The Initial Mass Function of Stars

Bruce G. Elmegreen

IBM T.J. Watson Research Center, 1101 Kitchawan Road, Yorktown Hts., NY 10598 USA, bge@watson.ibm.com

Abstract. Observations and theory of the IMF are briefly reviewed. Slight variations have been observed, although they are difficult to prove unambiguously. Most detailed theoretical models reproduce the IMF, but because they use different assumptions and conditions, there is no real convergence of explanations yet.

1. Introduction

Stars are born with a mass distribution function that has a nearly constant stellar mass in each log interval of mass above about 0.5 M⊙. A common fit to observations is a power law IMF with a slope \( \alpha \) between \(-2.1\) and \(-2.6\), i.e., for equal intervals of mass, \( dn(M) = n_0 M^{-\alpha} dM \). The center of this range is \( \alpha = -2.35 \), which is the Salpeter (1955) IMF. The coefficient \( n_0 \) is given by the total stellar mass or the cluster mass, \( n_0 = (\alpha - 2) M_{min}^{\alpha-2} M_{cl} \), where the minimum star mass in the power law part is \( M_{min} \) and the cluster mass in this expression is assumed for simplicity to be the mass of the power law part. At low mass, the IMF rises less steeply than the Salpeter function. For an IMF with a typical slope of \(-1.35\) between 0.05 and 0.5 M⊙ and a slope of \(-2.35\) between 0.5 and 50 M⊙, the fractional mass in each factor of ten interval of mass, from 0.05 to 50 M⊙, is 21%, 54%, and 24%. The peak between 0.5 and 5 M⊙ is a characteristic mass. It may be defined more precisely as the mass where the steep and shallow power laws meet. In the Kroupa (2001) IMF, it is 0.5 M⊙.

The IMF is not constant from region to region (Scalo 1998), but many of the observed variations in slope and characteristic mass could be stochastic for the typically small samples that are observed (Elmegreen 1999; Kroupa 2001). Thus the observations are consistent with typical star clusters sharing a common probability distribution function for the IMF, with more or less random sampling around that function as stars form.

Some IMF variations seem more significant than this because they recur for regions with peculiar physical properties, such as starbursts. Starbursts have long been suspected of having a flatter slope at intermediate to high mass (Rieke et al. 1980, 1993). However, the early inferences of top-heavy IMFs for starbursts appear now to be premature because of excessive extinction corrections and other problems (Devereux 1989; Satyapal 1995; see review in Elmegreen 2005). The most recent reports of IMF flattening, which are for super star clusters (see below), have also been questioned lately, as there could be a lack of dynamical equilibrium in these clusters (Bastian & Goodwin 2006) or non-isothermal velocity dispersions. IMF flattening has also been reported for the young bursting phases of elliptical galaxies and galaxy clusters (see references
below). Conversely, an IMF steepening has been claimed for low surface brightness disks (Lee et al. 2004). If these subtle variations are real, then they suggest a slight trend toward more massive stars with increasing density (Elmegreen 2004).

Most systematic variations in the IMF are small, just several tenths in $\alpha$ (except for the LMC “extreme” field, see below). This has led to the idea of a universal IMF. The reason for such general uniformity is not clear. It could be that hierarchical fragmentation of any type gives the basic $dn/dM \sim M^{-2}$ shape (equal mass in equal log intervals of mass for a pure hierarchy), with a slight preference for lower masses giving the Salpeter and steeper functions. Such a preference could come from slightly faster collapse at low mass, which seems natural for a hierarchical medium as the density is usually larger at lower mass (Elmegreen 1999). The basic IMF form could also come from accretion (Bonnell et al. 2001) or coalescence (Shadmehri 2004) or a combination of these processes (Bonnell et al. 2006). On the other hand, the intrinsic IMF may not be a simple power law – it could be a composite of functions reflecting different processes in different mass ranges (Elmegreen 2004).

The characteristic mass for star formation is not well understood, nor are its variations and trends. It is commonly thought to be the thermal Jeans mass in the cloud core, but this is a poorly defined quantity when the core pressure should vary with position. For example, it is not clear why the most massive dense clusters, which appear to have high internal pressures, have the same characteristic mass in the IMF as star formation in lower pressure regions. Is there thermal feedback involving both temperature and pressure that keeps the Jeans mass relatively constant? Or does the characteristic mass have a different origin? We don’t know.

The IMF extends down from the characteristic mass by more than a factor of $\sim 30$ (Luhman et al. 2000; Lucas et al. 2005). Is the star formation process completely different for these low masses (e.g., Bate, Bonnell & Bromm 2002)? Is the Jeans mass highly reduced in some places (Padoan et al. 2004)? Does the lower mass limit for star formation vary from region to region?

