The Astrophysical Journal, 683:L183–L186, 2008 August 20

EVIDENCE FOR A TURNOVER IN THE INITIAL MASS FUNCTION OF LOW-MASS STARS AND SUBSTELLAR OBJECTS: ANALYSIS FROM AN ENSEMBLE OF YOUNG CLUSTERS

M. Andersen
Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125; mortena@ipac.caltech.edu
and
M. R. Meyer, J. Greissl, and A. Aversa
Steward Observatory, University of Arizona, Tucson, AZ 85721
Received 2008 June 5; accepted 2008 July 1; 2008 July 29

ABSTRACT

We present a combined analysis of the low-mass initial mass function (IMF) for seven star-forming regions. We first demonstrate that the ratios of stars to brown dwarfs are consistent with a single underlying IMF. By assuming that the underlying IMF is the same for all seven clusters and by combining the ratio of stars to brown dwarfs from each cluster, we constrain the shape of the brown dwarf IMF and find it to be consistent with a lognormal IMF. This provides the strongest constraint yet that the substellar IMF turns over ($dN/dM \propto M^{-\alpha}$, $\alpha < 0$).

Subject headings: stars: formation — stars: low-mass, brown dwarfs — stars: luminosity function, mass function — stars: pre–main-sequence

1. INTRODUCTION

Speculations concerning the existence and frequency of brown dwarfs can be traced to before the introduction of the term (Kumar 1963; Hayashi & Nakano 1963). Since then, wide-field surveys have uncovered hundreds of candidates in the field and revealed two new spectral types, the L and T dwarfs (Kirkpatrick 2005). Yet the frequency of brown dwarfs compared to stars has remained a topic of confusion and debate. In a pioneering work, Reid et al. (1999) attempted the first census of the substellar initial mass function (IMF) based on results from the Two Micron All Sky Survey (Skrutskie et al. 2006). They presented evidence for a low-mass IMF that was more shallow than a Salpeter (Salpeter 1955) slope, suggesting that brown dwarfs were not a significant contributor to dark matter. Allen et al. (2005) used a Bayesian approach to constrain the power-law slope below 0.08 $M_{\odot}$ to be in the range $-0.6 < \alpha < 0.6$ with a confidence level of 60%, where a Salpeter slope is $\alpha = 2.35$. These results indicate that, although brown dwarfs do not contribute significantly to the mass of typical stellar populations, they might still be as abundant as stars (Chabrier 2002).

The classical approach to deriving the mass function for stars and substellar objects is to take an observed luminosity function and apply a mass-luminosity relationship in order to derive the present-day mass function. Then, corrections, based on the theory of stellar evolution, permit one to estimate an *initial* mass function from the present-day mass function (see, e.g., Scalo 1986, Kroupa 2001, and Chabrier 2003 for complete descriptions of this process). The confounding variable in these analyses is the star formation history of the Galactic disk, which is vital for substellar objects whose mass-luminosity relationship evolves with time.

A different approach is to use star clusters of known age as laboratories to measure the IMF. Open clusters are, in principle, good candidates because of their richness. Yet they suffer from the effects of dynamical evolution, mass segregation, and evaporation (e.g., Lada & Lada 2003). Young (<10 Myr) embedded clusters are attractive alternatives as they are compact and rich (from hundreds to thousands of stars within 0.3–1 pc), and yet to emerge as unbound OB/T associations, and the low-mass objects are 10–1000 times more luminous than their older open cluster counterparts (0.1–16 Gyr) because they shrink and cool as they age.

Indeed, embedded clusters have been the targets of aggressive photometric and spectroscopic surveys in an attempt to search for variations in the IMF as a function of initial conditions. Meyer et al. (2000) found that the ratio of high-mass (1–10 $M_{\odot}$) to low-mass (0.1–1 $M_{\odot}$) stars for an ensemble of young clusters within 1 kpc was consistent with (1) each other and (2) having been drawn from the field star IMF. More recent studies have pushed well into the substellar mass regime (see Luhman et al. 2007 for a recent review). There have been some claims for variations in the brown dwarf IMF between nearby star-forming regions. Briceño et al. (2002) argued that the low-density Taurus dark cloud had a dearth of brown dwarfs compared to the rich Orion Nebula Cluster (ONC). However, this preliminary result has been updated as additional data have become available and as the statistics improved for both clusters (Guieu et al. 2006; Slesnick et al. 2004).

