Scalo 1986 – The Stellar Initial Mass Function

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Outline

- Introduction and formalism (Section 1)
- How is the IMF determined? (Sections 1 and 2)
  - Skip lots of details because Miller & Scalo cover it
- IMFs from field stars (Section 2)
  - Advantages, disadvantages
  - Results
- IMFs from clusters (Section 3)
  - Advantages, disadvantages
  - Results
- Results and conclusions from rest of paper (Section 8)

“All theories are wrong” –Scalo, basically - (1.1)

“The extensive theoretical literature on the IMF presents a bewildering jumble of approaches and ideas, usually motivated by observational evidence which is either extremely uncertain or subject to ambiguous interpretation”

- Everyone’s totally different theories predict values close to the Salpeter IMF slope
- Most likely, the IMF is explained by multiple nonlinear processes
  - Ex. Turbulence, which isn’t understood even in the lab, is probably crucial

Defining the IMF usefully is difficult! - (1.2)

- If star formation were randomly distributed in space and time, could just say f0(m) dm is fraction of stars with mass range delta_m in a given volume
  - But they form in clusters! So average over all clusters?
    - Still fails if IMF is variable non-stochastically over time or space
- Determine avg. frequency distribution of stellar masses from a large sample of similarly-aged clusters, then do that for many cluster ages
  - Different ages -> different mass ranges because of HR diagram turnoff
  - Averaging clusters is hard! They are not all the same. How do we correct/average them?
- We cannot obtain empirical mass distribution that corresponds to a consistent IMF definition and can be related to theory without major assumptions

Parameterization of IMF - (1.3)

- Power law – simple and widely used
- A million others:
  - The gamma distribution
  - The Rayleigh distribution
  - The lognormal distribution
  - The generalized Rosin-Rammler function
  - Multimodal distributions
- All empirical fits should be used only as tools for predicting integrated properties of large numbers of stars

Definitions - (1.3)

- Mass spectrum f(m) such that f(m)dm is # stars formed at same time in some volume of space with mass between m and m+dm at birth
  - Treat as probability density function normalized to 1
- Mass function F(log m) = (ln 10)m*f(m) is the log of this
- Both are referred to as IMF
- g_n(>m) = integral of f(m) dm from m to m_max
- Indices of mass spectrum/mass function
  - gamma_m = dlog f(m) / dlog m
  - Gamma_m = dlog f(logm) / dlog m

Field Star IMFs

Determining the Field Star IMF - I (2.1)

- This discussion parallels and updates Miller & Scalo 1979
- The short version: Field star luminosity distribution -> mass-luminosity relation -> correction for stellar death
  - This is what Salpeter got famous for doing
- Field star = non-cluster star in Solar neighborhood
  - “neighborhood” depends on how you do your distance estimates
    - 40 pc for stars <= 2 m_sun, with reliable trigonometric parallaxes
    - 5 kpc for stars >= 10 m_sun, with spectroscopic parallaxes (not actually parallax)
- Older stars have moved significantly in their lifetimes (~40 km/s) so hard to know where they actually formed
  - Any field star determination samples a significant portion of the Galactic disk

Determining the Field Star IMF - II (2.1)

- Mass function at mass m represents the average of IMF over a time equal to lifetime of stars with mass m
  - So we are also averaging the IMF over time
- Luminosity function – Phi(M_v) – the main observational quantity
- Phi(M_v) converted to Phi(log m), the present-day mass function (PDMF), defined as the # main sequence stars at mass m per mass interval per area
  - Phi(log m) is per unit *area* because more massive stars concentrate to the midplane of the disk
  - Note an average luminosity over a stellar lifetime is used here, not the ZAMS luminosity. This effect approximately compensates for brightening of stars during hydrogen burning

Determining the Field Star IMF - III (2.1)

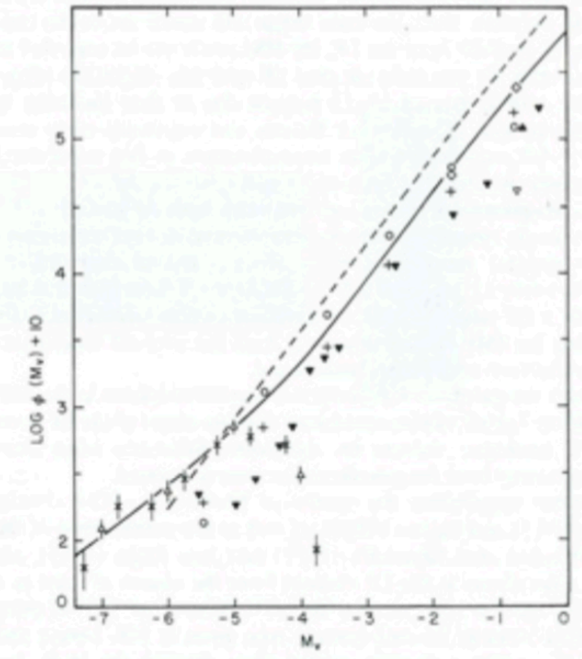
- PDMF is converted to IMF using stellar evolution considerations
  - Stellar creation function C(log m,t) - # stars born/area in disk within mass interval dm and time interval dt
  - Phi(log m) = integral C dt from t=0 to present time T_0 for stars with lifetimes longer than T_0
  - Phi(log m) = integral C dt from t=T_0 – tau_m to T_0 for stars with lifetime of tau_m
  - This is easier if C(log m,t) = F(log m)B(t); separable birthrate and mass function
    - This is adopted in absence of evidence for or against it being actually true, but is necessary to have a useful definition of IMF as said before
  - And even easier if B(t) = <B>, some average value. Validity of this also unknown
- We get IMF xi(log m) = F(log m)*T_0*<B>

Determining the Field Star IMF - IV (2.1)

- Define b(t) = B(t)/B, the relative stellar birthrate
- Finally: separable creation function divides IMF determination into:
  1) Estimate PDMF from luminosity function
  2) Estimate the history of the relative stellar birthrate b(t) and the age of the galactic disk T_0

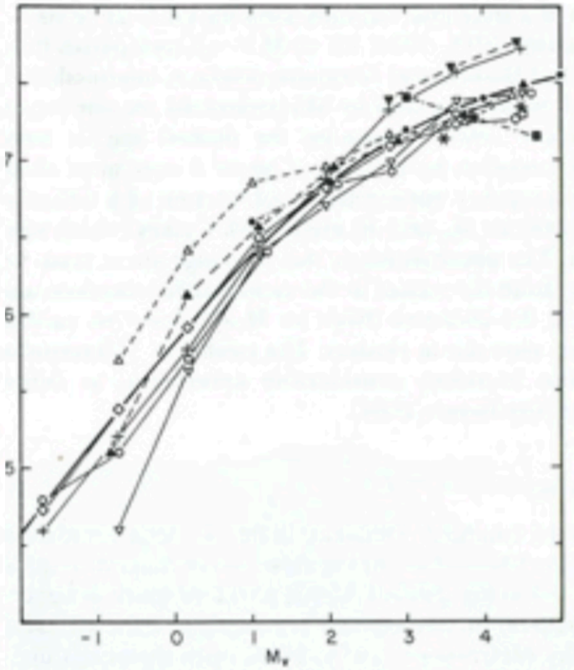
Measuring the Luminosity Function - (2.2)

1. count number of stars as function of apparent magnitude
2. estimate distances to those stars
    - Parallax – most straightforward way
        - works for close, bright stars only
        - must correct for low-proper-motion stars
    - Spectroscopic/photometric – only way to get at longer distances
        - Need to know density of stars in space as function of spectral class, which is uncertain
        - Interstellar absorption may be important



GURE 2 Determinations of the luminosity function of bright stars. Sources of data given in Table I.

