CLUSTER DENSITY AND THE IMF

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Abstract
Observed variations in the IMF are reviewed with an emphasis on environmental density. The local field IMF is not a dependable representation of star-forming regions because of uncertain assumptions about the star formation history. The remote field IMF studied in the LMC by several authors is clearly steeper than most cluster IMFs, which have slopes close to the Salpeter value. Local field regions of star formation, like Taurus, may have relatively steep IMFs too. Very dense and massive clusters, like super star clusters, could have flatter IMFs, or inner-truncated IMFs. We propose that these variations are the result of three distinct processes during star formation that affect the mass function in different ways depending on mass range. At solar to intermediate stellar masses, gas processes involving thermal pressure and supersonic turbulence determine the basic scale for stellar mass, starting with the observed pre-stellar condensations, and they define the mass function from several tenths to several solar masses. Brown dwarfs require extraordinarily high pressures for fragmentation from the gas, and presumably form inside the pre-stellar condensations during mutual collisions, secondary fragmentations, or in disks. High mass stars form in excess of the numbers expected from pure turbulent fragmentation as pre-stellar condensations coalesce and accrete with an enhanced gravitational cross section. Variations in the interaction rate, interaction strength, and accretion rate among the primary fragments formed by turbulence lead to variations in the relative proportions of brown dwarfs, solar to intermediate mass stars, and high mass stars. The observed IMF variations may be explained in this way.

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1. Introduction

The initial stellar mass function proposed by Edwin Salpeter in 1955 followed remarkably soon after the discovery of star formation itself.
Only several years earlier, Ambartsumian (1947) noted that the clusters h and χ Persei and NGC 6231 were too rarefied to resist galactic tidal forces. He said they should be elongated by galactic shear, and because they were not, they had to be young, expanding, and dispersing. Soon after, Blaauw (1952) found the predicted 10 km s\(^{-1}\) proper motions in the ζ Perseus association, and Zwicky (1953) proposed that stellar expansion followed gas expulsion from bound newborn clusters. This was the beginning of the recognition that stars had to form and evolve continuously (Spitzer 1948; Hoyle 1953).

Salpeter (1955) reasoned that if stars form continuously, and if their lifetimes depend on mass because of nuclear burning with a steep mass-luminosity relation, then many more remnants from massive stars than from low mass stars should populate the Milky Way disk. Consequently, the stellar birth rate is a shallower function of mass than the present day mass distribution.

The local field initial stellar mass function (IMF) derived by Salpeter (1955) was based on the available population studies, some of which were old even then, and on simple assumptions about stellar lifetimes and galactic star formation history. The result was a power law initial mass function with a slope of \(\Gamma \sim -1.35\) (when plotted with equal intervals of \(\log M\)). Considering the improvements in modern stellar data, there is no reason to expect the mass function derived in 1955 would be the same as today’s. Indeed, subsequent studies almost always got steeper field IMFs for the solar neighborhood: Scalo (1986) got \(\Gamma \sim -1.7\) at intermediate to high mass, and Rana (1987) got \(\Gamma \sim -1.8\) for \(M > 1.6 \, M_\odot\). The Salpeter value of \(\Gamma \sim -1.35\) predicts three times more massive stars (\(10 - 100 \, M_\odot\)) than intermediate mass stars (\(1 - 10 \, M_\odot\)) compared to the Scalo or Rana functions. Such an excess can be ruled out for the local field today.

The steep slope of field IMFs becomes even more certain in recent studies. Parker et al. (1998) derived \(\Gamma = -1.80 \pm 0.09\) for the LMC field that was far away from the HII regions catalogued by Davies, Elliot & Meaburn (1976). Note the small statistical error in this study. Massey et al. (1995, 2002) also surveyed the remote field in the LMC and SMC: at distances greater than 30 pc from Lucke & Hodge (1970) or Hodge (1986) OB associations, in a survey complete to 25 \(M_\odot\), \(\Gamma \sim -3.6\) to \(-4\) for a constant star formation rate during the last 10 My. There were 450 stars in the most recent Massey et al. LMC sample, which would give a statistical uncertainty in the slope of only \(\pm 0.15\) (Elmegreen 1999).

