The Initial Stellar Mass Function

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slope =$-1.35$

Salpeter ‘55
IMF: Frontiers

• NEW OBSERVATIONS
  – new IMFs
  – a flat IMF for galactic center disk stars
  – the falling low-mass part of the IMF
  – a shifted IMF for low-metal halo stars
  – missing Hα compared to FUV at low surface density
  – pre-stellar cores

• THEORY SAMPLER
  – Competitive accretion, turbulence-regulated, magnetic-regulated, a characteristic mass
Schmalzl +08 IMF of association NGC 602 in the SMC: like local IMFs
Wang + 08: IMF of Rosette from x-ray observations looks like the Orion IMF from its x-ray stars.
Bonatto & Bica 09: IMF for the Rosette Nebula cluster based on 2MASS+optical. Overall slope slightly shallower than Salpeter.
Westerlund 2:
\~5000 stars observed,
7000M_☉, 2Myr old, 2.8 kpc,
behind 5.8 mag extinction,
mass segregation.

**IMF slope = -1.2pm0.16**
(\~Salpeter)
Harayama +07: A flat IMF in NGC 3603

7500 stars: uncertainties from counting statistics: +0.02

mass segregation from dynamical evolution not significant: no steepening beyond the HM radius (25-50")

uncertainties from binaries: +0.04

(Solte et al. 06: $\Gamma = -0.9 \pm 0.15$)

HST image
Kim +06: The IMF in the Arches cluster based on deep AO images is only slightly flatter than Salpeter, $\Gamma = -1$ to -1.1, considering Fokker-Planck models to account for mass segregation over its age
Arches cluster

Espinoza +09: AO, VLT, use natural photometric system of instrument, Bayesian determination of M and reddening. Overall slope = -1.1pm0.2 Mclust=2x10^4 M_☉, suggests max Mstar~120 (the most massive stars observed)
The flat IMF for galactic center disk stars
Bartko +09: Early type stars in the galactic center disk.

Flat IMF with slope=0.45 (Salpeter 2.35)
The falling low mass part of the IMF
Oliveira +08: Low mass IMF of M16 cluster (2-3 Myr old, 2x more massive than ONC). The peak mass is higher than in other similar regions, but like that in Taurus, which is low density. Therefore proximity to massive stars does not affect the IMF, nor does cluster density.
Spitzer image (J. Hernandez)

Lodieu +09 low mass IMF in $\sigma$ Ori cluster
$a=0$ (Salpeter=2.35)
Scholz +09: NGC 1333: find 12 new BD, 19 total in a survey complete to 0.004 $M_\odot$ for $A_V<5$mag.

**Overabundance of BD** relative to low mass stars by x5.

**Deficit of planetary mass objects** compared to $\sigma$ Ori, ONC, Cha I

planet mass $< 0.015 \text{Msun}$

where deuterium burning stops
Lower limit of $13M_{\text{Jup}} (=0.012 \, M_{\odot})$ suggests opacity limit to fragmentation (Observational limit is much lower)

(All known BD secondaries)

Zuckerman & Song 09: Mass function for BD binary companions to stars
Thies & Kroupa 08, BD and stars have **discontinuous** IMFs when binaries are accounted for.
Da Rio +09: IMF below $1 \, M_\odot$ in LH95
(a $2.4 \times 10^3 \, M_\odot$ cluster in the LMC)
(open symbols: recent work, filled symbols deGrijs +02

\begin{itemize}
  \item Liu +09: low-mass IMFs of 3 pairs of clusters in the LMC: 4 with break, 2 without, and the same for each cluster in each pair.
\end{itemize}
The shifted IMF for low metal halo stars
IMF in the First and Second Stars

• Population III at zero metallicity: dominated by moderately massive stars, \( M_c \sim 10-100 \, M_\odot \)
  – \( M_c \) high from a lack of cooling (Larson 98; Abel +02; Bromm +02)
  – But not supermassive stars: Fe-peak and r-process abundances in halo stars are incompatible with \( M>140M_\odot \) pair-instability SNe, which have no r-process (Tumlinson +04; but see Karlsson +08 who discuss selection effects)

• Then, a critical metallicity, \( Z/\dot{Z}_\odot \sim 10^{-5.5} \) to \( 10^{-3.5} \) for cooling and fragmentation to low mass stars (Schneider +02; Bromm & Loeb 03; Santoro & Shull 06; Frebel +07)

• By the time \( Z/\dot{Z}_\odot \sim 10^{-2} \) to \( 10^{-1} \), globular clusters form with normal IMFs

What was the IMF at \( 10^{-4} < Z/\dot{Z}_\odot < 10^{-2} \)?
Carbon Extremely Metal Poor (CEMP) Stars

• EMP stars: \([\text{Fe/H}] < -2.0\); CEMP stars: \([\text{C/Fe}] > 1.0\) (Beers & Christlieb 05).
  - 20\% of Population II stars at \([\text{Fe/H}] < -2\) are CEMP
  - 40\% at \([\text{Fe/H}] < -3.5\) are CEMP
  - all three stars known with \([\text{Fe/H}] < -4.5\) are CEMP (Christlieb +02; Frebel +05; Norris +07).
  - Carbon from C-rich ejecta of an asymptotic giant branch (AGB) binary companion with mass 1.5–8 M\(_\odot\) (Suda +04; Lucatello +05; Komiya +07; Tumlinson 07)
  - why AGB, why binary origin:
    - 80\% of CEMP are “CEMP-s” with \([\text{Ba/Fe}] > 1\) ("main s-process" element) from AGB stars (Busso +99; Aoki +07),
    - CEMP-s stars show radial velocity variations consistent with binarity (Lucatello +05).

