THE IMF IN STARBURSTS

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Abstract

The history of the IMF in starburst regions is reviewed. The IMFs are no longer believed to be top-heavy, although some superstar clusters, whether in starburst regions or not, could be. General observations of the IMF are discussed to put the starburst results in perspective. Observed IMF variations seem to suggest that the IMF varies a little with environment in the sense that denser and more massive clusters produce more massive stars, and perhaps more brown dwarfs too, compared to intermediate mass stars.

Keywords: IMF, Star Formation, Starbursts

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1. Introduction: History of Starburst IMFs

Early starburst observations suggested the luminous mass from young massive stars is comparable to the dynamical mass from the rotation curve (see reviews in Telesco 1988; Scalo 1990; Zinnecker 1996; Leitherer 1999). This implied there was a deficit in low mass stars. The nearby starburst galaxy, M82, was one of the best cases. Rieke et al. (1980, 1993) modeled M82’s gas mass, luminous star mass, rotation curve mass, $2.2 \mu m$ flux, Lyman continuum flux, CO index for supergiants, and the Br/Br ratio, giving an extinction $A_V = 25$ mag. They concluded that only the usual IMF models with lower mass limits $M_L > 3.6 M_\odot$ worked. Kronberg et al. (1985) used the Lyman continuum flux from radio emission in M82 to determine the star formation rate, and used the total gas mass combined with an efficiency estimate to conclude that the IMF is top-heavy compared to the Miller & Scalo (1979) IMF. Bernlohr (1992) fit the same M82 properties as Rieke et al., plus the heavy element abundance and FIR line ratios, and concluded that either the IMF slope is shallower than the Scalo (1986) IMF by 1, or there is a lower mass cutoff greater than 1.5-2
Independent models of M82 by Doane & Mathews (1993), emphasizing the SN rate and the total dynamical mass, led to the same lower cutoff even for the Salpeter IMF, which is shallower than both the Miller & Scalo and Scalo functions.

Early observations obtained truncated IMFs in other starbursts too. Wright et al. (1988) found $M_L > 3.6 M_\odot$ from low M/L ratios in 12 starburst galaxies assuming a Miller-Scalo IMF. For the merger remnant NGC 3256, Doyon, Joseph & Wright (1994) modeled the Br equivalent width, HeI $\lambda 2.66$ m/Br, CO index, and N(Lyc)/LIR ratio with different IMFs and star formation histories. The HeI $\lambda 2.66$ m/Br index suggested an upper mass limit $M_U = 30 M_\odot$, the rotation curve and CO molecular cloud observations gave $M_{gas} / M_{total}$, and all constraints gave either an IMF slope shallower than the Salpeter slope by 0.5 or $M_L > 3 M_\odot$. For the merger remnant UGC 8387, Smith et al. (1995) suggested $M_L > 8 M_\odot$ for a Miller-Scalo IMF using the low ratio of 1-500 $\mu$m flux to Ly$\alpha$, as obtained from the 5 GHz flux. Smith, Herter & Haynes (1998) got the same result from IR excesses in 20 starburst galaxies, suggesting that the IMF slope for $M > 10 M_\odot$ was 2.7 0.2 ( = 1.7, see below), shallower than the Miller-Scalo slope of 3.3 ( = 2.3) in this mass range, but steeper than Salpeter (2.35; = 1.35).

At about the same time as these observations were suggesting the IMF was top-heavy in starburst galaxies, several other observations suggested it was normal. Devereux (1989) observed 20 nearby starbursts like M82, and using 2.2 m, FIR, and estimates for the central dynamical masses, found acceptable fits to the Miller-Scalo IMF from 0.9 30 M$\odot$ (and the Miller-Scalo function is the least top-heavy of the main IMF models). He also suggested that extinction corrections in M82 made by others were too high, and this made it appear like M82 had a truncated IMF when really it didn’t. Satyapal (1995) indeed found low extinction in M82 from Pa$\alpha$ /Br$\gamma$, which gave $A_V = 2^m 12$ mag compared to 25 mag in Rieke et al. (1980). Satyapal then got a K-band luminosity 3 times lower than Rieke et al., and saw no need for IMF truncation. Satyapal (1997) also found an age gradient in the center of M82 and fit an IMF with the Salpeter slope from 0.1 100 M$\odot$, accounting for only 36% of the dynamical mass.