Very Bright
-7 < M_v < 0
small number statistics
M_v -> mass is not one-to-one for big stars



Determinations of the luminosity function in the range −2 < M
ta are given in Table I.

Bright
-2 < M_v < 5

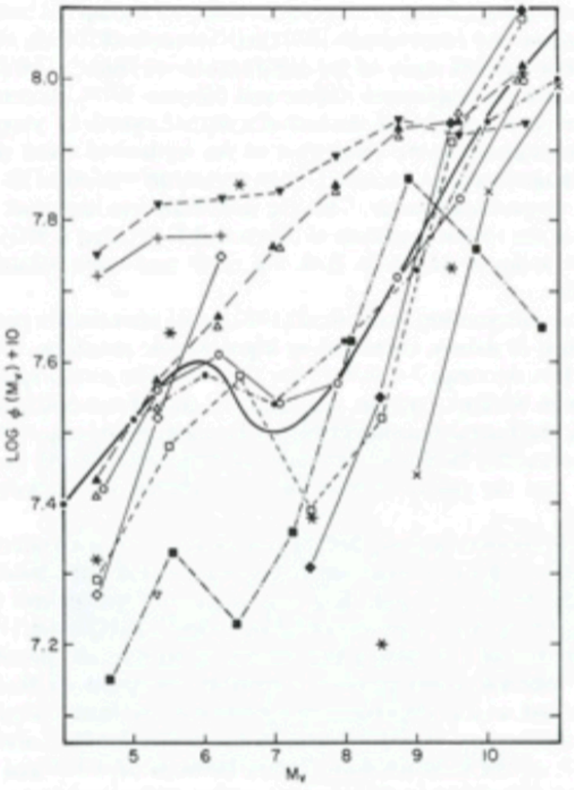


FIGURE 4 Determinations of the luminosity function in the range $4 < M_v$
Sources of data are given in Table I.

Intermediate
4 < M_v < 11
Dip at M_v~8 might be real,
but maybe local variations
Slopes agree except at dip

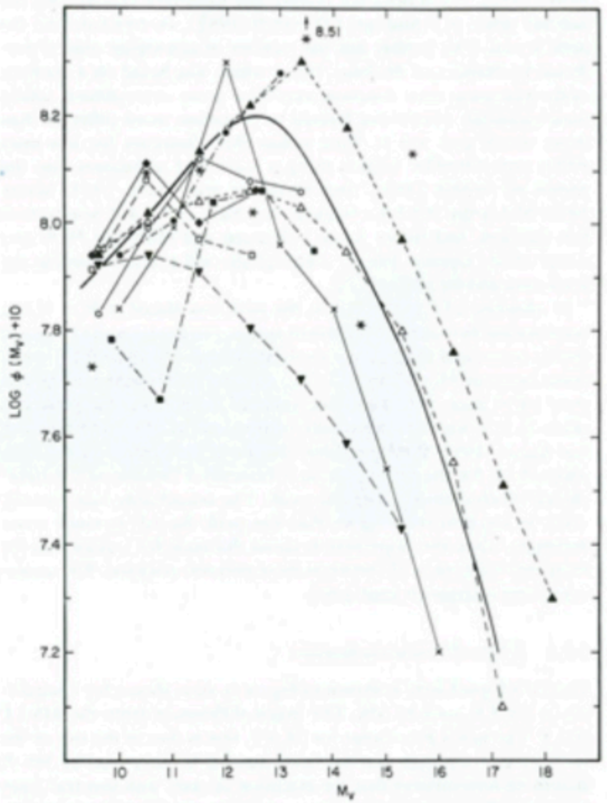


FIGURE 5 Determinations of the luminosity function of faint stars. Sources of data are given in Table I.

Faint
9 < M_v < 19
Hard because faint!
Peak is assumed real –
statistics appear good enough
to support that