2. Observations

2.1. Clusters

The IMF is observed in many types of regions with diverse selection effects and limitations. Star clusters have the advantage that all of the stars have about the same age and distance, but mass segregation, field contamination, small number statistics, and evaporation can be problems. In OB associations too, the stars have about the same distance, but there is usually a range of ages and the possibility of dispersal over time into the surrounding field. Field IMFs can have a large number of stars, making the statistical accuracy large, but the inferred mass function, which is expressed per unit volume or area, depends on the star formation history, vertical disk heating, selective drift away from clusters, and other things. The IMFs in whole galaxies have been determined from abundance ratios (e.g., Fe comes from low and high mass stars whereas O comes from high mass stars) and star counts, but poor resolution, faintness, and
unknown star formation histories can be problems. Extinction variations can affect all of these measurements.

Generally only massive clusters have been used to determine the high mass IMF. Low mass clusters do not usually have high mass stars. Massive stars also form in peripheral gas, however, because of triggering or independent processes. It is not clear how to include such regions in the IMF. Should their stars add to the total in the cluster or stand alone? The answer may depend on whether one thinks the cluster environment is important for the IMF.

Many dense clusters are observed to have about the Salpeter IMF slope at intermediate to high mass: R136 in 30 Dor (Massey & Hunter 1998), h and χ Persei (Slesnick, Hillenbrand & Massey 2002), NGC 604 in M33 (Gonzalez Delgado & Perez 2000), NGC 1960 and NGC 2194 (Santer & al. 2000), NGC 6611 (Belikov et al. 2000), and many others. The upper Scorpius OB association has a steeper IMF, $dn/dM \propto M^{-2.8}$ between 0.6 and 2 $M_\odot$ and $dn/dM \propto M^{-2.6}$ between 2 and 20 $M_\odot$ (Preibisch et al. 2003). The intermediate stars in W51 have a steep slope too, $M^{-2.8}$, but at high mass there is a clear excess of stars compared to this slope in two of four stellar subgroups (Okumura et al. 2000). NGC 604, mentioned above, is particularly interesting because there appear to be no clusters there, leading Hunter et al. (1996) to suggest that the IMF is independent of density.

Mass segregation is a severe effect in most clusters. The slope of the IMF is generally shallower in a cluster core than around the periphery, which means that massive stars prefer the center. For example, Sung & Bessell (2004) found segregation in the massive young cluster NGC 3606. The Arches cluster in the Galactic center has a shallow IMF (Yang et al. 2002; Stolte et al. 2005), but it is not known whether these massive stars are all there ever was in the cluster. An envelope of low density stars could have been tidally stripped (Kim et al. 2000; de Marchi, Pulone, & Paresce 2006).

Some super star clusters have low mass-to-light ratios suggesting a relative excess of high mass stars compared to a standard IMF. Sternberg (1998) found a low M/L in NGC 1705-1, as if the slope is shallower than −2 or the characteristic mass is higher than normal. Smith & Gallagher (2001) found a low M/L in M82F, suggesting an inner cutoff of 2-3 $M_\odot$ for the Salpeter IMF. Alonso-Herrero et al. (2001) observed a low M/L in the starburst galaxy NGC 1614. McCrady et al. (2003) found that in M82, MGG-11 is deficit in low mass stars. Mengel et al. (2003) found the same in NGC 4038/9. Other super star cluster have normal IMFs: NGC 1569-A (Ho & Filippenko 1996; Sternberg 1998), NGC 6946 (Larsen et al. 2001), and M82, MGG-9 (McCrady et al. 2003). The IMF is difficult to measure in super star clusters. One has to observe the velocity dispersion and radius of the cluster to get the binding mass, and then combine this with the luminosity. The velocity dispersion may vary with radius, however (e.g. NGC 6946), and the value of radius is uncertain. The cluster could be evaporating, out of equilibrium, non-isothermal, multi-component or non-centralized (Bastian & Goodwin 2006); the core could be poorly resolved too. Field star corrections may be uncertain as well.

The low mass part of the IMF varies from place to place also. Studies by Luhman et al. (2000, 2003), Briceno et al. (2002), Muench et al. (2003) and others suggest denser clusters have more low mass stars and brown dwarfs.
2.2. Field

Scalo (1986) and Rana (1987) suggested that the slope of the IMF in the local field is steeper than Salpeter, −2.7 to −2.8 (compared to −2.35). In an extensive study of the LMC field, Parker et al. (1998) got the same slope, −2.80 ± 0.09, for masses larger than 2 M⊙. Massey et al. (1995, 2002) got a steeper slope, −5, in regions more than 30 pc from a Lucke & Hodge (1970) or Hodge (1986) OB association, complete down to 25 M⊙. He assumed the star formation rate was constant over the last 10 My and had 450 stars in the LMC sample. However, in a field region near 30 Dor, the IMF slope was found to be more like Salpeter, −2.38 ± 0.04 for 7-40 M⊙ (Selman & Melnick 2005). For low mass field stars in the LMC, 0.6-1.1 M⊙, Holtzman et al. (1997) got a slope of -2.0 to -3.1. In a field region near the supershell LMC4, the slope is −6 for 0.9-2 M⊙ and −3.6 for 0.9-6 M⊙ (Gouliermis, Brandner & Henning 2005). The origin of these variations is unknown. Field regions near OB associations could be overpopulated with low mass stars that disperse further from their birthplaces than high mass stars (Elmegreen 1999; Hoopes, Walterbos & Bothun 2001; Tremonti et al. 2002).

