Scalo 1998: “The IMF Revisited: A Case for Variations”

“You know nothing about the IMF, Jon Snow!”

-- Stellar Populations –
Irina Ene, Sep 21, 2016

Introduction

- “The organizers have asked me to summarize my impressions of IMF studies since the time of my earlier review paper (Scalo 1986, hereafter S86).”
- Only stellar (protostellar, substellar) counts
- Emphasizes sources of uncertainty
- IMF -> differential probability distribution of mass per unit log mass F(log m)
- !!! Local ”index” Γ = d log F(log m)/d log m !!!
- Estimating IMF using least squares fit to a histogram is common practice

Field Star IMF

- Conclusions of S86
  - IMF not lognormal as found in Miller & Scalo 1979
    - For m>1, IMF roughly a power law, showed signs of flattening with increasing mass (MS79 showed steepening)
  - Uncertainties are “huge” -> didn’t attempt a functional form fit
  - Clusters -> Γ = -1.5 to -1.8 for 1-10 M_sun (probably -1.2 at higher masses)
- No updated treatments of field star IMF over the entire stellar range (with some exceptions, but those only concerned with m<1 e.g. Kroupa 1990s papers)

Field Star IMF

- Basu & Rana 1992 look at field star IMF ingredients
- Claim to use recent (>1986) LF
  - Gilmore & Reid 1983 LF is actually MS79 for m>0.8
  - Eaton et al. 1984 LF is Allen 1973 (summary of older work)
  - Robin & Creze 1986 LF is also from Allen 1973 for m>8
- Useful discussion of scale height and m-L relation

Field Star IMF

- For low-mass stars, “convergence” -> Γ between 0 and -0.5 for 0.1 to 1 M_sun
- Dependence on SFR because of PMS -> can’t say anything about a turnover at 0.1 M_sun
- Lots of problems , so below 0.1 M_sun should use open clusters (SFR not so severe, but need to worry about radial segregation, unresolved binaries, etc.)
- Globular clusters -> Di Marchi & Paresca 1997: IMF flattens out and drops below 0.2 M_sun

Field Star IMF

- Massive stars
  - LF is inadequate
  - No 1-1 correspondence absolute magnitude – mass
  - Optical and near-UV only sample low-frequency tail of energy distribution -> need spectroscopy (e.g. Massey et al 1995)
  - Van Buren 1985: Γ = -1.1 to -1.4
- S86 for high mass is extinct
- S86 only valid for 1.5 to 15-20 M_sun (if at all)
  - $\Gamma \approx$ -2.6 for 1.4-3.5 M_sun
  - $\Gamma \approx$ -1.8 for (1.9 or 2.5)-12 M_sun

Massive Stars in Clusters and Associations

- Largest uncertainty comes from small sample size
- Milky Way results issues
  - 6 to 93 stars used for IMF estimation
  - Largest mass bin has 1 or 2 stars
  - Uncertainties from 0.2 to 0.6
  - Γ from -0.7 to -2.1, weighted mean of -1.1
  - "Massey et al. point out that all the Γ values are within 2-sigma of the mean value, suggesting to them that all the IMFs are the same within the statistical uncertainties."
  - Lowest mass bin at 5-7 M_sun was omitted due to incompleteness, but in 11/13 cases the omitted point is above the fitted power law

Massive Stars in Clusters and Associations

- Massey et al 1995 results in 4 LMC, 1 SMC clusters
  - $\Gamma = -1.1 \pm 0.1$ to -1.6 ± 0.2
- Oey 1996 LMC HII regions
  - $\Gamma = -1.0 \pm 0.1$ to -1.8 ± 0.4 for $m>10$
- Independent studies of the same region, LMC superbubble LH47
  - Oey & Massey 1995: $\Gamma = -1.3 \pm 0.2$
  - Will et al. 1997: $\Gamma = -1.2 \pm 0.1$
    - Fit only between 2.5-30 M_sun
    - 12-85 M_Sun (O&M range) $\Gamma = -2.1$

Massive Stars in Clusters and Associations

- Independent studies of R136 (LMC)
  - Massey & Hunter 1997: Γ = -1.3 to -1.4 for 20-120 M_sum (spectroscopy only for m>50)
  - Hunter, O'Neill et al. 1996: Γ ≈ -1 for intermediate-mass
    - No evidence for mass segregation
  - Brandle et al. 1996: Γ = -1.6 ± 0.1 for 6-100 M_sun
    - R<0.4pc: Γ = -1.3
    - 0.4pc<R<0.8pc: Γ = -1.6
    - 0.8pc<R: Γ = -1.5 for 4-25 M_sun and Γ = -2.2 for 12-50 M_sun
    - Strong evidence for mass segregation

Massive Stars in Clusters and Associations

- Agrees with some of the conclusions of Massey et al.
  - "within observational uncertainties", no trend of IMF with metallicity, galactocentric radius in MW, or stellar density over a factor of about 100
- "My impression of the situation is that either the systematic uncertainties are so large that the derived values of Γ are relatively meaningless or else there are probably significant variations for massive stars in different clusters and associations."