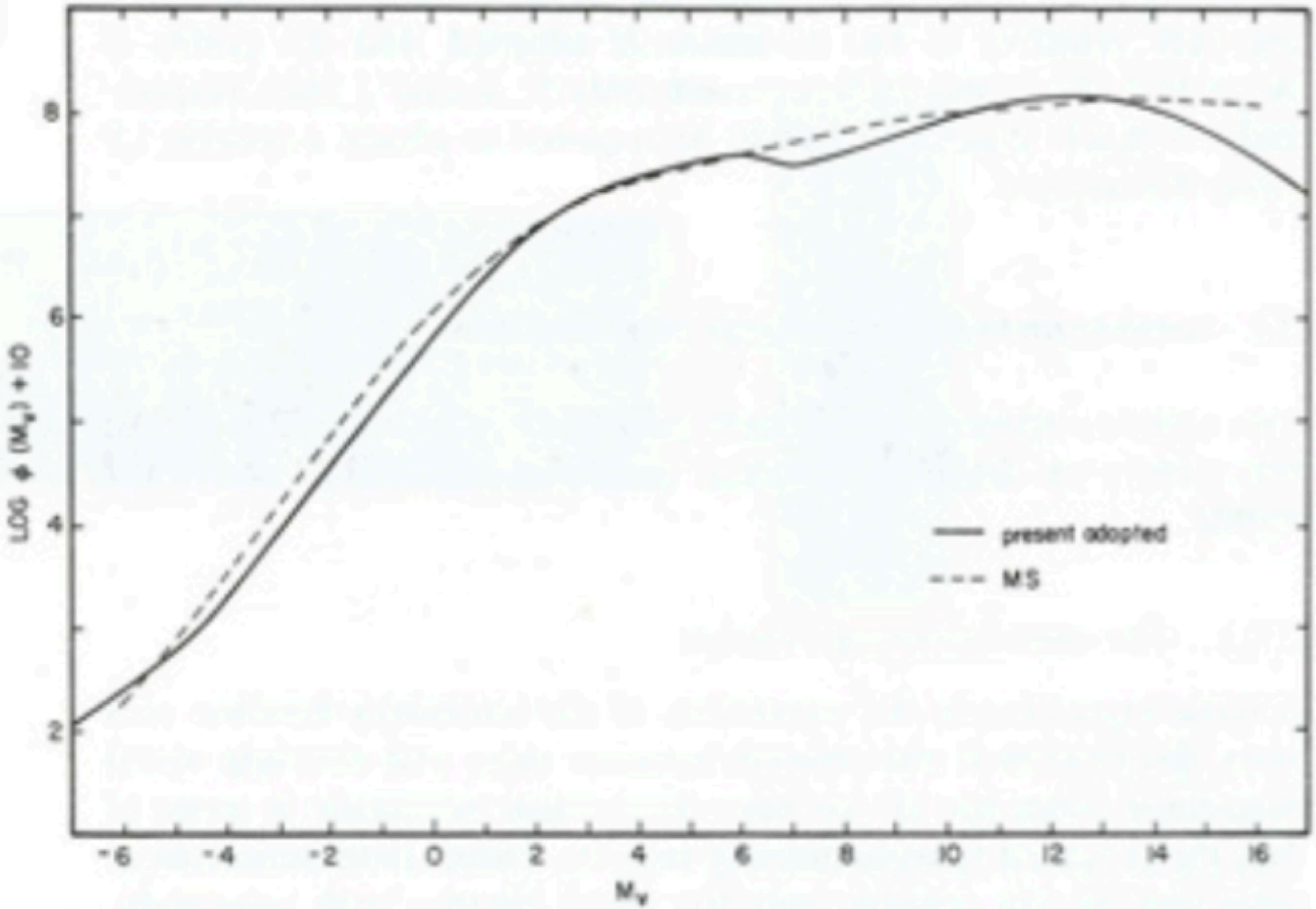


FIGURE 6 Adopted luminosity function (solid line) compared with luminosity function used by Miller and Scalo (1979, dashed line).

Conversion to mass function (2.3)

- Direct mass and magnitude determinations are only possible for visual binaries with trigonometric parallaxes
- Can add double-eclipsing binaries with resolved spectral lines of both components
  - But here need to assume M_v based on spectral type
- Relation uncertain above M_v <~ -1 and below M_v >~ 12
- Semi-theoretical mass-M_v relation (from stellar modeling) also uncertain at high and low masses
- Added confounding factor is spatial distribution of mean age – younger stars are nearer the galactic midplane
- Correction for non-main-sequence stars

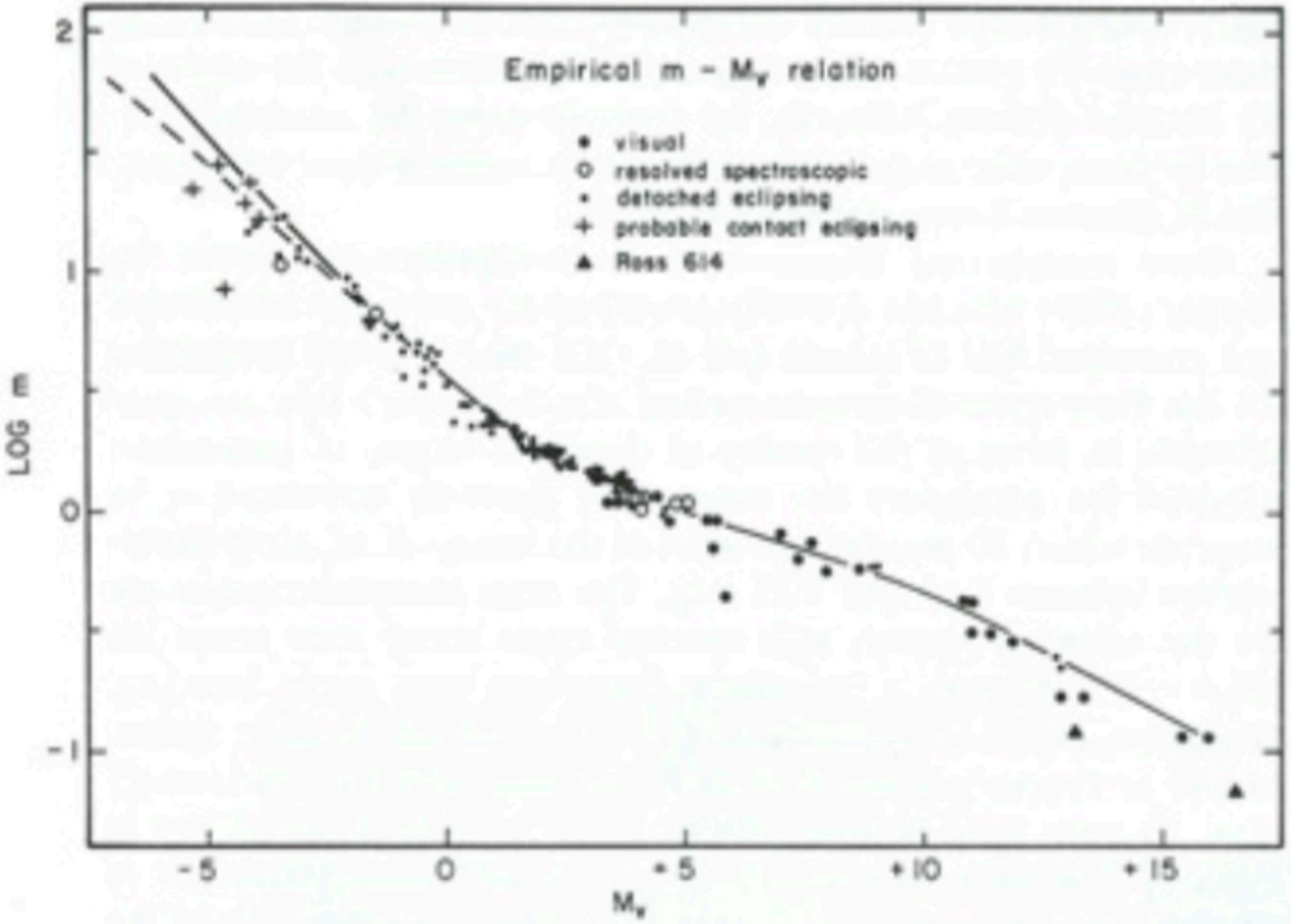


FIGURE 7 Empirical mass-luminosity relation from binary star data. Solid line is relation used by Miller and Scalo (1979); dashed line is modification adopted in present work.