Here we use observations of seven nearby star clusters to constrain the combined brown dwarf IMF. In § 2 we describe the data, illustrate that there is no strong evidence for variation in the substellar IMF between the star-forming regions, and outline our approach to constrain the low-mass IMF. In § 3 we present our results, and in § 4 we discuss our results in the context of previous work as well as theories of star (and substellar object) formation.

2. THE APPROACH

We have compiled the ratio of stars to brown dwarfs in nearby, well-studied young embedded clusters and the Pleiades. The regions included in this study are described briefly below, where the ratio of stars (0.08–1.0 $M_{\odot}$) to brown dwarfs (0.03–0.08 $M_{\odot}$) is calculated. For all the regions, we consider the *system* IMF, uncorrected for multiplicity within 200 AU. The sample is focused on embedded clusters, in which spectroscopy has been used to determine the age of the cluster, field star contamination has been taken into account, and an extinction-limited sample has been defined. Furthermore, we have included the Pleiades, because it is one of the best-studied open

TABLE 1
Ratio of Stars to Substellar Objects in Young Clusters

Cluster	Distance (pc)	Age (Myr)	N_{obj}	Maximum A_V (mag)	$\frac{N(0.08–1.0)}{N(0.03–0.08)}$	$P(R \geq R_{obs})$ (Chabrier)	$P(R \geq R_{obs})$ ($\alpha = -0.6$)	$P(R \geq R_{obs})$ ($\alpha = 0$)	$P(R \geq R_{obs})$ ($\alpha = 0.6$)
Taurus	140	1–3	112	4.0	$6.0^{+2.6}_{-2.0}$	0.286	0.030	0.002	2.47×10^{-5}
ONC	480	1	185	2.0	$3.3^{+0.8}_{-0.7}$	0.993	0.744	0.365	0.066
Mon R2	830	1	19	10	$8.5^{+13.6}_{-5.8}$	0.359	0.182	0.093	0.035
Chamaeleon	160	2	24	5.0	$4.0^{+3.7}_{-2.1}$	0.795	0.569	0.375	0.187
Pleiades	125	120	200	1.0	$4.9^{+1.5}_{-1.2}$	0.560	0.056	0.002	7.39×10^{-6}
NGC 2024	460	1	50	11.0	$3.8^{+2.1}_{-1.5}$	0.877	0.591	0.317	0.097
IC 348	315	2	168	4.0	$8.3^{+3.3}_{-2.6}$	0.031	3.00×10^{-4}	1.88×10^{-6}	8.21×10^{-10}

Notes.—The first six columns give the name of the cluster, the distance, the age, the number of objects in the sample, the extinction limit used for the embedded clusters, and the ratio. The last four columns give the probability of the observed ratio having been drawn from the assumed IMFs.

clusters and because its substellar IMF has been estimated. The break point at 0.08 $M_\odot$ has been adopted in accordance with the break point for the Kroupa (2001) IMF, similar to the characteristic mass in the Chabrier (2003) single-object IMF. Only a few of the clusters adopted here have the IMF derived in an extinction-limited sample reaching 0.02 $M_\odot$, and we have opted for 0.03 $M_\odot$ as a lower mass limit to obtain a larger sample of clusters.

Taurus.—Luhman (2004) imaged a 4 deg^2 region of Taurus that focused on the denser filaments, to identify cluster candidates. Candidates were confirmed as cluster members, by the use of follow-up intermediate-resolution optical spectroscopy, on the basis of their effective temperature, luminosity, and spectral features. In total, 112 objects were confirmed members with derived masses between 0.03 and 1.0 $M_\odot$ and extinctions $A_V \leq 4$ mag. Some 96 objects were stars, and 16 were brown dwarfs. Thus, the ratio of stars to brown dwarfs in Taurus was found to be $R = 96/16 = 6.0^{+2.6}_{-2.0}$, where the errors are estimated using the method of Gehrels (1986).

IC 348.—Luhman et al. (2003) imaged a 42′ × 28′ region of the IC 348 cluster to identify cluster candidates. By the use of intermediate-resolution spectroscopy, most of the candidates were confirmed as cluster members on the basis of their effective temperature, luminosity, and spectral features, which indicated that the objects were young. In total, Luhman et al. (2003) found 168 cluster members with masses between 0.03 and 1.0 $M_\odot$ and extinctions $A_V \leq 4$ mag. The ratio of stars to brown dwarfs was found to be $R = 8.3^{+3.3}_{-2.6}$.