In other observations of starburst IMFs, Schaerer (1996) applied evolutionary models to the WR/O star ratios and found a Salpeter IMF slope, although $M_L$ could not be determined. Stasiński & Leitherer (1996) modeled the emission line spectra of giant HII region and starburst galaxies, having a factor-often range in metallicities, and also found a Salpeter IMF up to 100 M$\odot$, with no information about the lower mass limit. Calzetti (1997) modeled multi-wavelength spectroscopy and broad-band infrared photometry of 19 starburst
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galaxies to derive reddening values and found a general consistency with the Salpeter IMF between 0.1 and 100 M⊙.

Finally, in returning to M82, Förster Schreiber et al. (2003) modeled it with 25 pc resolution using near-IR integral field spectroscopy and mid-IR spectroscopy. An upper mass limit to stars greater than 50 M⊙ was derived from the $L_{bol}/L_{LyC}$ and [NeIII]/[NeII] ratios; short decay times were observed for star formation locally (1-5 My), and the models were insensitive to the shape or slope of IMF at intermediate to high mass. An IMF turnover somewhere below 1 M⊙ was concluded.

There were also suggestions that top-heavy IMFs would cause problems with stellar populations or metallicities. Charlot et al. (1993) suggested that an inner-truncated IMF would produce a very red population of red giants, without the corresponding main sequence stars, after the turnoff age reaches the stellar lifetime at the truncation mass. Wang & Silk (1993) suggested that the truncated model gives an oxygen abundance that is too high when the star formation process is over. These red populations or elevated oxygen abundances have not been observed.

At the present time, the observations suggest that the Salpeter IMF with a lower mass flattening somewhere between 0.5 M⊙ and 1 M⊙ is a reasonable approximation to the IMF in large integrated regions of starburst galaxies.

2. Local IMFs

The Field

Starburst IMFs are useful for understanding star formation only in comparison to local IMFs or IMFs in non-starburst regions, where many of the star formation processes can be observed in more detail. There are many such observations of non-starburst IMFs, as reviewed in the conference proceedings *The Stellar Initial Mass Function* edited by ed. Gilmore, Parry & Ryan (1998) or in Chabrier (2003). We give a brief summary here.

In 1955, Salpeter showed that if 10% of a star’s mass is converted into Helium on the main sequence, if the star formation rate in the local Milky Way disk is constant over time, and if the present day mass function is that given by the available catalogs (some of which dated back several decades – even into the 1920’s), then the mass function of stars at birth has a slope of $\alpha = 1.35$ on a log-log plot.

More recent derivations of this field star IMF generally give steeper slopes. Miller & Scalo (1979) fitted the observations to a log-normal IMF, which has about the Salpeter slope near one solar mass, but an increasingly steep slope toward higher masses, reaching $\alpha = 2.3$. Scalo (1986) found a field star IMF with a slope between 1.5 and 1.7 in the range from 1 to 10 M⊙, and a slightly shallower slope, between 1.35 and 1.5, at higher mass. Rana (1987)
derived a field IMF with somewhat different data than Scalo (1986) and found
\[ = 1.8 \text{ for } M > 1.6 M. \]

The difference between these field star IMFs and Salpeter’s IMF is significant: for a slope difference of 0.5, the number of high mass stars between 10 M\(_\odot\) and 100 M\(_\odot\) compared to the number of intermediate mass stars between 1 M\(_\odot\) and 10 M\(_\odot\) is three times larger in the Salpeter IMF than in the others. This excess factor of 3 for nearby high mass stars can easily be ruled out. However, Salpeter did not have observations that extended to the high mass range. In the region of overlap, which is near 1 M\(_\odot\), the modern field star IMF slope is comparable to Salpeter’s value. The big question for starburst regions is how the IMF near 1M\(_\odot\) extrapolates to OB stars.