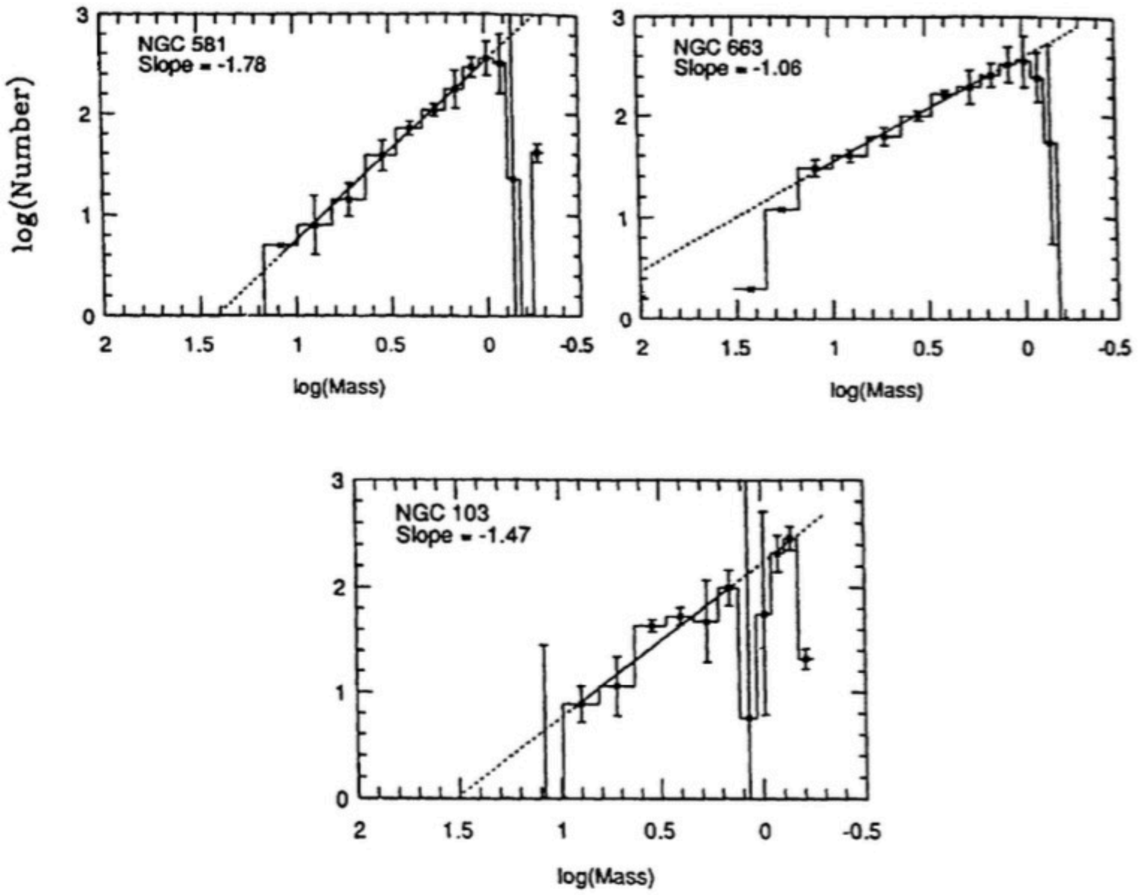
Intermediate-Mass Stars in Clusters

- Pros
  - If old enough (>10 Myr), MS is well-defined, no problems due to pre- or post- MS contamination
  - M-L relation ”reasonably well-understood”
  - Unresolved binaries not a very big problem
  - Don’t have to worry about SFR history
  - Don’t have to worry about scale height
  - Cluster stars are formed in same volume -> specific realization of IMF
    - Don’t need to worry about uncertainties in distance
- Cons
  - Field stars contamination
  - Completeness at small masses
  - Mass segregation
  - Small sample size