Mon R2.—Andersen et al. (2006) imaged the central 1′ × 1′ of the embedded cluster associated with Mon R2 by utilizing the Near-Infrared Camera and Multi-Object Spectrometer on board the *Hubble Space Telescope* (*HST*). An extinction-limited sample $A_V \leq 10$ mag was defined, and a total of 19 objects were detected with masses between 0.03 and 1 $M_\odot$. The ratio of stars to brown dwarfs was found to be $R = 8.5^{+13.6}_{-5.8}$.

Chameleon 1.—Luhman (2007) obtained an extinction-limited sample in Chameleon 1 that was complete down to 0.01 $M_\odot$ for $A_V \leq 5$ mag, by use of observations of a 0.22° × 0.28° region with the Advanced Camera for Surveys on board *HST* and a subsequent spectroscopic follow-up of cluster member candidates. The subsample from 0.03 to 1 $M_\odot$ includes 24 objects, and the ratio R was found to be $R = 4.0^{+3.7}_{-2.1}$.

Pleiades.—The Pleiades is one of the best-studied open clusters, and numerous derivations of the IMF have been published. Here we focus on the survey by Moraux et al. (2003), who covered a 6.4 deg^2 region of the Pleiades. The survey had a saturation limit of 0.48 $M_\odot$. For higher masses, the survey was combined with a mass function using the database by Prosser & Stauffer (1998). The Pleiades suffer relatively low ($A_V < 1$ mag), mostly uniform, extinction, with negligible impact on the completeness of this sample, so we did not apply a reddening criterion. The ratio of stars to brown dwarfs was found to be $R = 4.9^{+1.5}_{-1.2}$.

The Orion Nebular Cluster.—The ONC has been the subject of extensive studies (Hillenbrand 1997; Hillenbrand & Carpenter 2000; Luhman et al. 2000; Muench et al. 2002). We take the adopted ratio of stars to substellar objects from the study of Slesnick et al. (2004). The total sample, covering the central 5.1′ × 5.1′, contains approximately 200 objects with masses between 0.02 and 0.6 $M_\odot$ and $A_V \leq 15$ mag. Using their Figure 14, and extrapolating the slope from 0.08–0.6 to 1.0 $M_\odot$ (one additional bin in their plot), we arrive at a ratio of stars to substellar objects of $R = 3.3^{+0.8}_{-0.7}$.

NGC 2024.—The ratio of stars to brown dwarfs in NGC 2024 was found by Levine et al. (2006), from their photometric and spectroscopic study covering the central 10′ × 10′. They assigned masses to the photometric objects on the basis of the mass distribution in each magnitude bin, determined from the spectroscopic sample in a similar manner as in Slesnick et al. (2004). The result was that a total of 148 objects in their survey area had masses between 0.02 and 1 $M_\odot$ and extinctions $A_V \leq 15$ mag. Based on their Figure 9, we find that there are 27 objects between 0.03 and 0.08 $M_\odot$, resulting in a ratio of stars to substellar objects of $R = 3.8^{+2.1}_{-1.5}$.

Table 1 shows the ratio of stars to brown dwarfs for nearby embedded clusters and the Pleiades, as described above, and the distribution of ratios is shown in Figure 1. The weighted mean of the ratios is found to be 4.3, and the standard deviation of the weighted mean is 1.6. All of the measurements presented are consistent with the weighted mean within 2 σ. There is thus little evidence for variation in the low-mass IMF between the different regions, and we have adopted the hypothesis that the IMF is universal. Under this assumption, the complete set of IMF determinations can be combined to place constraints that are stronger than each of the individual measurements.

3. THE RESULTS

For each cluster, we have calculated the probability of obtaining the observed ratio of stars to brown dwarfs for a given IMF or greater. The ratio of stars to brown dwarfs drawn from a given sample size with an assumed IMF is determined by the binomial theorem. The predicted distribution of ratios from both segmented power laws and a (Chabrier 2005; $dN/(d\log m) \propto \exp(\log m - \log m_0)^2/2\sigma^2$, $m_0 = 0.25$, $\sigma = 0.55$) lognormal IMF for a cluster of 100 objects with unresolved binaries is shown in the lower panel in Figure 1. The peak mass in the lognormal is slightly higher, and the width is slightly more narrow than is presented in Chabrier (2003). The change in the best-