These steep field IMF slopes are reminiscent of that found by Garmany et al. (1982). In a survey of the solar neighborhood out to 2.5 kpc, and complete for \(M > 20 \, M_\odot\), Garmany et al. found \(\Gamma = -1.6\) overall,
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They proposed that the difference between these values arose because of an excess of massive stars in the associations of the Carina and Cygnus spiral arms, which are inside the Solar circle. That is, the low density regions have steep IMF slopes and the high density regions have shallow IMF slopes. This observation led to the concept of bimodal star formation: Güsten & Mezger (1983) proposed that metallicity gradients in the Galaxy arose from an interarm IMF that was steeper than the spiral arm IMF. Larson (1986) proposed that a sub-population formed with a shallow IMF would have more remnants contributing to dark matter. Such extreme bimodality was never confirmed, although the steep field IMF slope persisted. Also, in contrast to Garmany et al., a recent study of the Milky Way disk by Casassus et al. (2000) got the same IMF inside and outside the Solar circle using IR sources in ultra-compact HII regions. They got the steep value in both places, however, $\Gamma \sim -2$.

The problem with most of the field IMFs is that they are subject to systematic uncertainties in the essential assumptions: the star formation history, the mass dependence of the galactic scale height, galactic radial migration, etc.. Fits to a constant historical star formation rate in the Milky Way are inconsistent with the Madau et al. (1996) result, for example, which suggests that cosmological star formation was significantly higher 10 Gyr ago, the likely age of the Milky Way disk (this excess could be from different galaxies, however). Also uncertain is the disk formation history, considering the possibility of gaseous accretion and minor mergers. Similar uncertainties arise for recent times: a burst of star formation from the most recent passage of a spiral density wave would give a decaying star formation rate locally, changing the history corrections in the IMF and making the slope shallower for $M > 5 M_\odot$. In fact it is likely that local star formation varies on a 100 My time scale. These uncertainties translate into unknown corrections for the IMF during the conversion from present day star counts to relative fractions at birth. For this reason, moderately steep field IMFs at intermediate to high mass may not be representative of the average IMF in field regions of star formation.

The extreme fields in the Large and Small Magellanic Clouds seem different, however. The steep slope differs from the Salpeter value by a statistically significant margin, there is no scale height uncertainty because the line of sight integrates through the entire disk, massive stars are easily detected, and their 10 My lifetimes minimize uncertainties in the star formation history. The resulting IMF seems trustworthy. In addition, small-scale local star formation, as in Taurus, could be unusually steep too for $M > 1 M_\odot$ (Luhman 2000).
Cluster IMFs are difficult to measure because of the small number of stars in most clusters (Scalo 1998) and because of mass segregation (de Grijs et al. 2002). Some clusters have the same steep IMF as the field (e.g., the upper Sco OB association – Preibisch et al. 2002), but other clusters have what appears to be an excess of high mass stars in certain subgroups, making their overall slopes shallower. W51 (Okumura et al. 2000) is an example where the intermediate mass IMF has a slope of $\sim -1.8$, but sub-regions 2 and 3 have a statistically significant excess of stars at $M \sim 60 M_\odot$ (a 2 to 3 $\sigma$ deviation).

After uncertain corrections for mass segregation, field contamination, and completeness, most clusters have IMF slopes that are significantly shallower than $\Gamma = -1.8$, and more like the original Salpeter value of $\Gamma = -1.35$. R136 in the 30 Dor region of the LMC is a good example (Massey & Hunter 1998). Other examples are h and $\chi$ Persei (Slesnick, Hillenbrand & Massey 2002), NGC 604 in M33 (González Delgado & Perez 2000), NGC 1960 and NGC 2194 (Sanner et al. 2000), and NGC 6611 (Belikov et al. 2000). Massey & Hunter (1998) proposed that the Salpeter IMF spans a factor of 200 in cluster density. If this is the case, then clustered star formation produces a shallower IMF than extreme field star formation.