IMF measurements outside starburst regions give a wide range of slopes. Parker et al. (1998) did photometry on 37,300 stars in the LMC & SMC, and found slopes concentrating near \[ = 1.7; 1.6, \text{ and } 2.0 \] for the Davies, Elliot & Meaburn (1976) HII regions, and \[ = 1.80 \pm 0.09 \] for all the field stars, considering only stars with \( M > 2 M. \) The IMFs near the HII regions are probably too shallow as a result of inadequate corrections for background and foreground stars (Parker et al. 2001), but the field star IMF appears to be free of this systematic effect. Note that the statistical accuracy is very high for this measurement.

Massey et al. (1995) and Massey (2002) surveyed the remote fields in the LMC and SMC, defining these to be regions more than 30 pc from a Lucke & Hodge (1970) or Hodge (1986) association. The survey was complete down to 25 M\(_\odot\) and included 450 stars, which should give a statistical uncertainty of 0.15 (Elmegreen 1999a). By assuming a constant star formation rate over the last 10 My, Massey et al. found significantly steeper in the remote field than in clusters, having a value between 3.5 and 4.

One could imagine several systematic effects that make this slope artificially steep. First note that runaway O stars could not do this, because the field has too few O stars compared to intermediate mass stars. Other likely processes could do it, however: (1) Selective evaporation of cluster envelopes into the field, considering that some cluster envelopes have already (de Grijs, et al. 2002). (2) Greater migration into the field of the longer-lived, low-mass stars compared to high mass stars. (3) Greater self-destruction of low pressure clouds in the field by OB star formation compared to high-pressure clouds in associations (Elmegreen 1999a). Hoopes, Walterbos & Bothun (2001) also explained the steep mass function required for diffuse interstellar ionization in nearby galaxies with the differential drift of low-mass stars into the field. Tremonti et al. (2002) found a Salpeter IMF for clusters and a steeper IMF for the field in the dwarf starburst galaxy NGC 5253, and explained this difference as a result of cluster dispersal after 10 My, when the most massive stars have disappeared.
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Another observation of a systematically steep IMF was by Lee et al. (2004). They fit the high M/L in low surface brightness galaxies with population synthesis models requiring low metallicity, recent (1-3Gy) star formation, and a steep IMF: \( \alpha = 2.85 \) from \( 0.1 \) to \( 60 \) M\( \odot \). These galaxies have a low pressure like the extreme field regions in Massey et al..

The Taurus region in the nearby field may have a steep IMF at high mass too (Luhman 2000). The pre-stellar condensations there are peculiar anyway, showing more extended structures, like isothermal spheres, than those in Perseus or Ophiuchus which appear truncated (Motte & André 2001).

Clusters

The IMF in the Sco-Cen OB association is best fit with a slope of \( \alpha = 1.8 \) (Preibisch et al. 2002). Another Galactic region, W51, has 4 subgroups, all with \( \alpha = 1.8 \) at intermediate to high mass, but two of the subgroups have a statistically significant excess by factor of 3 of stars in the highest mass bin (\( > 60 \) M\( \odot \); Okumura et al. 2000). There are other anomalies like this too. Scalo (1998) suggested that the IMF varied significantly from cluster to cluster, but Elmegreen (1999a) and Kroupa (2001) showed that most of these variations could be statistical in origin, given the small number of stars usually observed.

Most clusters have Salpeter IMFs. A good example is the R136 cluster in the 30 Dor region of the LMC. The slope is \( \alpha = 1.3 \) out to stellar masses greater than \( 100 \) M\( \odot \) (Massey & Hunter 1998). In addition, h and Persei (Slesnick, Hillenbrand & Massey 2002), NGC 604 in M33 (González Delgado & Pérez 2000), NGC 1960 and NGC 2194 (Sanner et al. 2000), NGC 6611 (Belikov et al. 2000) and many other clusters have Salpeter IMFs (e.g., Sakhibov & Smirnov 2000; Sagar, Munari, & de Boer 2001). Massey & Hunter (1998) concluded that the Salpeter IMF occurs in star-forming regions spanning a factor of 200 in density.