Scale height vs magnitude

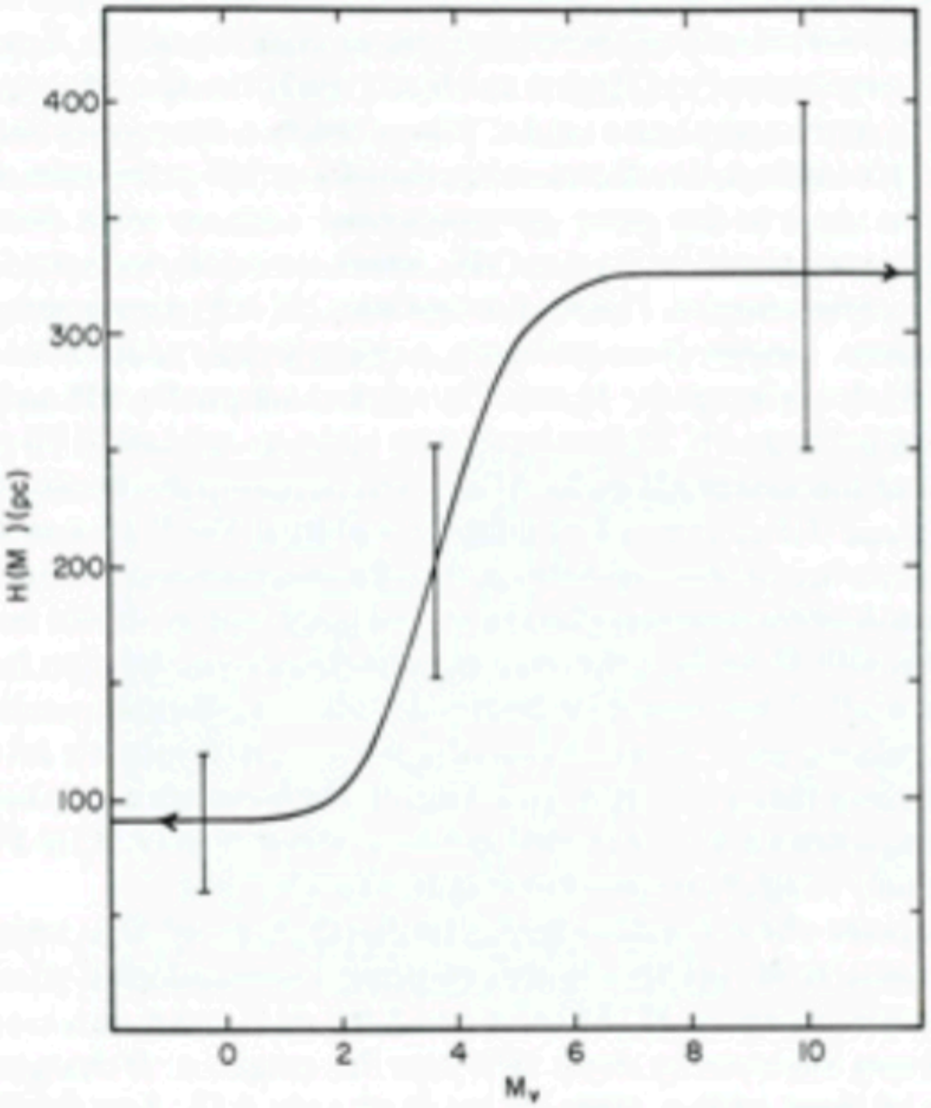


FIGURE 10 Adopted relation between stellar scale height and absolute visual magnitude; indicated uncertainties are rough estimates.

Fraction on main sequence vs magnitude

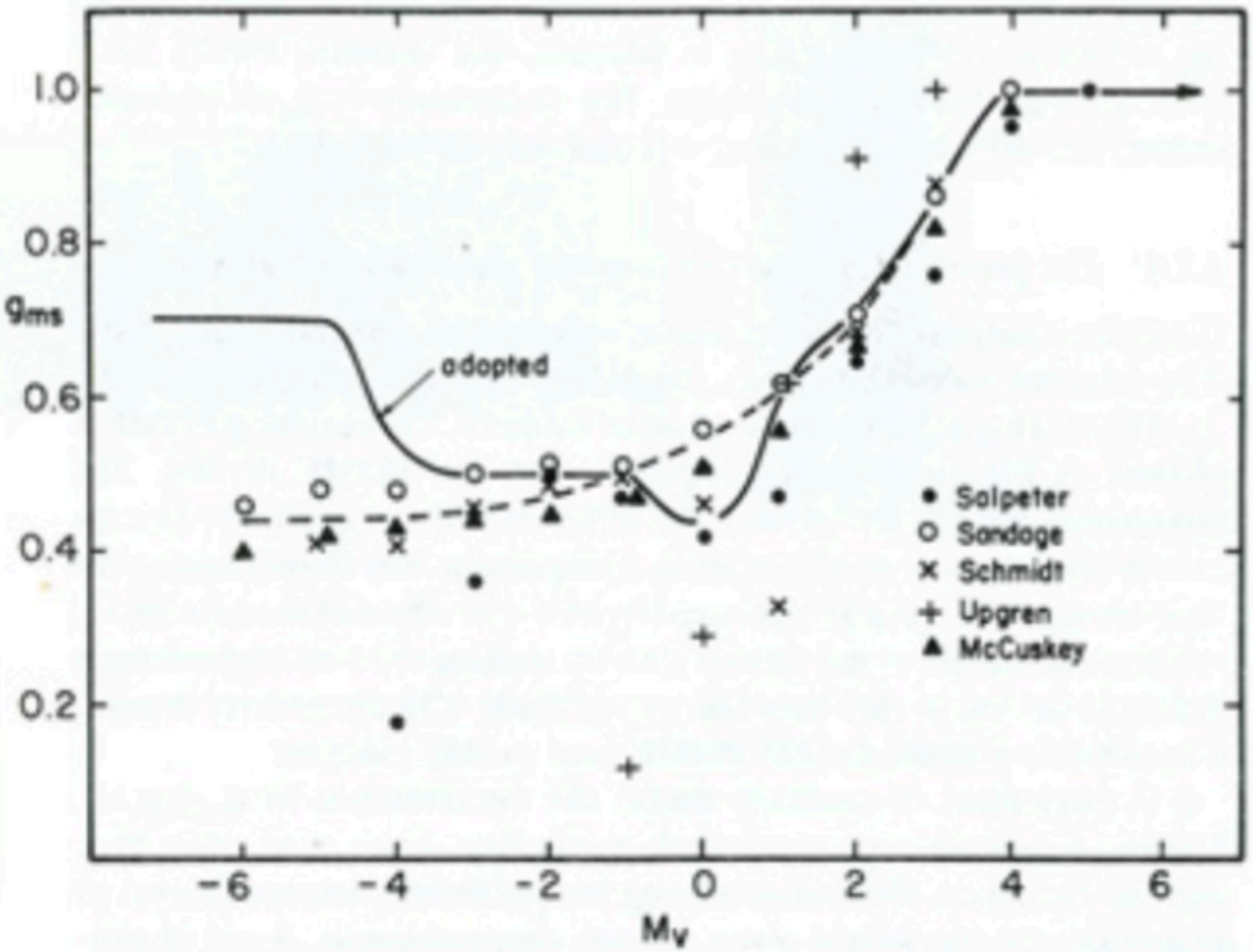


FIGURE 11 Estimates of the fraction of stars which are in the core hydrogen-burning phase as a function of absolute visual magnitude. Dashed line is from Mamon and Soneira (1983). Solid line is relation adopted in present work.