Intermediate-Mass Stars in Clusters

- Phelps & Janes 1993
- 8 clusters aged 10-70 Myr
- 1.2-1.9 to 7.9-18 M_sun
- Γ range between -1.1 (NGC 663, 659) to -1.8 (NGC 581)
- Structure in IMF is important
- “evidence for a non-universal IMF”

Fig. 1 -- Phelps & Janes 1993



Intermediate-Mass Stars in Clusters

Universal IMF

- Vazquez et al 1997: -1.8
- Brown et al. 1994: -1.8

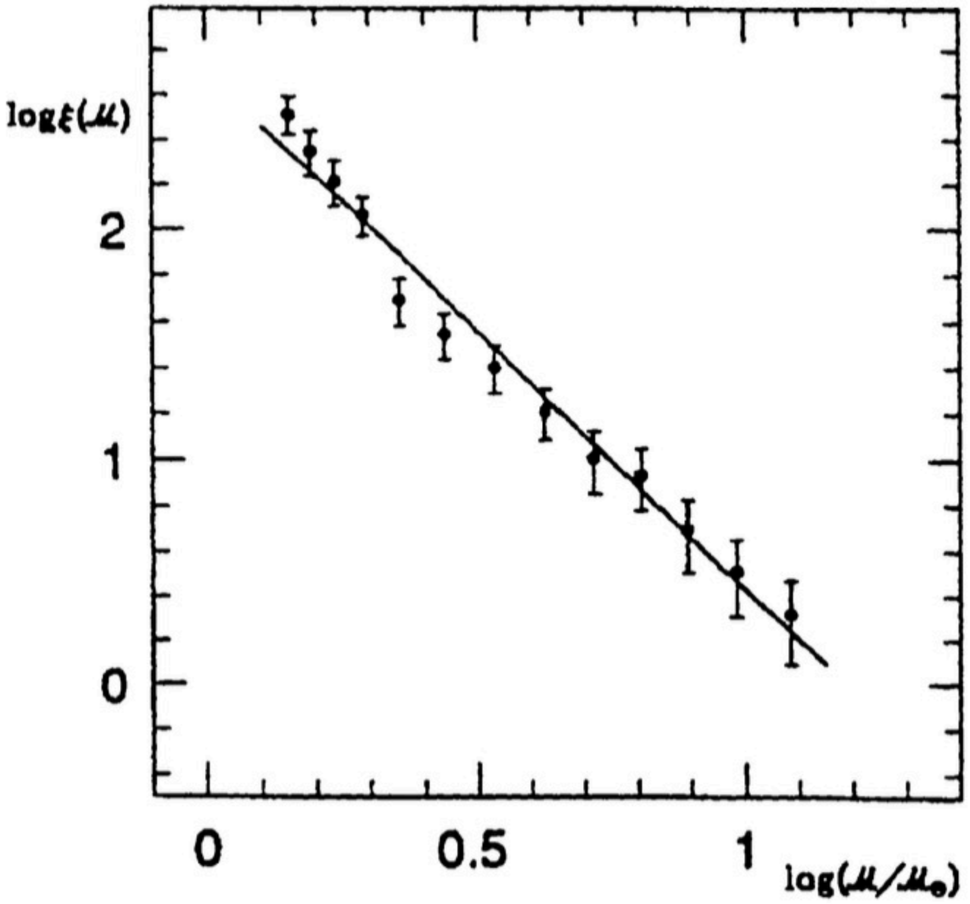
Variations in IMF

- Meusinger et al. 1996
  - 0 below 1.1 M_sun
  - -2.3 for 1.1-3.5 M_sun
- Williams et al. 1995
  - 0 for 0.4-1 M_sun
- Deeg & Ninkov 1996
  - Give -1.3 ± 0.3 for 1.1-20 M_sun
  - Better fit by -0.6 for 3-16 and -2.7 for 1.2-3.5 M_sun

Intermediate-Mass Stars in Clusters

- Discrepancy in young clusters and associations in LMC
  - Mateo 1988: -2
  - Elson et al. 1989: 0
- Sagar & Richtler 1991
  - Unresolved binary corrections
  - -1.1 -> -1.5 if binary fraction > 0.4
- IMF sensitive to data, analysis, completeness correction
- “true” IMF lies between the two extremes

Fig. 3 -- Grondin et al 1992



Pre-Main Sequence Stars

- No 1-1 relation between luminosity and mass
- LF is affected by the SFR
- Rate of evolution is affected by physical effects -> features in LF that are not related to IMF
- Accretion
- Membership
- Radial mass segregation
- Unresolved binaries