Whole galaxies are often observed to have the Salpeter slope too. There were many studies in the 1990’s using H equivalent widths, spectro-photometry, metallicity, and galaxy evolution models (see review in Elmegreen 1999b). More recently, Baldry & Glazebrook (2003) derived the Salpeter IMF from the cosmic star formation rate, Rejkuba, Greggio & Zoccali (2004) got it for the halo of NGC 5128 (Cen A), and Pipino & Matteucci (2004) fit the photochemical evolution of elliptical galaxies with a Salpeter IMF.

If whole galaxies have the same average IMF as clusters, and if most stars form in clusters, which is believed to be the case (Lada & Lada 2003), then the mass of any star cannot depend on the cluster mass. That is, any type of star can form in any type of cluster (as long as the cluster mass is larger than the stellar mass). If this were not the case, then the summed IMFs would differ from the
cluster IMFs. For example, if low mass clusters were able to form only low mass stars, and high mass clusters formed all types of stars, as observed, then the sum of the low and high mass clusters would produce far more low mass stars than each cluster's IMF (Elmegreen 1999b).

3. Top heavy IMFs in Super Star Clusters

Some super star clusters (SSC) apparently have “top heavy” or “bottom light” IMFs. Sternberg (1998) found a high L/M ratio in NGC 1705-1 and concluded that either \( j < 1 \) or there is an inner-mass cutoff. Smith & Gallagher (2001) got a high L/M in M82F and inferred an inner cutoff at 2-3 M for \( = 1 \); they also confirmed inner truncation for NGC 1705-1 found by Sternberg. Alonso-Herrero et al. (2001) observed a high L/M in the starburst galaxy NGC 1614, suggesting a top-heavy IMF. McCrady et al. (2003) found that MGG-11 in M82 is deficit in low mass stars. Mengel et al. (2002) found the same for the antennae, NGC 4038/9, and noted that the clusters in the high pressure regions had more normal IMFs, as if the Jeans mass were lower there.

Other SSCs have normal IMFs, however. This is the case for NGC 1569-A (Ho & Filippenko 1996; Sternberg 1998), NGC 6946 (Larsen et al. 2001), and M82: MGG-9 (McCrady et al. 2003).

Measuring the IMF in SSCs is subject to many uncertainties. It requires observations of the velocity dispersion and radius to get the mass, and observations of the luminosity. One problem is that \( v \) can vary inside a cluster (i.e., it may not be isothermal – e.g. NGC 6946) and it is often measured with large uncertainties. The value of R is uncertain too if the core is unresolved or the outer part of the cluster is blended with field stars. The luminosity is uncertain because of possible field star blending. Mass segregation makes the IMF vary with radius (de Grijs et al. 2002), so the cluster colors vary with radius, giving another uncertainty about the core radius. The average IMF depends on where the outer cutoff is placed. The cluster could also be evaporating or out of radial equilibrium, in which case the usual expressions for cluster mass in terms of \( v \) and R do not apply. Several SSCs are observed to have sub-clusters inside their halos, giving irregular and asymmetric light profiles.

Implications

These observations suggest a correlation between and star formation density. In the extreme field, \( 2 \); in low surface brightness galaxies, \( 1 \); in the Milky Way and LMC fields, \( 1 \); in many clusters, \( 1 \); in some SSC, \( j < 1 \) or there is an inner-mass truncation, and in starburst regions as a whole, \( 1 \) with or without inner-truncation (this is uncertain). We should probably remove the local field from this list because it is a mixture of dispersed clusters and cluster envelopes integrated
over time; both the mixing process and the local star formation history are uncertain. Aside from this, the trend suggests significantly denser regions have slightly shallower IMF slopes at intermediate to high mass. More observations are needed to confirm this. If true, it could imply that enhanced gas accretion and protostellar coalescence are important for high mass stars in the densest environments (see more extensive reviews of this point in Stahler, Palla, & Ho 2000; Elmegreen 2004; Shadmehri 2004).

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