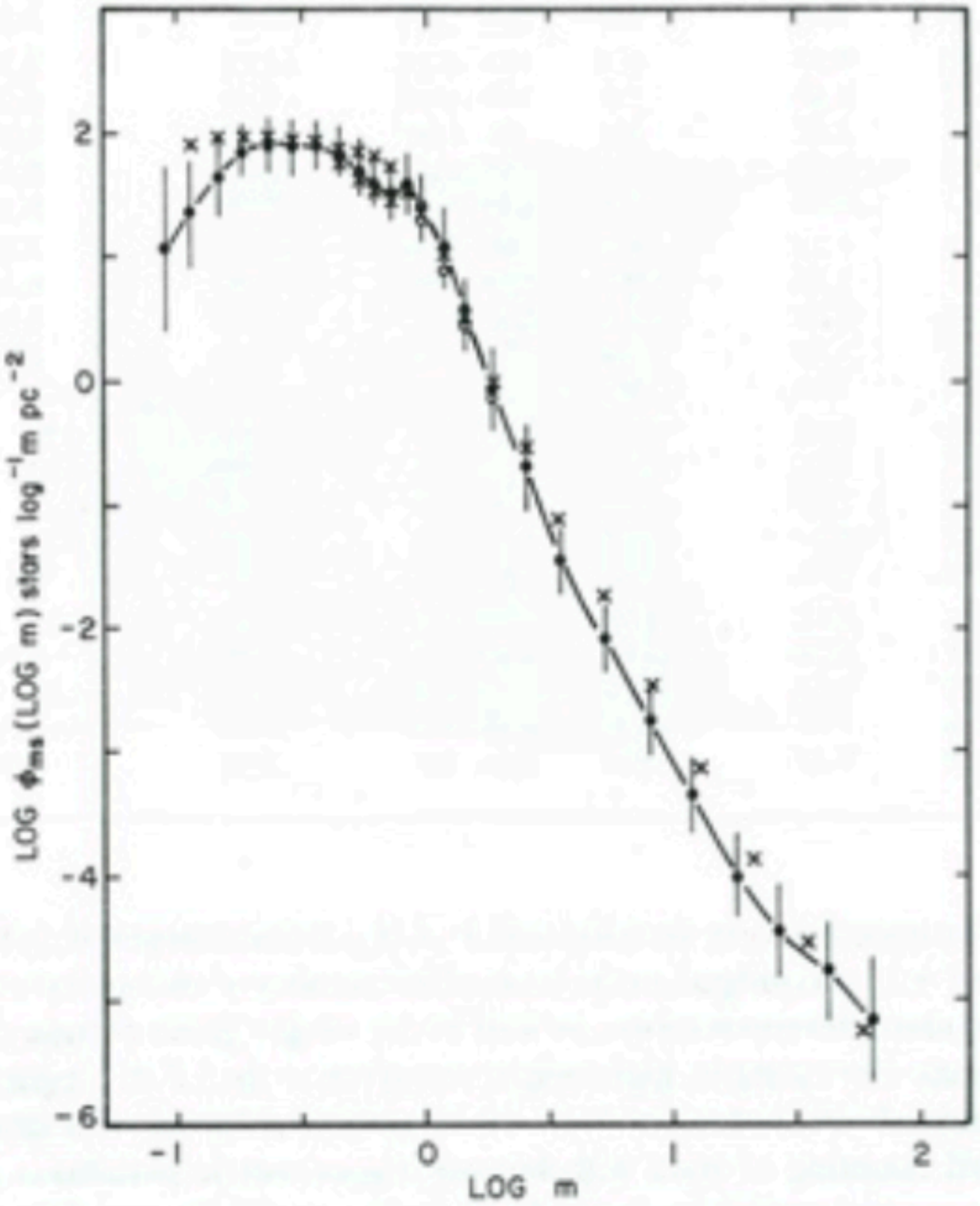


FIGURE 12 Present day mass function (PDMF) with uncertainty estimates. Crosses represent the PDMF derived in Miller and Scalo (1979).

Conversion from PDMF to IMF – I (2.4)

- Need to know main sequence lifetime as function of mass tau_m
  - Can be easily estimated within a factor of 3 for most masses
  - “common lore” is that numerical calculation gives hydrogen burning lifetimes within ~10%. This is not correct - depends on lots of poorly-known physics.
  - Actual uncertainty is optimistically estimated at ~40% for m > 1.5 m_sun and ~20% for smaller masses

Conversion from PDMF to IMF – II (2.5)

- Need to know history of the relative stellar birthrate b(t)
  - For star masses >~ 2 m_sun, characteristic lifetime tau(m) << T_0 where T_0 is time at present day.
    - then shape of IMF is independent of the detailed history of b(t) – just depends on b(T_0) and <b(t)>
  - For m ~ 1-2 m_sun, problem is hard because birthrate history actually matters
    - Impossible to estimate accurately at present
  - How to estimate b(T_0)?
    1) Assume continuous IMF – this requires b(T_0)/<b(t)> within a factor of two of unity
    2) Count radio HII regions to estimate massive star birth rates
    3) Stellar age distributions, i.e. star formation histories
    4) Look at SFR in other galaxies
  - They go with assumption that birthrate is constant in absence of more info