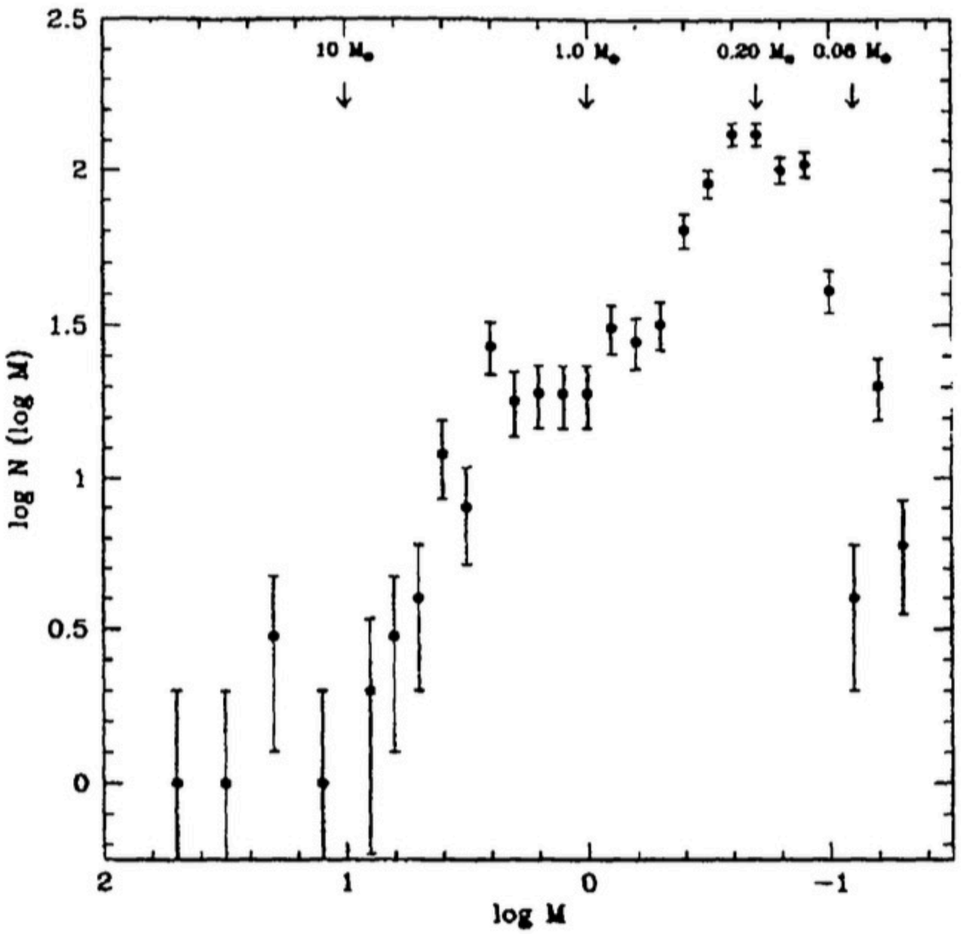
Pre-Main Sequence Stars

- Williams et al. 1995
  - ρ Oph cluster
  - Γ = -0.1 into substellar range
  - IMF per unit log mass is basically flat up to 4 M_sun
  - Meusinger et al found Γ ≈ -2.6 for same mass range
- Comeron, Rieke, & Rieke 1997
  - NGC 2024
  - Γ ≈ -0.2 for 0.06-1 M_sun
- (Almost) no evidence for low-mass turnover

Pre-Main Sequence Stars

- Hillenbrand 1997 – Orion Nebula Cluster
- Turnover at m ≈ 0.3
- Mass segregation
  - Carpenter et al 1997 do not find segregation at m < 2

Fig. 4 – Hillenbrand 1997



Pre-Main Sequence Stars

- Ninkov et al. 1995
  - $\Gamma = -1.4 \pm 0.2$ for 3.5-21 M_sun
- Williams, Rieke et al. 1995
  - -0.3 for 0.2-0.6 M_sun
  - -1.2 above 0.6 M_sun
  - This result (flat, then steep) is similar to other cluster results, Kroupa et al. 1993, Reid & Gizis 1997
- Open, embedded clusters, and field stars show “rough agreement”, $\Gamma \approx 0$ to -0.5 for 0.1-1 M_sun
  - Results depend on m-L, models, segregation, unresolved binaries, etc