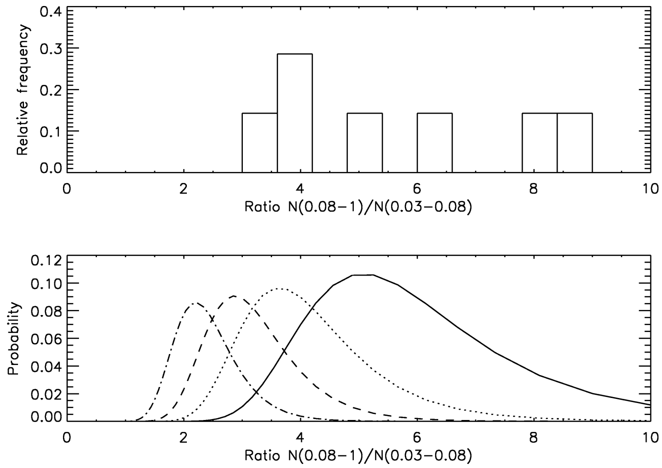

FIG. 1.—*Top panel*: Histogram of the observed ratios of stars to brown dwarfs described in the text and summarized in Table 1. *Bottom panel*: Binomial distribution for a cluster with 100 objects drawn from either the Chabrier (*solid line*), the falling ($\alpha = -0.6$; *dotted line*), the flat ($\alpha = 0$; *long-dashed line*), or the rising ($\alpha = 0.6$; *long-dash–dotted line*) IMF. Distributions that continue to rise in linear mass units below the hydrogen-burning limit are least consistent with the observations.

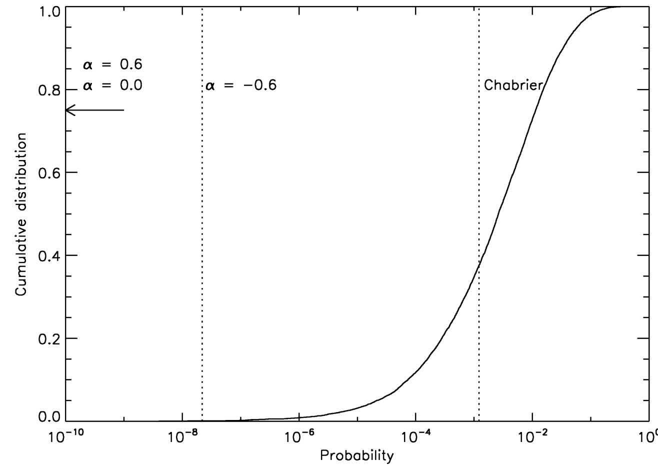

FIG. 2.—Test of the distribution of the product of probabilities if seven clusters are randomly drawn from a Chabrier IMF. For each of the seven clusters, the probability of obtaining the ratio of stars to brown dwarfs or higher drawn is calculated, and the product of the seven probabilities is determined for each of the 10,000 simulations. The vertical dotted lines indicate the combined probability of obtaining the observed ratios of stars to brown dwarfs for the Chabrier IMF (*right vertical dotted line*) and the power-law IMF that is falling in linear units in the brown dwarf regime ($\alpha = 0.6$; *left vertical dotted line*). The probabilities for the flat and rising IMFs are both outside the plotted range and did not happen in any of the Monte Carlo simulations.

fit parameters in Chabrier (2005) is due to an updated luminosity relation (Reid et al. 2002). A similar increase in the peak mass has been suggested by Covey et al. (2008).

The slope of the segmented power law between 0.08 and 1.0 $M_\odot$ was chosen to be $\alpha = 1.3$, and the slope has been varied below 0.08 $M_\odot$ in the range $-0.6 < \alpha < 0.6$, which is the 60% confidence interval presented by Allen et al. (2005). It is clear that the rising and flat IMFs ($\alpha = 0.6$ and 0.0, respectively) are difficult to reconcile with the observed distribution of ratios. We have quantitatively assessed the likelihood of obtaining the observed ratios from an assumed IMF as follows. For each of the seven measurements, the probability of obtaining that ratio or higher, assuming an underlying IMF, is calculated by adopting the binomial theorem. The product of the seven probabilities is then calculated. We find these values, which we refer to as the binomial tail product, or BTP, to be 0.0012, 2.2×10^{-8}, 1.8×10^{-14}, and 1.0×10^{-24}, for a Chabrier, falling, flat, and rising IMF, respectively. If each cluster sample was drawn from the assumed underlying IMF, and if each cluster had an infinite number of objects, we would expect the combined product of this statistic for a sample of seven clusters to be $0.5^7 = 7.8 \times 10^{-3}$. The lognormal IMF appears to reproduce the observed ratios best, followed by the falling power-law IMF.