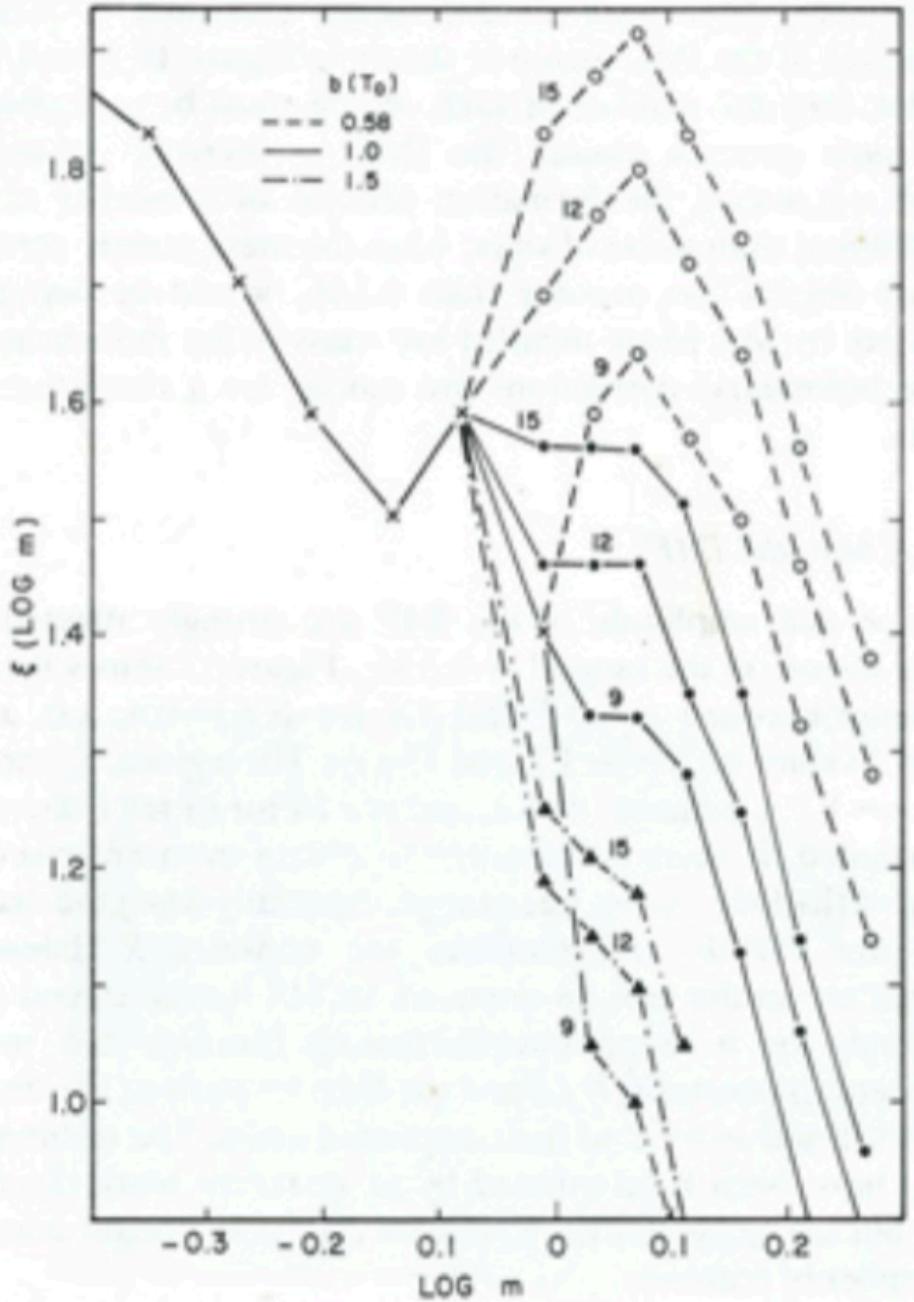


FIGURE 17 Form of the derived IMF around $1M_{\odot}$, for nine combinations of the relative birthrate $b(T_0)$ and disk age T_0.

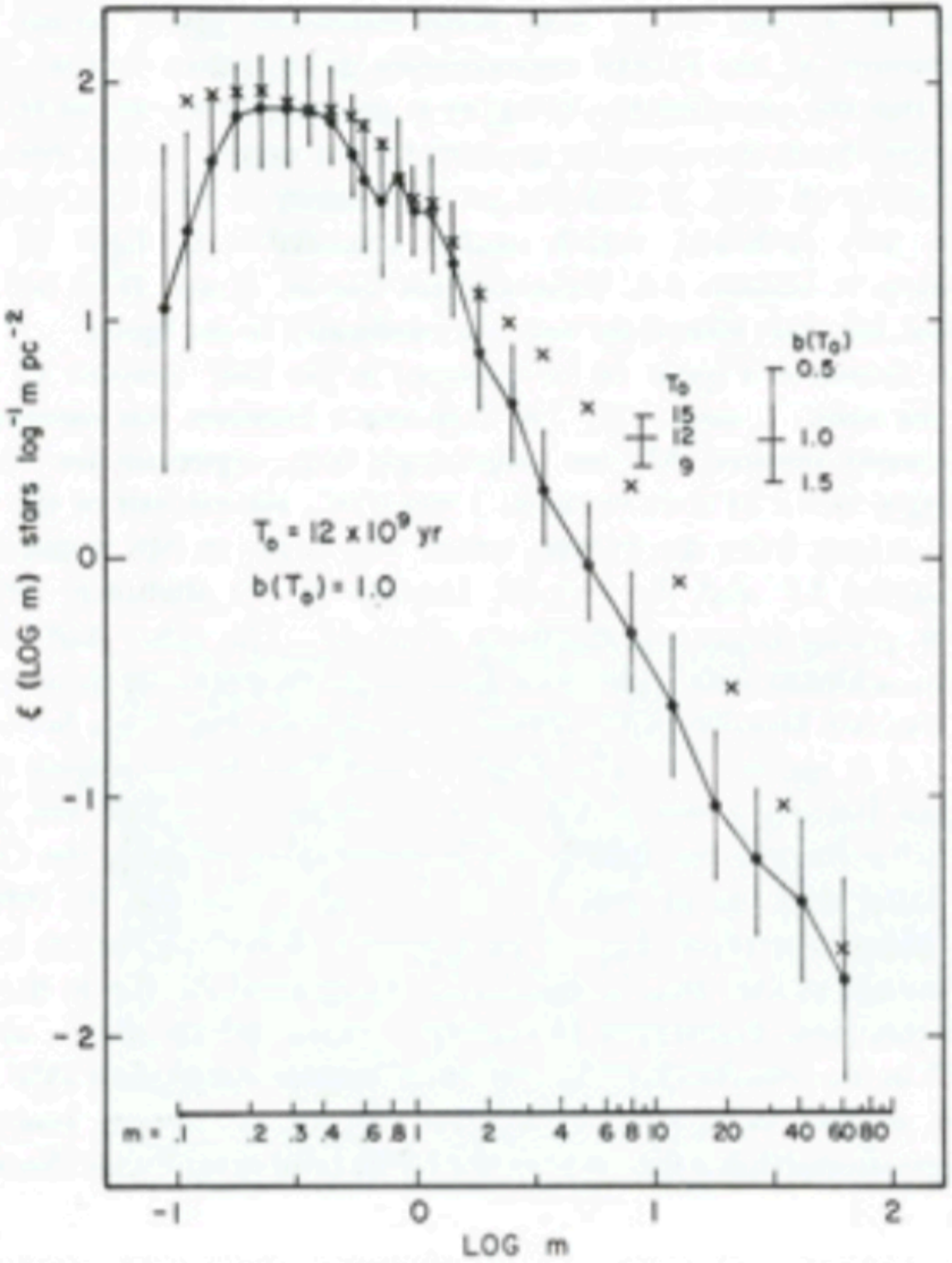


FIGURE 16 Derived field star IMF. Uncertainty estimates do not include relative birthrate $b(T_0)$ and disk age T_0, whose effects are indicated in the figure. Crosses represent the IMF derived in Miller and Scalo (1979).