Galaxies Beyond the Magellanic Clouds

- “The IMF […] remains effectively inaccesible to star counts except to say that the similarity in LFs for the brightest stars in several galaxies seems to rule out severe variations (e.g. Bresolin et al. 1996), where the meaning of “severe” is currently unknown.”
- Hunter et al. 1996a: M31 OB association NGC 206
  - $\Gamma = -1.4 \pm 0.5$
  - 4 mass bins between 6.8 and 13.5 M_sun
  - IMF doesn’t resemble a power law
- Hunter et al. 1996b: NGC 604
  - $\Gamma = -1.6 \pm 0.7$
  - 4 mass bins between 7.5 and 16 M_sun

Galaxies Beyond the Magellanic Clouds

- Grillmair et al. 1997: Draco dwarf spheroidal galaxy
  - Γ is -0.5 to -1.6, depending on the adopted age (10 to 15 Gyr)
- Need to use integrated light and chemical evolution constraints

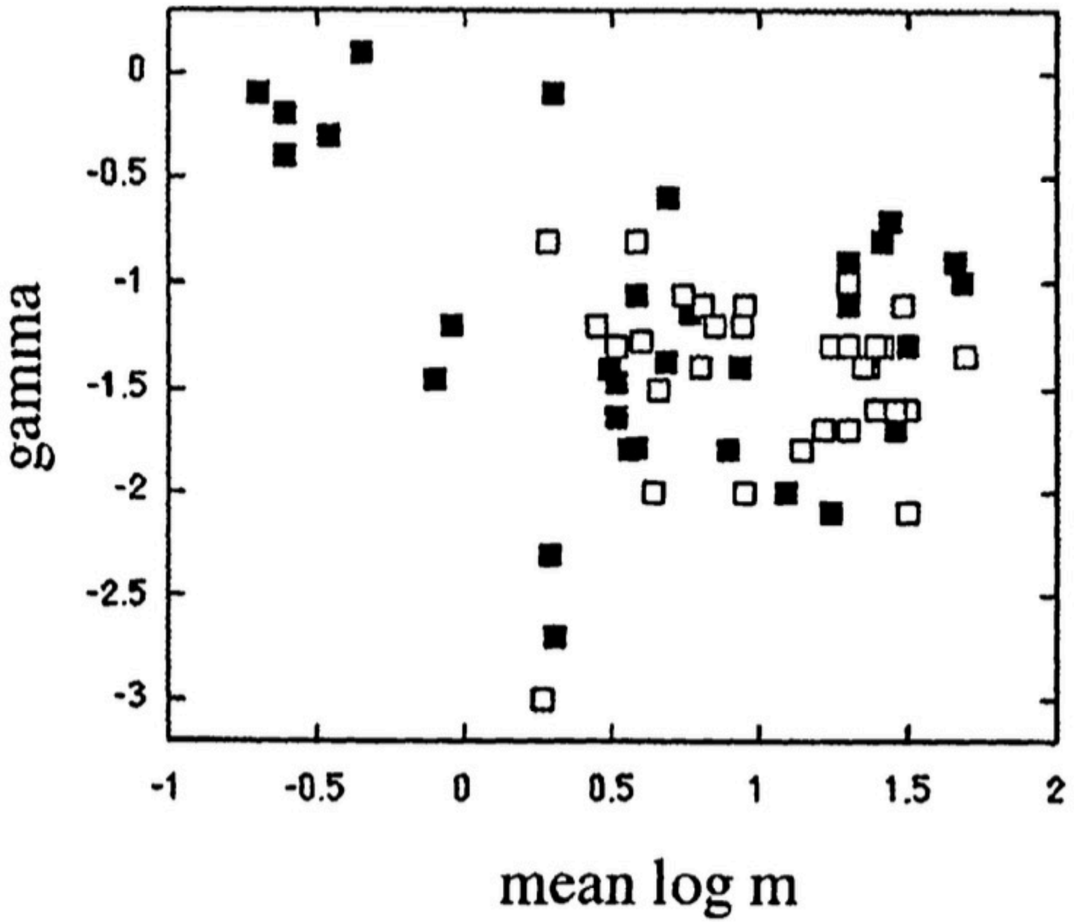
Conclusions

- Usual IMF derivation of “questionable use”
- 0.9-1.4 M_sun -> dominated by assumed SFR
- Above 15 and below 0.1 M_sun -> m-L relation is not single-valued, need comparison with evolutionary tracks in H-R diagram
  - PMS stars -> assumed SFR
- Corrections for scale height and evolved stars
- Field stars sample to different distances and ages
  - ”hopeless mixture which does not give a usefully defined “average IMF.””