The most extreme cases of clustered star formation are in starburst regions (Rieke et al. 1993), particularly in super star clusters. Sternberg (1998) derived a high $L/M$ for the super star cluster NGC 1705-1, and inferred that either $|\Gamma| < 1$ or there is an inner-mass cutoff greater than the local value of 0.5 $M_\odot$ (Kroupa 2001). Smith & Gallagher (2001) got a high $L/M$ in M82F and proposed an inner cutoff of 2 to 3 $M_\odot$ for $\Gamma = -1.3$. They also confirmed the Sternberg result for NGC 1705-1. Alonso-Herrero et al. (2001) got a high $L/M$ in the starburst galaxy NGC 1614. Förster Schreiber et al. (2003) found the same for M82, proposing an inner IMF cutoff of 2 to 3 $M_\odot$ for $\Gamma = -1.35$. Similarly, McCrady et al. (2003) found a deficit in low mass stars in the cluster MGG-11 of M82. Not all super star clusters require an inner IMF cutoff: N1569-A (Sternberg 1998), NGC 6946 (Larsen et al. 2001), and M82: MGG-9 (McCrady et al. 2003) do not.

We might summarize these results as follows: The field IMF is systematically steeper than the cluster IMFs, but both are uncertain. Nevertheless, in the field and in low-density clustered regions, the IMF slope is fairly steep, perhaps $\Gamma = -1.8$ or steeper, while in clusters it is more shallow, $\Gamma = -1.3$ or shallower, with even more of a high mass bias for the most extreme clusters in starburst regions. This IMF difference suggests a difference in star formation mechanisms, and is reminiscent of Motte & Andrè’s (2001) suggestion that accretion processes
and pre-stellar condensation sizes are different in the low density regions of Taurus compared to the higher density associations in Perseus and Ophiuchus. Significantly steep IMFs in some dispersed associations, and very steep IMFs in remote fields contribute to this picture. In the disks of low surface brightness galaxies, a high mass-to-light ratio suggests the entire IMF is steep with $\Gamma = -2.85$ (Lee et al. 2004); star formation in the low-density “field” mode could be pervasive.

In addition to these observations, the segregation of stellar mass in many clusters, apparently at birth (Bonnell & Davies 1998), also suggests high mass stars prefer dense environments (Pandey, Mahra & Sagar 1992; Subramaniam, Sagar & Bhatt 1993; Malumuth & Heap 1994; Brandl et al. 1996; Fischer et al. 1998; Hillenbrand & Hartmann 1998; Figer, McLean, & Morris 1999; Le Duigou & Knödlseder 2002; Stolte et al. 2002; Sirianni et al. 2002; Muench et al. 2003; Gouliermis et al. 2004; Lyo et al. 2004).

We conclude that dense regions favor massive star formation. A more comprehensive survey of the observations is in Elmegreen (2004).

2. Theoretical expectations

There has long been a notion that massive star formation should be more likely in dense environments. It takes ultra-high pressures to confine the winds and radiation from massive stars (Garay & Lizano 1999; Yorke & Sonnhalter 2002; Churchwell 2002; McKee & Tan 2003), and these pressures require high density cloud cores. Massive stars could also form by enhanced accretion from high density gas reservoirs (Zinnecker 1982; Larson 1999, 2002; Myers 2000; Bonnell et al. 1997, 2001, 2004), by the coalescence of pre-stellar condensations (Zinnecker 1986; Larson 1990; Price & Podsiałowski 1995; Stahler, Palla & Ho 2000), coalescence after accretion drag (Bonnell, Bate, & Zinnecker 1998), or coalescence after accretion-induced cloud-core contraction (Bonnell, Bate & Zinnecker 1998; Bonnell & Bate 2002). Indeed, numerical simulations in Gammie et al. (2003) showed that the high-mass part of the IMF gets shallower with time as a result of coalescence and enhanced accretion. Li, et al. (2004) also found enhanced accretion and coalescence played a role in massive star formation.