• Carbon enrichment among EMP stars is so common that the ratio of intermediate mass stars (the AGB star) to low mass stars (the observed EMP) had to be high when the EMP star formed long ago
Tumlinson +07 reproduces the CEMP fraction in the halo with a model of hierarchical buildup assuming a log-normal IMF and a characteristic mass increasing with redshift because of cosmic microwave background heating.

\[ M_c = M_{BE} = M_{\text{norm}}\left\{ \max[2.73K(1+z),8K]/10K \right\}^{\alpha} \]
Constraints on $M_c$ with 4 possible binary mass ratios:
A: $n(q) = \text{const.}$, B: $n(q) \sim q$,
C: $n(q) \sim 1/q$, D: independent

Theoretical CEMP fraction if all EMPs born as binaries

Fraction if half of EMPs are born as binaries

Komiya +09 reproduce the CEMP fraction and the CEMP-s to CEMP-nos ratio assuming CEMP-s primaries are 0.8-3.5 $M_\odot$ and CEMP-nos primaries are 3.5 - 6 $M_\odot$ [M<3.5M_\odot stars make s-process, and 6 $M_\odot$ is the SN limit]
The time integral over the past cosmic SF rate is larger than the cosmic stellar mass for all redshifts. Is SF rate wrong?

Wilkins +08 The evolution of stellar mass density assuming a Salpeter or Kroupa IMF. (shaded= uncertainty envelope of the SFH in HB06.) The points are observed values from compilation of WTH08.
Fit of stellar mass to integrated SF history using a varying IMF:

\[ n(M) = n_{\text{Kroupa}}(M) + n_{\text{Salpeter}}(M_{\text{lower}} = 5M_\odot) \times (1 - \exp[-0.6z]) \]

At \( z=1 \), a 45% contribution from the truncated IMF,

At \( z=2 \), a 70% contribution

Wilkins + 08
[\alpha/\text{Fe}] vs galaxy velocity dispersion needs SFR-dependent IMF

Salpeter IMF (constant) $x=1.35$

$x=1$ (constant)

slope = -1.35 for SFR < 100 M$_\odot$/yr,
slope = -1 SFR > 100 M$_\odot$/yr

Calura & Menci 09
Other Flat IMFs for high SF Rate

• Massive elliptical galaxies had slightly flatter IMFs
  – Pipino & Matteucci 2004; Nagashima et al. 2005
• Clusters of galaxies suggest a history of flat IMFs in elliptical galaxy bursts
The steep IMF from missing Hα compared to FUV at low surface density
Hoversten & Glazebrook 07 fit SF model to Hα EW and g-r color in 140,000 SDSS galaxies, minimizing over variations in $\Gamma$, metallicity, ages, and SF history.
Meurer +09: 
H\(\alpha\)/FUV increases for brighter regions

Models: SF durations @ solar Z: 
0.1, 10, 100, 1000 Myr (top to bot)

purple: 0.2 Z\(_{\odot}\), green: 2.5 Z\(_{\odot}\) 
for 1 Gyr population
Gogarten +09: age effect

Star formation ended >16 Myr ago for the UV-bright-Hα-faint regions, and less than 10 Myr ago for the HII regions.

Also, stars in the HII regions are still in clusters while stars in the Hα –free regions are more dispersed (e.g., older)
Kotulla +08: There is Hα if you look hard enough

far-UV image of Arp 78 with Hα contours: good correspondence. FUV-to-Hα ratio of SFRs = 0.5-1.2, as for normal IMF
Pre-Stellar Cores
Enoch +06: Perseus 1.1 mm clumps spatially correlated
Pre-stellar cores

- move at sub-virial, near sonic, speeds
  - $\Delta v \approx 0.17 \text{ km/s}$ (Di Francesco +04), $\Delta v \approx 0.4 \text{ km/s}$ (Andre +07)
    - Belloche +01, Di Francesco +04, Walsh +04+07, Jorgensen +07, Kirk +07

- resemble Bonner-Ebert spheres, P-bound & gravitating, perhaps stable, but sometimes with evidence for inflow (e.g., Andre +07)

- mass fractions in clouds are $\sim 2$-$10\%$, like the average SF efficiency

- cluster together hierarchically, like young stars
  - Johnstone +00,01, Enoch +06, Young +06, ...