Conclusions

- “Instead we are in the rather uncomfortable position of concluding that either the systematic uncertainties are so large that the IMF cannot yet be estimated, or that there are real and significant variations of the IMF index at all masses above about 1 M_sun”.

Fig. 5 – Papers (clusters) discussed in review



Conclusions

- “Instead, I suggest that theorists should predict the magnitude and nature of variations in IMF (say the variance as a function of mass).”
- Very low-mass IMF is relatively flat and stable in solar neighborhood, steeper above about 1 M_sun.
- $\Gamma = -0.2 \pm 0.3$ for 0.1 to 1 M_sun
- $\Gamma = -1.7 \pm 0.5$ for 1-10 M_sun
- $\Gamma = -1.3 \pm 0.5$ for 10-100 M_sun
- ± -> empirical uncertainties or real IMF variations (or both)

Scalo 2005 – Fifty Years of IMF Variations: The Intermediate-mass Stars

"You still don't know anything about the IMF, Jon Snow!"

Introduction

- Outline major development, with focus on recent results for star counts in the mass range 1.2 to 15-20 M_sun for galactic field stars and open clusters
- Everybody is focused on low-mass IMF
- “Surprisingly, the IMF above 1 M_sun has not been critically examined, although statements that the stellar IMF in this range is invariant are now common in the literature.”
- IMF = d N/ d log m
- Γ = slope of log-log power law fit over some range

Introduction

- Nowadays, IMF steeper at intermediate and large masses than at subsolar masses
- “Nevertheless, it has become common in the last decade to interpret various data as consistent with the Salpeter slope for masses above 1 M_sun; as will be seen below, there is currently little basis for assigning a given average, let alone universal, value, at least from star counts.”