Nearly every attempt to confirm these ideas has been incomplete or fraught with selection effects. The observation of larger most-massive stars in denser clusters would support this picture (Testi, Palla, & Natta 1999), but it appears instead to be the result of sampling statistics: all of the clusters in their survey were about the same size and so the cluster density correlated with total cluster mass (Bonnell & Clarke 1999;
Elmegreen 2000). More massive clusters usually give more massive most-massive stars by sampling further out in the IMF. Earlier observations of cloud-mass versus star-mass correlations (Larson 1982) apparently had the same size of sample effect (Elmegreen 1983).

We are concerned with a more subtle effect here however, and one dependent on both density and mass rather than just mass. The observations suggest all clusters are more or less the same, i.e., having a fairly shallow IMF, so differences between clusters will be dominated by sampling, selection, and mass segregation. However, star formation at very low density, in the extreme field or in low surface brightness galaxies, is apparently different, producing steep IMFs. We choose to emphasize here the difference between clusters as a whole and the remote field,
rather than a density dependence for the IMF among the clustered population alone. With this more extreme comparison, it seems reasonable to think that the relatively isolated star formation of remote field regions will not produce much coalescence of pre-stellar condensations, and will therefore lack the “cluster-mode” of competitive accretion and dense core interactions that are illustrated by numerical simulations (e.g., Bonnell, Bate, & Vine 2003). In this limited sense, we believe the massive-star IMF should vary with density (Elmegreen 2004; Shadmehri 2004).

Figure 1 shows the mm-wave continuum emission in the Orion B region, from Johnstone et al. (2001). The tiny knots of emission are examples of pre-stellar condensations, similar to those found in many other regions (Motte et al. 1998). The figure shows how closely packed many of these condensations are, giving credence to the idea that some will interact or coalesce with their nearest neighbors. A statistical study of such coalescence, limited to the pre-stellar condensation phase when the objects are fairly large ($\sim 10^4$ AU), suggests that the most massive and dense clusters should have the most coalescence (Elmegreen & Shadmehri 2003). That is, the ratio of the coalescence time to the collapse time of pre-stellar condensations decreases for more massive clusters or for denser clusters. The mass dependence arises because more massive clusters have more massive stars, which are more strongly attracting to other pre-stellar condensations. The pre-stellar condensations are more widely separated in Taurus (Motte & Andrè 2001) than in Orion B. This supports our view that interactions at this phase are relatively less important in the low-density field environment.

Theoretical considerations in Elmegreen (2004) and Shadmehri (2004) suggest there are three distinct regimes of physical processes in the IMF:

- For solar to intermediate mass stars, cloud or gas processes connected with turbulence and the thermal Jeans mass, $M_{J0}$, are important for the formation of pre-stellar condensations (e.g., see review in Mac Low & Klessen 2004, and see Gammie et al. 2003; Li, et al. 2004).

- Brown dwarfs differ because gravitational instabilities at such low mass require ultra-high pressures. These naturally occur inside the $M_{J0}$ pieces formed by cloud processes; i.e., in disk instabilities surrounding $M_{J0}$ protostars, in the ejecta from collisions between $M_{J0}$ objects, in the early ejection of accreting protostars from tight clusters, and so on, as in the usual models (Padoan & Nordlund 2002; Reipurth & Clarke 2001; Bate, Bonnell & Bromm 2002; Preibisch et al. 2003; Kroupa & Bouvier 2003). In addition, collisions between $M_{J0}$ objects should induced gravitational insta-
Figure 2. Three component models of the IMF with the distinct components indicated by dashed lines. The top panel shows the IMFs and the bottom panel shows the slopes along with observations from Scalo (1998). Each component is a log-normal with a characteristic amplitude, central mass (indicated by arrows along the abscissa of the top panel), and dispersion. Curves A, B, and C correspond in the top and bottom panels. The combined IMFs have pseudo-power laws at intermediate to high mass. Based on a figure in Elmegreen (2004).