Low Surface Brightness Galaxies have been suggested to have a steep slope throughout, −3.85 for 0.1-60 M⊙ (Lee et al. 2004). Red halos in BCD galaxies, and deep, stacked-image halos around edge-on galaxy disks, also seem to have a steep IMF slope: −4.5 (Zackrisson, et al. 2004).

The low mass IMF in the solar neighborhood has been observed by many groups. Chabrier et al. (2005) suggested it continues to rise at low mass, with no evidence for a turnover (on a log-log plot) down to 0.12 M⊙. Schultheis et al. (2006) observed the low mass IMF in the thick disk of the Milky Way, where there seems to be relatively few low mass stars compared to the low mass IMF in the solar neighborhood.

3. IMF Theory

In the modern theory of star formation, turbulence causes dense gas structures and fragmentation in intersecting shocks, protostars form in the collapsing cores of these dense regions, and then the protostars move around and accrete gas, possibly coalescing or getting ejected from dense sub-clusters. Simulations of these processes end up with a reasonable IMF (Bonnell et al. 2006).

Bate & Bonnell (2005) tested the importance of the Jean mass with an SPH simulation having no magnetic field. Two simulations containing 50 Jeans-masses initially but with different values for this Jeans mass showed that the mean mass of the fragments scaled with the Jeans mass. Jappsen et al. (2005) also did SPH simulations with no magnetic fields. They varied the equation of state to give a ratio of specific heats less than 1 at low density and greater than 1 at high density. The resulting IMF depended on transition density: higher transition density resulted in a lower Jeans mass and more cores. Still, the Salpeter IMF resulted. Martel et al. (2005) did isothermal SPH with particle splitting and no magnetic fields. They found that the core mass function depends on resolution so that higher resolution gives a lower characteristic mass. Tilley & Pudritz (2005) used ZEUS-MP MHD with a 256³ grid, considering different ratios of gravitational to magnetic energy; bound cores with a reasonable IMF formed in all of the highly supercritical cases. Padoan et al. (2004) did adaptive
mesh MHD in $1024^3$ cells and a Mach number of 6; they formed brown dwarfs by turbulent fragmentation. Nakamura & Li (2005) did 2D MHD with magnetic diffusion enhanced by turbulent compression. They found diffusion-regulated collapse in compressed regions and a low SF efficiency.

4. Conclusions

IMF observations suggest a more or less constant IMF in many diverse environments, although small but significant variations have been found in all mass intervals. There are no generally recognized systematic trends with these variations, however, making it difficult to find causes. The only trend that has been suggested is with density, in the sense that the IMF is sometimes steep at intermediate to high mass at very low density, as in field regions or low surface brightness galaxies, and it is sometimes relatively shallow at very high densities, as in some super star clusters or the bursting phases of galaxy formation. Cloud fragmentation, protostellar coalescence, protostar accretion, ejection from sub-clusters etc. could all play a role, as demonstrated by simulations.