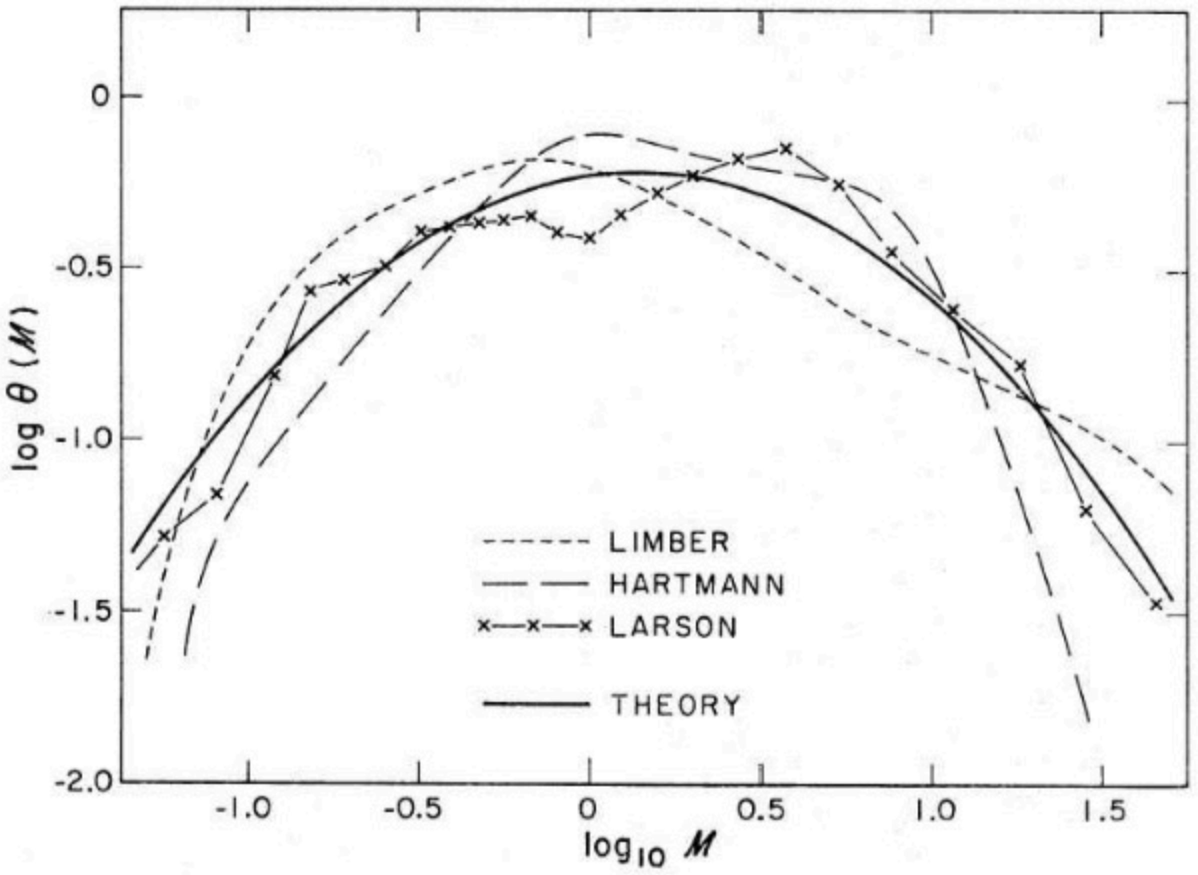
Introduction

- IMF universality
- Star formation is complex -> universal IMF?
- Uncertainties in empirical estimates are so large that “all evidence is consistent with a universal IMF”
- “Partly because of its appeal and simplicity (and because the physicist’s need for universality runs deep), the former interpretation [universal IMF] is nearly always adopted.”

Historical Divergence: Field Star IMF

- All models turn over above 1 M_sun, but incomplete at low masses
- IMFs do not agree with each other even above 1 M_sun
- Large variations in both shape and slope

Fig. 2 – Empirical estimates before 1973



Historical Divergence: Field Star IMF

- MS79: half of lognormal function IMF fit, “concave”
- Scalo86
  - 1.4-15 M_sun, IMF is “convex”
  - Γ = -2.6 for 1.4-3.5 M_sun
  - Γ = -1.8 for 2-12 M_sun

Historical Divergence: Field Star IMF

- M-L relation very important for low-mass IMF
  - D’Antona & Mazzitelli 1983
  - Kroupa et al. 1990, 1993
  - Kroupa 2002
  - deGrijs et al. 2002a
  - Kroupa et al. 1991
  - Chabrier 2003b
- No advances for 1-15 M_sun
  - Yuan 1992 = Scalo 1986
  - Kroupa et al. 1993 = new result below 1 M_sun + Scalo 1986 for higher masses

Historical Divergence: Field Star IMF

- Rana 1991
  - $\Gamma = -1.3$ for 1.4-100 M_sun
  - But use very uncertain LF above 15-20 M_sun
  - $\Gamma \approx -1$ for 1-15 M_sun
- Basu & Rana 1992a,b
  - same LF and M-L as Rana
  - $\Gamma = -1.5$ to -1.7 for 1.4-100 M_sun
  - Excluding higher masses, $\Gamma \approx -1.2$

Historical Divergence: Field Star IMF

- Advances: Hipparcos, DENIS, 2MASS
- Ried et al. 2002 $\Gamma = -1.8$ (or -1.5) for 1.1 (or 0.6) and 3 M_sun, depending on m-L choice
- Schroder & Pagel 2003 $\Gamma = -1.7$ for 1.1-1.6 M_sun and -2.1 for 1.6-4 M_sun
- ”optimistically interpreted” $\Gamma = -1.9 \pm 0.4$ for 1.1-4 M_sun
- “It is probably safe to say that the field star IMF in the 3-20 M_sun range is unknown, or at least extremely uncertain.”

Historical Divergence: Open Cluster IMFs

- Pros
  - Best opportunity to understand IMF and test universality
  - Same age, distance, and metallicity
- Cons
  - Few clusters cover a wide mass range
  - Usually only 50-200 stars per cluster
  - Mass segregation even in young clusters -> larger radii
  - Issues determining membership; corrections for contamination and incompleteness
  - Unresolved binaries

Historical Divergence: Open Cluster IMFs

- Cons
  - Adopted cluster properties
  - Uncertainties in evolutionary tracks
  - Preferential escape of low-mass stars during dispersal of residual gas in initially virialized clusters
- Mass segregation, unresolved binaries, ejection -> IMF that is too flat
- ”*every estimate of Γ derived for clusters should be considered an upper limit*”

Historical Divergence: Open Cluster IMF

- Many papers using Scalo 1986 m-L relation
- Taff 1974: $\Gamma = -1.7$ for 1-20 M-sun
  - No comments on variations, never been re-examined
- Claudius & Groble 1980: $\Gamma = -1.6$ to -2.0
  - Samples too small
- Tarrab 1982: $\Gamma \approx 0$ to about -3
  - Inhomogeneous, old sources of data, small sample, recent studies show different results