- High mass stars form by cloud processes too, but their formation rate can be greatly enhanced by the coalescence of $M_{J0}$ pieces and by gas accretion. These are runaway processes considering gravitationally enhanced cross sections, and so become more prominent when the condensation mass exceeds $M_{J0}$ by a factor of $\sim 10$.

We consider that these three regimes of star formation produce three separate IMFs that usually combine into one in a way that gives the seemingly universal power law with a low mass turnover at about $M_{J0}$.
However, variations in the importance of these three processes, particularly with variations in the ambient cloud density, produce variations in the relative amplitudes of the three IMFs, and these variations have the effect of changing the slope of the power-law fit at intermediate to high mass.

Such variations can also change the proportion of brown dwarfs and normal stars. IC 348 (Preibisch, Stanke & Zinnecker 2003; Muench et al. 2003; Luhman et al. 2003) and Taurus (Luhman 2000; Briceño et al. 2002) have brown dwarf-to-star ratios that are \( \sim 2 \) times lower than in many other local clusters, including the Orion trapezium cluster (Hillenbrand & Carpenter 2000; Luhman et al. 2000; Muench et al. 2002), the Pleiades (Bouvier et al. 1998; Luhman et al. 2000), M35 (Barrado y Navascués et al. 2001) and the galactic field (Reid et al. 1999). IC 348 and Taurus differ even in the subsolar range (Luhman et al. 2003).

Figure 2 shows an example of how variability in three distinct mass intervals, separated by factors of 10, can produce variability in the summed IMF that is similar to what is observed (from Elmegreen 2004). Three distinct log-normals, one for each physical process, are shown to sum to a near power law between 1 and 100 \( M_\odot \). The intermediate-to-high mass slope gets shallower as the high-mass contribution increases. The brown dwarf range can be made to vary too.

Figure 3 shows IMF models where a cloud forms stars with a locally log-normal mass distribution that has a central mass and dispersion increasing with cloud density (from Elmegreen 2004). The cloud density has the form \( \rho_c(r) = \left(1 + \left| r/r_0 \right|^2 \right)^{-1} \) for core radius is \( r_0 \). The local IMF is taken to be \( f(M) = A \exp \left(-B \log \left\{ M/M_0 \right\}^2 \right) \) for exponential factor \( B = B_1 - B_2 \rho_c(r) \) and central mass \( M_0 = M_1 + M_2 \rho_c(r) \). With these expressions, the local log-normal is broader and shifted toward higher mass in the cloud core. The Miller-Scalo (1979) IMF has \( B_1 = 1.08 \) and \( M_1 = 0.1 \ M_\odot \) with no density dependence. The total mass function in the cloud is determined by integrating over radius out to \( r_{\text{max}} \) with a weighting factor equal to the \( 3/2 \) power of density; this accounts for the available mass and a star formation rate locally proportional to the dynamical rate. The figure shows the Miller-Scalo IMF (\( B_2 = M_2 = 0 \)) as a dotted line and sample IMFs with \( B_2 = B_1, M_2 = 1, \) and \( r_{\text{max}} = 2r_0 \) (solid line), \( 5r_0 \) (dashed), and \( 10r_0 \) (dot-dashed). The IMF slope is shallower for smaller \( r_{\text{max}} \), indicating mass segregation. The bottom panel plots mean separation between the logs of the masses in the IMF along with observations of R136 from Massey & Hunter (1998). The slope of the distribution of points is the negative power, \(-\Gamma\), of a power-
Figure 3. (top) IMF model based on a log-normal mass distribution in which the dispersion increases with density. The IMF is integrated over a cloud density profile out to 2, 5, and 10 cloud core radii for solid, dashed, and dot-dashed lines. The dotted line is the Miller-Scalo (1979) IMF. (bottom) The mean separation between the log of the masses for the model IMFs shown in the top and for the R136 cluster in the LMC.

law IMF. The R136 points have $\Gamma \sim -1.1$. Clearly a variable IMF can be made to fit this observation using only local IMFs that are log-normal in form.