Xi(log m) = Phi(log m) T_0 / int(b(t)) dt

Cluster IMFs

Star cluster IMF - I (3.1)

- In the disk: open clusters and OB associations
    - Most or all stars form in these groups, massive stars are almost always found there
- In the halo: globular clusters
    - High mass ~10^5 m_sun
    - Formed long ago in different conditions
    - May reveal dependence of IMF on metallicity
- Clusters are nice because
    - All the stars formed at about the same time – no need for time dependence in IMF, birthrate histories, etc.
    - All the stars formed in the same environment
    - All the stars are at the same distance

Star cluster IMF - II (3.1)

- Open star clusters and associations are not nice because
  - Only contain a few hundred observable stars -> large statistical uncertainties
  - Membership is hard to assign b/c they're in the galactic plane, so lots of foreground and background field stars
  - Stellar mass segregation – massive stars tend to be in the center, so the faint stars are in the periphery where it's most difficult to assign membership
    - Dynamical modeling of segregation remains difficult – lots of physics involved
  - Spread in formation times may be relatively large for young clusters
    - May need to know birthrate history just like for field stars
    - The IMF may be time-dependent just like field stars, favoring heavier stars later on

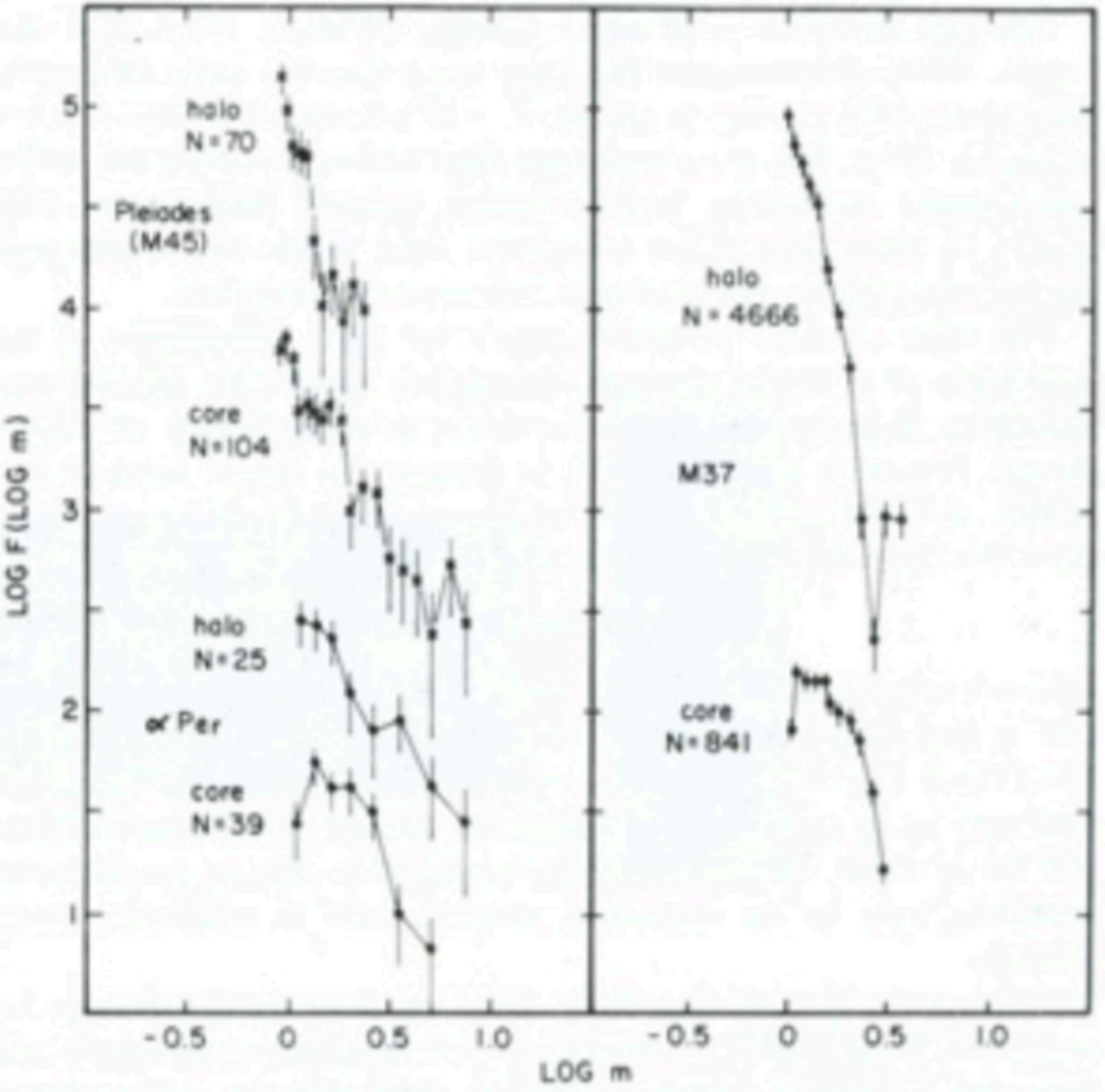


FIGURE 25 IMFs for several clusters derived from luminosity functions presented in Kholopov and Artyukhina (1972), Artyukhina (1972), and Archemashoili (1976), illustrating the existence of mass segregation.

Star cluster IMF - III (3.1, 3.8)

- Globular clusters are not nice because
  - Importance of mass segregation is unknown, as central regions can’t be sampled
  - Large distances to most globular clusters makes individual star counting difficult
  - Masses above ~0.9 m_sun cannot be studied
    - Unknown how many massive stars they had
  - IMF itself may vary between clusters

Composite cluster mass functions (3.3)

- Better statistics are possible if you combine data from many open clusters
- But…
    - Not a complete volume-limited sample of stars
    - Clusters differ in age, # stars
    - Different mass limits to which individual IMFs can be estimated for each cluster (diagram)
    - High mass limit may be governed by amt. of gas originally available
    - Cluster IMF studies differ in technique
    - IMFs themselves may differ