Historical Divergence: Open Cluster IMF

- Cluster-to-cluster IMF variation:
  - 2 clusters with similar ages, number of members, limiting magnitude, same reduction procedure etc.
  - NGC 663: $\Gamma = -1.1$
  - NGC 581: $\Gamma = -1.8$
  - Very small fitting uncertainties

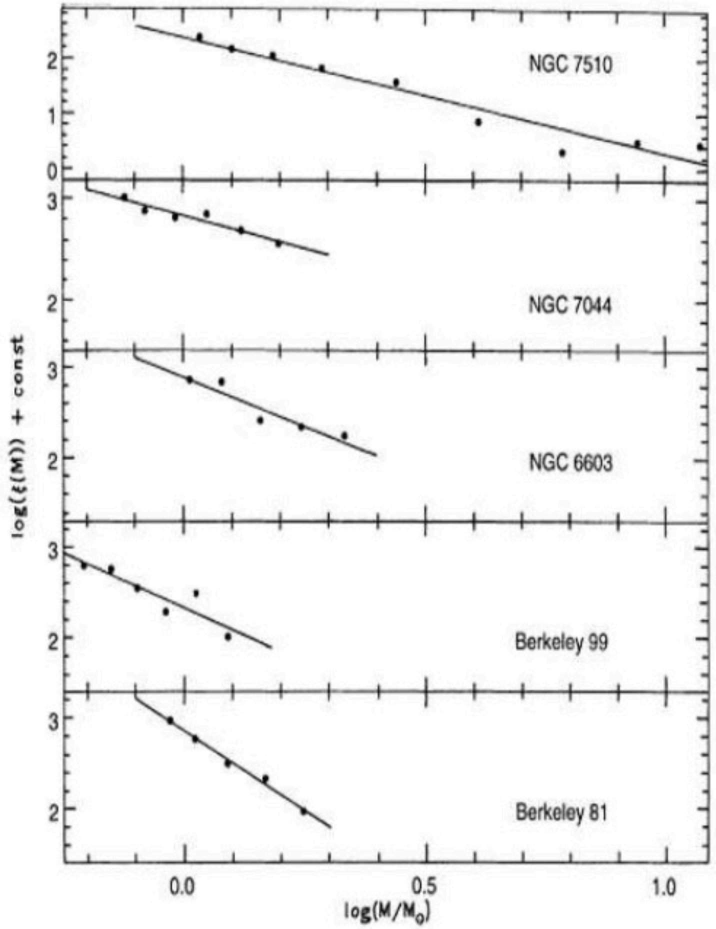
Historical Divergence: Open Cluster IMFs

- Γ = -2 for 1-2 to 4-10 M_sun
  - NGC 2422, Stock 2, NGC 2323, NGC 4815, NGC 6631, Pleiades, Orion Nebula Cluster
- Γ = -0.9 for similar mass range
  - NGC 2244, NGC 2451A, NGC 3603
- Γ between -1.1 to -1.6
  - NGC 1960, NGC 2194, h and chi Persei, NGC 2421, Tr 1 and Be 11, NGC 7510 (Γ = -1.1 for 1-13 M_sun), Upper Scorpius OB association ($\Gamma \approx$ -1.6 for 2-20 M_sun)

Historical Divergence: Open Cluster IMFs

- Variations just as large for studies using homogeneous data and same reduction procedures
    - -1.1 to -1.8
    - -0.7 to -2.3
    - -0.8 to -1.9
    - -1.0 to -1.5
    - -0.3 to -2.5 (Sagar and Griffiths 1998)
- Different IMFs in different subregions of same cluster (NGC 7654, Pandey et al. 2001)

Fig. 4 – Sagar & Griffiths 1998



Conclusions

- Re-convergence has not yet occurred in 1-15 M_sun range
- The observations are consistent with universal IMF because uncertainties are very large
- “A balance must be struck between convenient interpretation of disparate results, and attention to uncertainties, physical effects, and convincing evidence [...]”
- Prevalent notion of universal IMF still holds
    - “[...] the default position became universality, with a corresponding projection of this belief onto interpretation of observations.”

Fun facts about John Scalo

- This is him ----------------------------->
- He was the MA advisor of Neil deGrasse Tyson
  - Star Formation models for Dwarf Galaxies
- NASA astrobiology institute