3. Summary

There is apparently no “Universal IMF.” Low-pressure star formation in remote field regions is characterized by widely-separated, pre-stellar condensations with masses centered on the thermal Jeans mass, ($M_{J0}$). These condensations rarely interact, so they produce a “gas-only” IMF with no high-mass component and a steep slope at intermediate to high stellar mass. High-pressure star formation in clusters produces the same gas-only IMF for pre-stellar condensations, but these condensations collapse and collide to make ultra-high pressure regions (disks, shocks, etc.),
leading to brown dwarfs. The same high-pressure cluster environment also promotes coalescence of pre-stellar condensations to build up more massive stars. Thus at least one process of brown dwarf formation correlates with the enhanced formation of massive stars.

Stellar IMFs for galaxies and clusters are about the same because most stars form in clusters. There is apparently little correlation (aside from sampling effects) between stellar mass and cluster mass for these stars. At very low densities and pressures, as in the field, or in low surface brightness galaxies, or in some dwarf galaxies, the IMF should be relatively steep ($\Gamma \leq -1.7$), with few massive stars because of a lack of significant pre-main-sequence coalescences, and relatively few brown dwarfs because of a lack of collision remnants. At very high densities, as in dense clusters, the IMF should be shallow, like the Salpeter IMF or perhaps shallower, because of the coalescence of pre-stellar condensations and because of enhanced gas accretion. Brown dwarfs should be relatively common in these regions too because of the high pressures formed by interactions.