- **Suggest the IMF forms in the cloudy phase**
  - but will they fragment? are they stable? transient?
Theory
Competitive Accretion (Clark +09)

• Applies to clusters
• Masses \( > M_{\text{Jeans}} \) accrete from the whole self-gravitating reservoir
• Three regimes:
  – **comotion**: stars and gas both fall to a common cloud center:
    • \( \frac{dn}{dM} \sim M^{-1.5} \) when \( \rho \sim R^{-2} \) (Bonnell +01)
  – star **orbital motion**: Bondi Hoyle accretion:
    • \( \frac{dn}{dM} \sim M^{-2} \) in uniform gas (Zinnecker 82)
    • with \( \rho(R) \) and mass segregation, \( \frac{dn}{dM} \sim M^{-2.5} \) (Bonnell +01)
  – static **central** accretion: stars at center of the cloud accrete matter falling in
• \( M_{\text{Jeans}} \) determines initial fragment number: subsequent collapse produces few additional fragments because of tidal forces
  – \( M_{\text{char}} \sim M_{\text{Jeans}} \)

• Caution, so far, mostly non-magnetic simulations
Core Mass Function from Ambipolar Diffusion  
(Kunz & Mouschovias 09)

Consider an equilibrium cloud with internal thermal pressure, external pressure, self gravity and a uniform magnetic field.

Perturb the boundary and find the wavelength of fastest growth.

Consider the mass in this wavelength, rewrite in terms of $\mu_0=\text{mass/flux ratio}$, and assume the distribution of this ratio is uniform $\Rightarrow$ IMF.

(Li & Nakamura ...09 get normal IMF in MHD simulations)
Hennebelle & Chabrier 08: Turbulence-regulated

- log-normal density pdf & dispersion that increases with size
- for each region size $R$, sets
  - number of unstable regions ($\rho > \rho[L_{\text{Jeans}}=R]$) equals number of regions with mass less than $M_{\text{Jeans}}(R,\rho)$
  - the first number comes from an integral over the density pdf, the second from the integral over the mass spectrum.

- Parameters: Mach number at the thermal Jeans length ($\text{Mach}^*$); Mach number of the whole cloud ($\text{Mach}$).
- High mass slope = $(n+1)/(2n-4) = 1.4$ (Salpeter = 1.35) for 3D Kolmogorov velocity power spectrum slope $n=11/3$
Mass functions for fixed Mach*(Jeans)=2^{1/2} and various Mach(cloud)

Hennebelle & Chabrier 08

Mass functions for fixed Mach(cloud)=6 and various Mach*(Jeans)
The Characteristic Mass

- \( M_{\text{char}} \sim M_{\text{Jeans}} \sim T^{1.5}/\rho^{0.5} \) is about constant:

- in dense cores where gas is heated by dust collisions and cooling is by molecular lines, \( \rho \sim T^2 \) and \( T^{1.5}/\rho^{0.5} \sim \rho^{0.25} \).
  - typically \( T_{\text{dust}} \sim U_{\text{rad}}^{0.2} \) and then \( T^{1.5}/\rho^{0.5} \sim U^{0.1} \) (weak dependence)

- Similar arguments for lower densities where the radiation field (and \( T_{\text{dust}} \)) depends on density through the Kennicutt SF law, and for compressed globules in HII regions, where the radiation field and density are related by ionization pressure.

- In all cases \( M_{\text{Jeans}} \sim 0.3M_\odot \) with only factor of 2 variations

Elmegreen, Klessen & Wilson 08
• Why would $M_{\text{char}}$ change with SFR or epoch in the Universe?
  – is it the CMB temperature? (Larson 98)

• $T_{\text{CMB}} \sim (1+z)$ and $\rho_{\text{cosmic}} \sim (1+z)^3$, so
  \[ M_{\text{Jeans}} = T_{\text{CMB}}^{1.5}/\rho_{\text{cosmic}}^{0.5} = \text{constant} \]

• Need relative changes between SF rates, heating rates, cooling rates, and density:
  – higher SF efficiency in the KS relation would do it (more L per $\rho$)
  – smaller grains at low metals would do it (smaller grains are hotter)
  – more powerful starbursts would evaporate low mass pre-stellar globules
  – ...

EKS08
Conclusions

• Salpeter IMFs are still the norm for SF regions
  – deviations not understood
  – no IMF correlation with metallicity down to \( Z \sim 0.1 \) (SMC), or
  – with density (M16)
  – the galactic center disk IMF is a little flat (slope \( \sim 1.0 \))

• The IMF falls into the BD regime, with some variations at
  the deuterium-burning limit of \( \sim 13 \, M_{\text{Jup}} \sim 0.012 \, M_\odot \)

• Stars forming with \( Z/Z_\odot = 10^{-4} \) to \( 10^{-2} \) (before globular
  clusters) may have had \( M_{\text{char}}\sim5M_\odot \) (CEMP; SFH of Univ.)

• The IMF may be slightly flatter at high SFRs ([\( \alpha/Fe \)] vs \( \Delta v \))

• The IMF may be slightly steeper at low SFR (missing H\( \alpha \) in
  small galaxies and outer spiral disks)

• Several different theories get the IMF, but no consensus