How consistent are the measured ratios with a Chabrier IMF and with what confidence can other IMFs be ruled out? We have investigated that question by performing Monte Carlo simulations. We created an artificial set of seven clusters, each containing 100 objects (the median number of objects in our sample). The 100 objects are then assigned masses according to the assumed underlying IMF, and the ratio of stars to brown dwarfs for each cluster is determined. For each of the ratios, the probability of observing that value or higher is calculated, and the seven probabilities are multiplied, as was done for the observed set of clusters. The BTP for the observed clusters is then compared with the distribution of BTPs just derived. Because each factor in the BTP is drawn from a binomial distribution (of varying shapes), each IMF gives the same expected distribution of BTPs. Figure 2 shows the cumulative distribution of BTPs for a set of 10,000 simulations.

Overplotted are the probabilities obtained above for the observed set of clusters assuming the four different underlying IMFs. We find that 37% of the simulations have a probability equal to or lower than what was found assuming a Chabrier IMF, and in only ~0.05%–0.1% of the simulations is the probability equal to or lower than found assuming a falling power-law IMF. In none of the simulations did the low probabilities for the flat or rising power-law IMFs occur ($P < 0.01\%$). The results indicate that the IMF is falling in the brown dwarf regime and that the Chabrier IMF is consistent with the observations.

4. DISCUSSION

The results on the IMF presented here are based on the system IMF, including binaries unresolved within 200 AU. As such, they may be difficult to compare directly with the locally derived (within 20 pc) field IMF discussed in Allen et al. (2005) that suffers from a much smaller fraction of unresolved binaries. Yet the overall binary frequency for ultracool dwarfs (M6 and later) appears to be low (~20%; Burgasser et al. 2007), and furthermore the *relative* number of companions with separations >15 AU and mass ratios $q > 0.4$ may be extremely low around very cool stars (~1%; Allen 2007).

Indeed, if the companion mass ratio distribution follows the Chabrier IMF at wide separations, then one could expect fewer very low mass companions as one surveys progressively lower mass primaries (e.g., Siegler et al. 2005), consistent with the observations by McCarthy & Zuckerman (2004). If the IMF follows a Chabrier IMF in the brown dwarf regime below 0.03 $M_\odot$ (say, down to the opacity limit for fragmentation of ~0.001–0.004 $M_\odot$; Whitworth & Stamatellos 2006), then the number of stars below 1 $M_\odot$ will outnumber brown dwarfs 4.7 to 1.

The sense of our results, that the mass function is falling in the BD regime, is consistent with various ideas put forward to explain the shape of the IMF (Bonnell et al. 2007 and references therein). Building on the ideas of Larson (2005), Bonnell et al. (2006) produced an IMF that is only weakly dependent on the Jeans mass through dynamical interactions in the cluster. However, Allen (2007) show that the turbulent fragmentation models by Bate & Bonnell (2005) predict too few low-mass binary systems.

Goodwin et al. (2004), on the other hand, suggest that the IMF should peak at higher masses in regions with low turbulence (e.g. Taurus), which would result in a higher ratio of stars to brown dwarfs. The lack of a strong variations in the ratio of stars to brown dwarfs is a problem for the turbulence models in general; for example, magnetic turbulence models predict strong variations in the low-mass IMF as a function of Mach number and density (Padoan & Nordlund 2002). If the preliminary results indicated here are borne out through further observations, then models that depend only weakly on initial conditions would be required (e.g., Adams & Fatuzzo 1996; Hennebelle & Chabrier 2008).

Possible IMF variations at least within 1 kpc are smaller than can be detected by comparing the currently observed clusters. Thus, there are two challenges in detecting IMF variations: (1) One needs clusters with a well-sampled population to minimize the inherently stochastic nature of populating an IMF, and (2) a larger set of clusters is needed to detect even small IMF variations with initial conditions. Although it appears that the variations in the IMF down to 30 $M_{\rm Jup}$ are modest, we still expect that variations will be seen at the lowest masses where the opacity limit for fragmentation can be reached (Low & Lynden-Bell 1976), and the metallicity of the star-forming region could be imprinted in the lower mass limit.

We thank Joanna Levine, Kevin Luhman, and Cathy Slesnick for helpful discussions, as well as Neill Reid, Charles Lada, and Pavel Kroupa for comments on a draft of this Letter. The referee is acknowledged for a very fast response and for suggestions that improved the manuscript. Finally, we thank the organizers of the Cool Stars 14 Splinter Session entitled "The Formation of Low-Mass Protostars and Proto–Brown Dwarfs" for the opportunity to present a preliminary version of this work. M. R. M. gratefully acknowledges the support of a Cottrell Scholar award from the Research Corporation, NASA grant GO-9846 from the Space Telescope Science Institute, and the Arizona Space Grant Consortium.