References

Alonso-Herrero, A., Engelbracht, C. W., Rieke, M. J., Rieke, G. H., & Quillen, A. C. 2001, ApJ, 546, 952
Ambartsumian, V.A. 1947, 1949 AZh, 26, 3
Barrado y Navascués, D., Stauffer, J.R., Bouvier, J., Martin, E.L. 2001, ApJ, 546, 1006
Bate, M.R., Bonnell, I.A. & Bromm, V. 2002, MNRAS, 332, L65
Belikov, A. N., Kharchenko, N. V., Piskunov, A. E., & Schilbach, E. 2000, A&A, 358, 886
Blaauw, A. 1952, BAN, 11, 405
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E., 1997, MNRAS, 285, 201
Bonnell, I. A., & Davies, M. B. 1998, MNRAS, 295, 691
Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, MNRAS, 298, 93
Bonnell, I.A., & Clarke, C.J. 1999, MNRAS, 309, 461
Bonnell, I. A., Clarke, C. J., Bate, M. R. & Pringle, J. E. 2001, MNRAS, 324, 573
Bonnell, I.A., & Bate, M.R. 2002, MNRAS, 336, 659
Bonnell, I.A., Bate, M.R., & Vine, S.G. 2003, MNRAS, 343, 413
Bonnell, I.A., Vine, S.G., & Bate, M.R. 2004, MNRAS, 349, 735
Bouvier, J., Stauffer, J. R., Martin, E. L., Barrado y Navascues, D., Wallace, B., & Bejar, V. J. S. 1998, A&A, 336, 490
Brandl, B., Sams, B. J., Bertoldi, F., Eckart, A., Genzel, R., Drapatz, S., Hofmann, R., Loewe, M. & Quirrenbach, A. 1996, ApJ, 466, 254
Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, ApJ, 580, 317
Casassus, S., Bronfman, L., May, J., Nyman, L.-Å 2000, A&A, 358, 514
Churchwell, E. 2002, ARAA, 40, 27
Davies, R.D., Elliott, K.H., Meaburn, J. 1976, Memoirs RAS, 81, 89
de Grijs, R., Gilmore, G. F., Johnson, R. A., & Mackey, A. D. 2002, MNRAS, 331, 245
Elmegreen, B.G. 1983, MNRAS, 203, 1011
Elmegreen, B.G. 1999, ApJ, 515, 323
Elmegreen, B.G. 2000, ApJ, 539, 342
Elmegreen, B.G. 2004, MNRAS, 354, 367
Elmegreen, B.G., & Shadmehri, M. 2003, MNRAS, 338, 817
Figer, D.F., McLean, I.S., & Morris, M. 1999, ApJ, 514, 202
Fischer, P., Pryor, C., Murray, S., Mateo, M., & Richtler, T. 1998, AJ, 115, 592
Förster Schreiber, N.M., Genzel, R., Lutz, D., & Sternberg, A. Th. 2003, ApJ, 599, 193
Garay, G., Lizano, S. 1999, PASP, 111, 1049
Gammie, C.F., Lin, Y.-T., Stone, J.M., & Ostriker, E.C. 2003, ApJ, 592, 203
Garmany, C.D., Conti, P. S., & Chiosi, C. 1982, ApJ, 263, 77
González Delgado, R. M., Pérez, E. 2000, MNRAS, 317, 64
Gouliermis, D., Keller, S. C., Kontizas, M., Kontizas, E., & Bellas-Velidis, I. 2004, A&A, 416, 137
Güsten, R. & Mezger, P.G. 1983, Vistas. Astron., 26, 159
Hillenbrand, L.A. & Hartmann, L.W. 1998, ApJ, 492, 540
Hillenbrand, L.A. & Carpenter, J.M. 2000, ApJ, 540, 236
Hodge, P.W. 1986, PASP, 98, 1113
Hoyle, F. 1953, ApJ, 118, 513
Johnstone, D., Fich, M., Mitchell, G.F., & Moriarty-Schieven, G. 2001, ApJ, 559, 307
Kroupa, P. 2001, MNRAS, 322, 231
Kroupa, P. & Bouvier, J. 2003, MNRAS, 346, 369
Larsen, S.S., Brodie, J.P., Elmegreen, B.G., Efremov, Y.N., Hodge, P.W., & Richtler, T. 2001, ApJ, 556, 801
Larson, R.B. 1982, MNRAS, 200, 159
Larson, R.B. 1986, MNRAS, 218, 409
Larson, R.B. 1990, in Physical processes in fragmentation and star formation, eds. R. Capuzzo-Dolcetta, C. Chiosi & A. Di Fazio, Dordrecht: Kluwer, p. 389
Larson, R.B. 1999, in Star Formation 1999, ed. T. Nakamoto, Nobeyama: Nobeyama Radio Observatory, 336
Larson, R.B. 2002, MNRAS, 332, 155
Le Duigou, J.-M., Knödlseder, J. 2002, A&A, 392, 869
Lee, H.-C., Gibson, B.K., Flynn, C., Kawata, D., & Beasley, M.A. 2004, MNRAS, 353, 113
Li, P.S., Norman, M.L., Mac Low, M.-M., & Heitsch, F. 2004, ApJ, 605, 800