References

Alonso-Herrero, A., Engelbracht, C. W., Rieke, M. J., Rieke, G. H., & Quillen, A. C. 2001, ApJ, 546, 952
Bastian, N., & Goodwin, S.P. 2006, MNRAS, in press, astro-ph/0602465
Bate, M.R., Bonnell, I.A. & Bromm, V. 2002, MNRAS, 332, L65
Bate, M.R., Bonnell, I.A. 2005, MNRAS, 356, 1201
Belikov, A. N., Kharchenko, N. V., Piskunov, A. E., & Schilbach, E. 2000, A&A, 358, 886
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 2001, MNRAS, 323, 785
Bonnell, I.A., Larson, R.B., & Zinnecker, H. 2006, in Protostars and Planets V, in press
Briceño, C., Luhman, K. L., Hartmann, L., Stauffer, J. R., & Kirkpatrick, J. D. 2002, ApJ, 580, 317
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P.H. 2005, astro-ph/0509798
de Marchi, G., Pulone, L., & Paresce, F. 2005, astro-ph/0512024
Devereux, N.A. 1989, ApJ, 346, 126
Elmegreen, B.G. 1999, ApJ, 515, 323
Elmegreen, B.G. 2004, MNRAS, 354, 367
Elmegreen, B.G. 2005, in Starbursts: From 30 Doradus to Lyman Break Galaxies, eds. R. de Grijs & R.M. González Delgado, Astrophysics & Space Science Library, 329, Dordrecht: Springer, p.57
González Delgado, R. M., Pérez, E. 2000, MNRAS, 317, 64
Gouliermis, D., Brandner, W., & Henning, Th. 2005, ApJ, 623, 846
Ho, L. C., & Filippenko, A. V. 1996, ApJ, 466, L83
Hodge, P. 1986, PASP, 98, 1113
Holtzman, J.A., Mould, J.R., Gallagher, J.S., III, et al. 1997, AJ, 113, 656
Hoopes, C.G., Walterbos, R. A. M., Bothun, G.D. 2001, ApJ, 559, 878
Hunter, D.A., Baum, W.A., O’Neil, E.J., Jr., & Lynds, R. 1996, ApJ, 456, 174
Jappsen, A.-K., Klessen, R. S., Larson, R. B., Li, Y., & Mac Low, M.-M. 2005, A&A, 435, 611
Kim, S. S., Figer, D. F., Lee, H. M., & Morris, M. 2000, ApJ, 545, 301
Kroupa, P. 2001, MNRAS, 322, 231
Larsen, S.S., Brodie, J.P., Elmegreen, B.G., Efremov, Y.N., Hodge, P.W., & Richtler, T. 2001, ApJ, 556, 801
Lee, H.-C., Gibson, B.K., Flynn, C., Kawata, D., & Beasley, M.A. 2004, MNRAS, 353, 113
Lucke, P. B., & Hodge, P. W. 1970, AJ, 75, 171
Lucas, P.W., Roche, P.F., & Tamura, M. 2005, MNRAS, 361, 211
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
Martel, H., Evans, N.J., II, & Shapiro, P.R. 2005, astrophy/0505008
Massey, P. 2002, ApJS, 141, 81
Massey, P. & Hunter, D.A. 1998, ApJ, 493, 180
Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188
McCready, N., Gilbert, A., & Graham, J.R. 2003, ApJ, 596, 240
Mengel, S., Leherty, M. D., Thatte, N., & Genzel, R. 2002, A&A, 383, 137
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
Nakamura, F., & Li, Z.-Y., 2005, ApJ, 631, 411
Okumura, S., Mori, A., Nishihaara, E., Watanabe, E., & Yamashita, T. 2000, ApJ, 543, 799
Padoan, P., Kritsuk, A., Norman, M.L., & Nordlund, A. 2004, astrophy/0411480
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., Stanke, T. & Zinnecker, H. 2003, A&A, 409, 147
Rana, N.C. 1987, A&A, 184, 104
Rieke, G.H., Lebofsky, M.J., Thompson, R.I., Low, F.J., & Tokunaga, A.T. 1980, ApJ, 238, 24
Rieke, G. H., Loken, K., Rieke, M. J., & Tamblyn, P. 1993, ApJ, 412, 99
Salpeter, E.E. 1955, ApJ, 121, 161
Sanner, J., Altman, M., Brunzendorf, J., & Geffert, M. 2000, A&A, 357, 471
Satyapal, S., et al. 1995, ApJ, 448, 611
Scalo, J.S. 1986, Fund.Cos.Phys, 11, 1
Scalo, J. 1998, in The Stellar Initial Mass Function, ed. G. Gilmore, I. Parry, & S. Ryan (Cambridge: Cambridge Univ. Press), 201
Schultheis, M., Robin, A.C., Reylié, C., McCracken, H.J., Bertin, E., Meller, Y., & Le Févre, O. 2006, A&A, 447, 185
Selman, F. & Melnick, J. 2005, A&A, 433, 851
Shadmehri, M. 2004, MNRAS, 354, 375
Slesnick, C.L., Hillenbrand, L.A., & Massey, P. 2002, ApJ, 576, 880
Smith, L.J., Gallagher, J.S. 2001, MNRAS, 326, 1027
Sternberg, A. 1998, ApJ, 506, 721
Stolte, A., Brandner, W., Grebel, E.K., Lenzen, R., & Lagrange, A.-M. 2005, ApJL, 628, 113
Sung, H. & Bessell, M. S. 2004, AJ, 127, 1014
Tilley, D.A., & Pudritz, R.E., 2005, astrophy/0505562
Tremonti, C.A., Calzetti, D., Leitherer, C., & Heckman, T.M. 2002, ApJ, 555, 322
Yang, Y., Park, H.S., Lee, M.G., & Lee, S.G. 2002, JKAS, 35, 131
Zackrisson, E., Bergvall, N., Marquart, T., & Mattsson, L. 2004, astrophy/0411537