, pp. 2191–+.
15. Y. Amelin, A. N. Krot, I. D. Hutcheon, and A. A. Ulyanov, *Science* 297, 1678–1683 (2002).
16. T. Guillot, *Planet. & Sp. Sci.* 47, 1183–1200 (1999), [arXiv:astro-ph/9907402](https://arxiv.org/abs/astro-ph/9907402).
17. E. W. Thommes, M. J. Duncan, and H. F. Levison, *AJ* 123, 2862–2883 (2002), [arXiv:astro-ph/0111290](https://arxiv.org/abs/astro-ph/0111290).
18. E. W. Thommes, M. J. Duncan, and H. F. Levison, *Icarus* 161, 431–455 (2003), [arXiv:astro-ph/0303269](https://arxiv.org/abs/astro-ph/0303269).
19. C. Hayashi, *Progress of Theoretical Physics Supplement* 70, 35–53 (1981).
20. C. J. Lada, A. A. Muench, K. E. Haisch, Jr., E. A. Lada, J. F. Alves, E. V. Tolstree, and S. P. Willner, *AJ* 120, 3162–3176 (2000), [arXiv:astro-ph/0008280](https://arxiv.org/abs/astro-ph/0008280).
21. C. J. Lada, A. A. Muench, K. L. Luhrman, L. Allen, L. Hartmann, T. Megeath, P. Myers, G. Fazio, K. Wood, J. Muzerolle, G. Rieke, N. Siegler, and E. Young, *AJ* 131, 1574–1607 (2006), [arXiv:astro-ph/0511638](https://arxiv.org/abs/astro-ph/0511638).
22. J. M. Carpenter, E. E. Mamajek, L. A. Hillenbrand, and M. R. Meyer, *ApJ* 651, L49–L52 (2006), [arXiv:astro-ph/0609372](https://arxiv.org/abs/astro-ph/0609372).
23. J. Bouwman, W. A. Lawson, C. Dominik, E. D. Feigelson, T. Henning, A. G. G. M. Tielens, and L. B. F. M. Waters, *ApJ* 653, L57–L60 (2006), [arXiv:astro-ph/0610853](https://arxiv.org/abs/astro-ph/0610853).
24. L. A. Cieza, D. L. Padgett, L. E. Allen, C. E. McCabe, T. Y. Brooke, S. J. Carey, N. L. Chapman, M. Fukagawa, T. L. Huard, A. Noriga-Crespo, D. E. Peterson, and L. M. Rebull, ApJ 696, L84–L88 (2009), [arXiv:astro-ph/0903.3057].
25. Z. Balog, J. Muzerolle, G. H. Rieke, K. Y. L. Su, E. T. Young, and S. T. Megeath, ApJ 660, 1532–1540 (2007), arXiv:astro-ph/0701741.
26. E. P. Mercer, J. M. Miller, N. Calvet, L. Hartmann, J. Hernandez, A. Sicilia-Aguilar, and R. Gutermuth, AJ 138, 7–18 (2009).
27. K. L. Luhman, L. E. Allen, P. R. Allen, R. A. Gutermuth, L. Hartmann, E. E. Mamajek, S. T. Megeath, P. C. Myers, and G. G. Fazio, ApJ 675, 1375–1406 (2008), [arXiv:astro-ph/0803.1019].
28. K. E. Haisch, Jr., E. A. Lada, and C. J. Lada, ApJ 664, 481–500 (2007), [arXiv:astro-ph/0704.1963].
29. K. E. Haisch, Jr., E. A. Lada, and C. J. Lada, AJ 126, 2997–3006 (2003), arXiv:astro-ph/0305284.
30. R. A. Gutermuth, S. T. Megeath, J. Muzerolle, L. E. Allen, J. L. Pipher, J. Muzerolle, A. Porras, E. Winston, and G. Fazio, ApJ 674, 336–356 (2008), [arXiv:astro-ph/0710.1860].
31. D. Barrado y Navascués, and E. L. Martín, AJ 126, 2997–3006 (2003), arXiv:astro-ph/0309284.
32. R. A. Gutermuth, S. T. Megeath, J. Muzerolle, L. E. Allen, J. L. Pipher, P. C. Myers, and G. G. Fazio, ApJS 149, 374–378 (2004), [arXiv:astro-ph/0406091].
33. K. L. Luhman, ApJ 602, 816–842 (2004), [arXiv:astro-ph/0402509].
34. K. L. Luhman, ApJ 629, 1784–1799 (2007), [arXiv:astro-ph/0709.0912].
35. J. Hernandez, N. Calvet, C. Briceño, L. Hartmann, A. K. Vivas, J. Muzerolle, J. Downes, L. Allen, and R. Gutermuth, ApJ 675, 1375–1406 (2008), [arXiv:astro-ph/0803.1019].
36. A. Sicilia-Aguilar, L. Hartmann, N. Calvet, S. T. Megeath, J. Muzerolle, L. Allen, P. D’Alessio, B. Merín, J. Stauffer, E. Young, and C. Lada, ApJ 638, 897–919 (2006).
37. K. M. Flaherty, and J. Muzerolle, AJ 135, 966–983 (2008), [arXiv:astro-ph/0712.1601].
38. K. L. Luhman, ApJ 602, 816–842 (2004), [arXiv:astro-ph/0406091].