Lucke, P.B. & Hodge, P.W. 1970, AJ, 75, 171
Luhman, K.L. 2000, ApJ, 544, 1044
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
Lyo, A.-R., Lawson, W.A., Feigelson, E.D., & Crause, L. A. 2004, MNRAS, 347, 246
Mac Low, M.-M., & Klessen, R.S. 2004, Rev. Mod. Phys., 76, 125
Madan, P., Ferguson, H.C., Dickinson, M.E., Giavalisco, M., Steidel, C.C., Fruchter, A. 1996, MNRAS, 283, 1388
Malumuth, E. M. & Heap, S. R. 1994, AJ, 107, 1054
Massey, P. 2002, ApJS, 141, 81
Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188
Massey, P. & Hunter, D.A. 1998, ApJ, 493, 180
McCray, N., Gilbert, A., & Graham, J.R. 2003, ApJ, 596, 240
McKee, C.F. & Tan, J.C. 2003, ApJ, 585, 850
Miller G. E. & Scalo J. M., 1979, ApJS, 41, 513
Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150
Motte F., & André P. 2001, A&A, 365, 440
Muench, A.A., Lada, E.A., Lada, C.J., & Alves, J. 2002, ApJ, 573, 366
Muench, A. A., Lada, E. A., Lada, C. J., Elston, R. J., Alves, J. F., Horrobin, M., Huard, T. H., Levine, J. L., Raines, S. N., Román-Zúñiga, C. 2003, AJ, 125, 2029
Myers, P.C. 2000, ApJ, 530, L119
Okumura, S., Mori, A., Nishihara, E., Watanabe, E., & Yamashita, T. 2000, ApJ, 543, 799
Padoan, P. & Nordlund, A. 2002, astrophy/0205019
Pandeay, A. K., Mahra, H. S., & Sagar, R. 1992, Astr.Soc.India, 20, 287
Parker, J.W., Hill, J.K., Cornett, R.H., Hollis, J., Zamkoff, E., Bohlin, R. C., O'Connell, R.W., Neff, S.G., Roberts, M.S., Smith, A.M. & Stecher, T.P. 1998, AJ, 116, 180
Preibisch, T., Brown, A.G.A., Bridges, T., Guenther, E. & Zinnecker, H. 2002, AJ, 124, 404
Preibisch, T., Stanke, T. & Zinnecker, H. 2003, A&A, 409, 147
Price, N. M., & Podsiadlowski, Ph. 1995, MNRAS, 273, 1041
Rana, N.C. 1987, A&A, 184, 104
Reid, I. N., Kirkpatrick, J. D., Liebert, J., Burrows, A., Gizis, J. E., Burgasser, A., Dahn, C. C., Monet, D., Cutri, R., Beichman, C. A., & Skrutskie, M. L 1999, ApJ, 521, 613
Reipurth, B. & Clarke, C. 2001, AJ, 122, 432
Rieke, G. H., Loken, K., Rieke, M. J., & Tamblyn, P. 1993, ApJ, 412, 99
Salpeter, E. 1955, ApJ, 121, 161
Sanner, J., Altmann, M., Brunzendorf, J., & Geffert, M. 2000, A&A, 357, 471
Scalo, J.M. 1986, Fund.Cos.Phys, 11, 1
Scalo, J.M. 1998, in The Stellar Initial Mass Function, ed. G. Gilmore, I. Parry, & S. Ryan, Cambridge: Cambridge University Press, p. 201
Shadmehri, M. 2004, MNRAS, 354, 375
Siriani, M.,Nota, A., De Marchi, G., Leitherer, C., Clampin, M. 2002, ApJ, 579, 275
Slesnick, C.L., Hillenbrand, L.A., & Massey, P. 2002, ApJ, 576, 880
Smith, L.J., Gallagher, J.S. 2001, MNRAS, 326, 1027
Spitzer, L. Jr. 1948, Phys. Today, 1, 6
Stahler, S. W., Palla, F., & Ho, P. T. P. 2000, in Protostars and Planets IV, eds. V.Mannings, A. P. Boss & S. S. Russell, Tucson: Univ. Arizona Press, p. 327
Sternberg, A. 1998, ApJ, 506, 721
Stolte, A., Grebel, E. K., Brandner, W. & Figer, D. F. 2002, A&A, 394, 459
Subramaniam, A., Sagar, R., & Bhatt, H.C. 1993, A&A, 273, 100
Testi, L., Palla, F., & Natta, A. 1999, A&A, 342, 515
Yorke, H.W. Sonnhalter, C. 2002, ApJ, 569, 846
Zinnecker, H. 1982, in Symposium on the Orion Nebula to Honor Henry Draper, eds. A. E. Glassgold, P. J. Huggins, & E. L. Schucking, New York: New York Academy of Science, p. 226
Zinnecker, H. 1986, in Luminous Stars and Associations in Galaxies, IAU Symposium 116, eds. C.W.H. de Loore, A.J. Willis, P. Laskarides, (Dordrecht: Reidel), p. 271
Zwicky, F. 1953, PASP, 65, 205