REFERENCES

Adams, F. C., & Fatuzzo, M. 1996, ApJ, 464, 256
Allen, P. R. 2007, ApJ, 668, 492
Allen, P. R., Koerner, D. W., Reid, I. N., & Trilling, D. E. 2005, ApJ, 625, 385
Andersen, M., Meyer, M. R., Oppenheimer, B., Dougados, C., & Carpenter, J. 2006, AJ, 132, 2296
Bate, M. R., & Bonnell, I. A. 2005, MNRAS, 356, 1201
Bonnell, I. A., Clarke, C. J., & Bate, M. R. 2006, MNRAS, 368, 1296
Bonnell, I. A., Larson, R. B., & Zinnecker, H. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 149
Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, ApJ, 580, 317
Burgasser, A. J., Reid, I. N., Siegler, N., Close, L., Allen, P., Lowrance, P., & Gizis, J. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 427
Chabrier, G. 2002, ApJ, 567, 304
———. 2003, PASP, 115, 763
———. 2005, in The Initial Mass Function 50 Years Later, ed. E. Corbelli & F. Palle (Dordrecht: Springer), 41
Covey, K. R., et al. 2008, preprint (arXiv:0807.2452)
Gehrels, N. 1986, ApJ, 303, 336
Goodwin, S. P., Whitworth, A. P., & Ward-Thompson, D. 2004, A&A, 419, 543
Guieu, S., Dougados, C., Monin, J.-L., Magnier, E., & Martín, E. L. 2006, A&A, 446, 485
Hayashi, C., & Nakano, T. 1963, Prog. Theor. Phys., 30, 460
Hennebelle, P., & Chabrier, G. 2008, ApJ, submitted (arXiv:0805.0691)
Hillenbrand, L. A. 1997, AJ, 113, 1733
Hillenbrand, L. A., & Carpenter, J. M. 2000, ApJ, 540, 236
Kirkpatrick, J. D. 2005, ARA&A, 43, 195
Kroupa, P. 2001, MNRAS, 322, 231
Kumar, S. S. 1963, ApJ, 137, 1121
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Larson, R. B. 2005, MNRAS, 359, 211
Levine, J. L., Steinhauer, A., Elston, R. J., & Lada, E. A. 2006, ApJ, 646, 1215
Low, C., & Lynden-Bell, D. 1976, MNRAS, 176, 367
Luhman, K. L. 2004, ApJ, 617, 1216
———. 2007, ApJS, 173, 104
Luhman, K. L., Joergens, V., Lada, C., Muzerolle, J., Pascucci, I., & White, R. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson: Univ. Arizona Press), 443
Luhman, K. L., Rieke, G. H., Young, E. T., Cotera, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, ApJ, 540, 1016
Luhman, K. L., Stauffer, J. R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C. J. 2003, ApJ, 593, 1093
McCarthy, C., & Zuckerman, B. 2004, AJ, 127, 2871
Meyer, M. R., Adams, F. C., Hillenbrand, L. A., Carpenter, J. M., & Larson, R. B. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 121
Moraux, E., Bouvier, J., Stauffer, J. R., & Cuillandre, J.-C. 2003, A&A, 400, 891
Muench, A. A., Lada, E. A., Lada, C. J., & Alves, J. 2002, ApJ, 573, 366
Padoan, P., & Nordlund, Å. 2002, ApJ, 576, 870
Prosser, C. F., & Stauffer, J. R. 1998, Open Cluster Database, http://www.noao.edu/noao/staff/cprosser
Reid, I. N., Gizis, J. E., & Hawley, S. L. 2002, AJ, 124, 2721
Reid, I. N., et al. 1999, ApJ, 521, 613
Salpeter, E. E. 1955, ApJ, 121, 161
Scalo, J. M. 1986, Fundam. Cosmic Phys., 11, 1
Siegler, N., Close, L. M., Cruz, K. L., Martín, E. L., & Reid, I. N. 2005, ApJ, 621, 1023
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Slesnick, C. L., Hillenbrand, L. A., & Carpenter, J. M. 2004, ApJ, 610, 1045
Whitworth, A. P., & Stamatellos, D. 2006, A&A, 458, 817