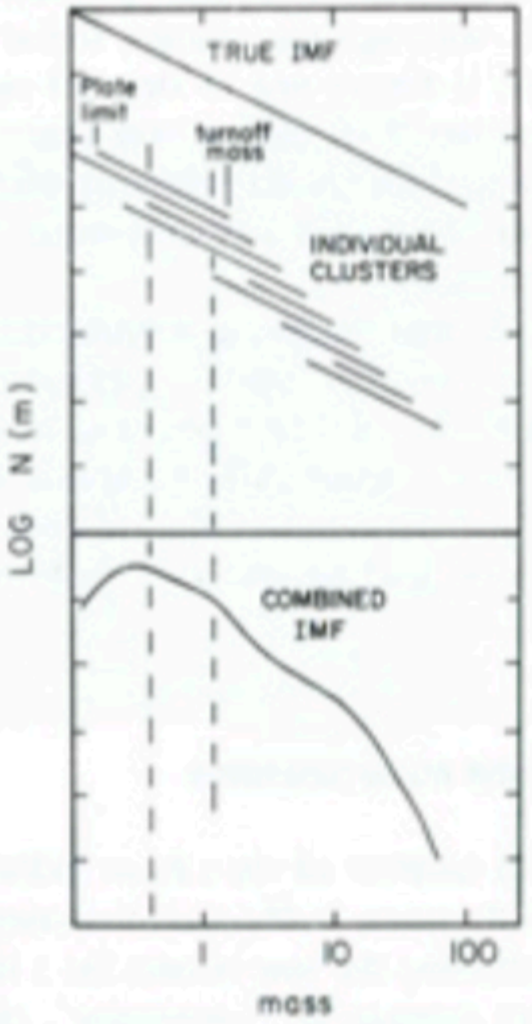


FIGURE 26 Distortions in derived composite IMF for clusters due to variations in limiting absolute magnitude (plate limit) and turnoff mass.

Star cluster IMF - IV (3.1)

- Open questions of interest
    1. Does average cluster IMF differ from field IMF?
    2. Are there cluster-to-cluster IMF variations?
    3. Are the ‘turnovers’ related to the IMF or dynamics/incomplete data

Pre-Main Sequence

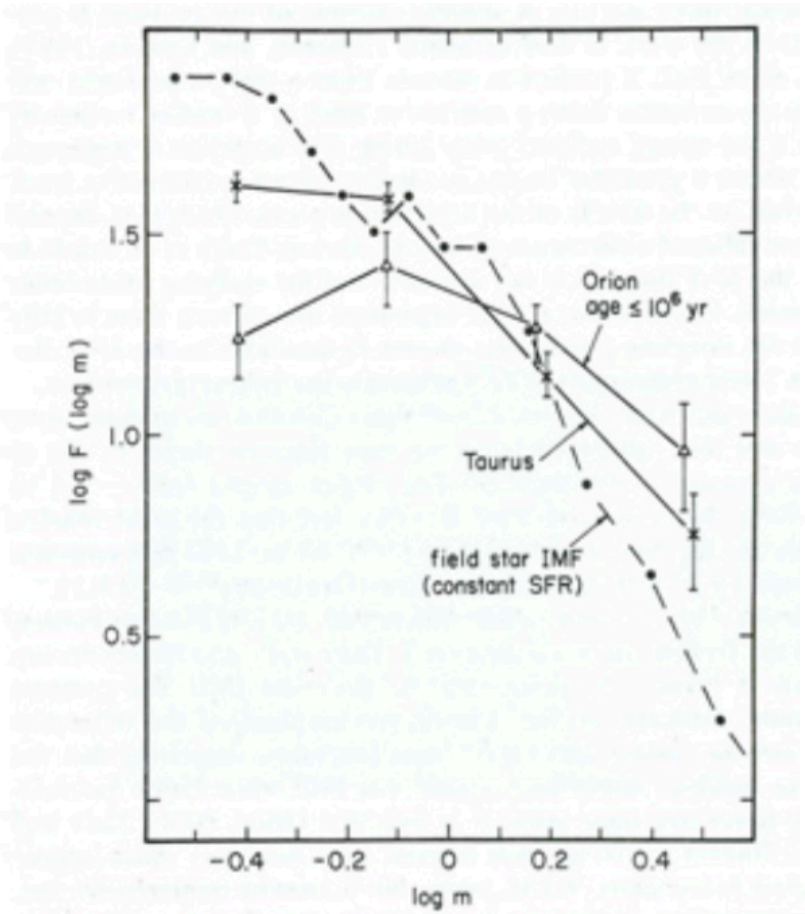


FIGURE 36 IMF estimates for pre-main sequence stars in Taurus and Orion by Larson (1983) based on masses given by Cohen and Kuhi (1979). Field star IMF is shown for comparison.

Young

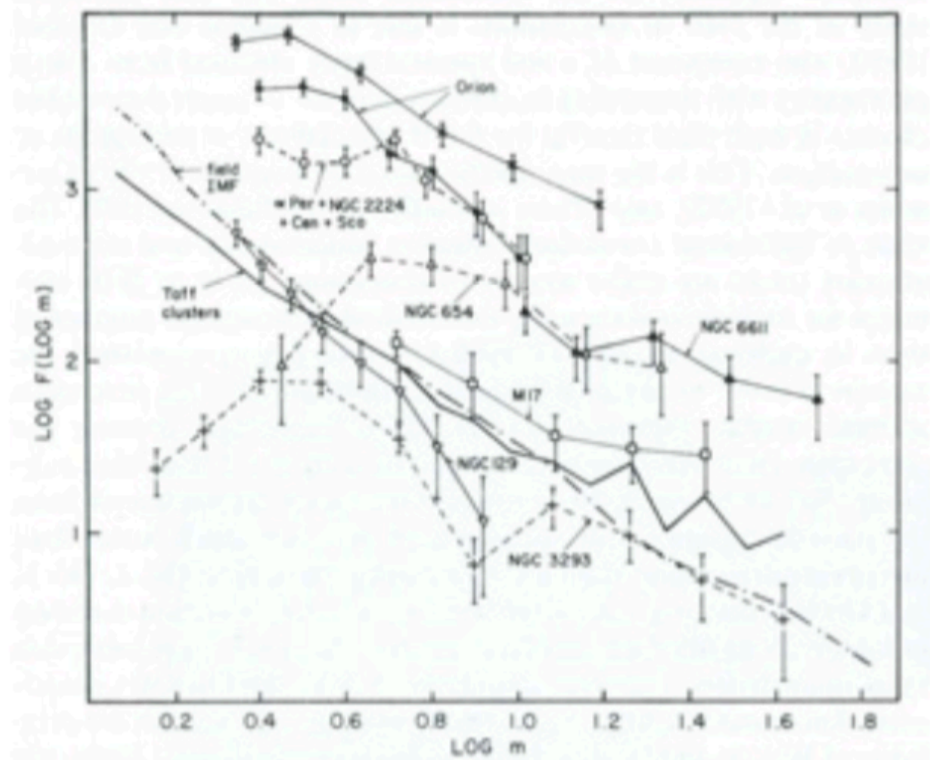


FIGURE 29 IMF estimates for young clusters and associations. See text for sources of data.

Intermediate

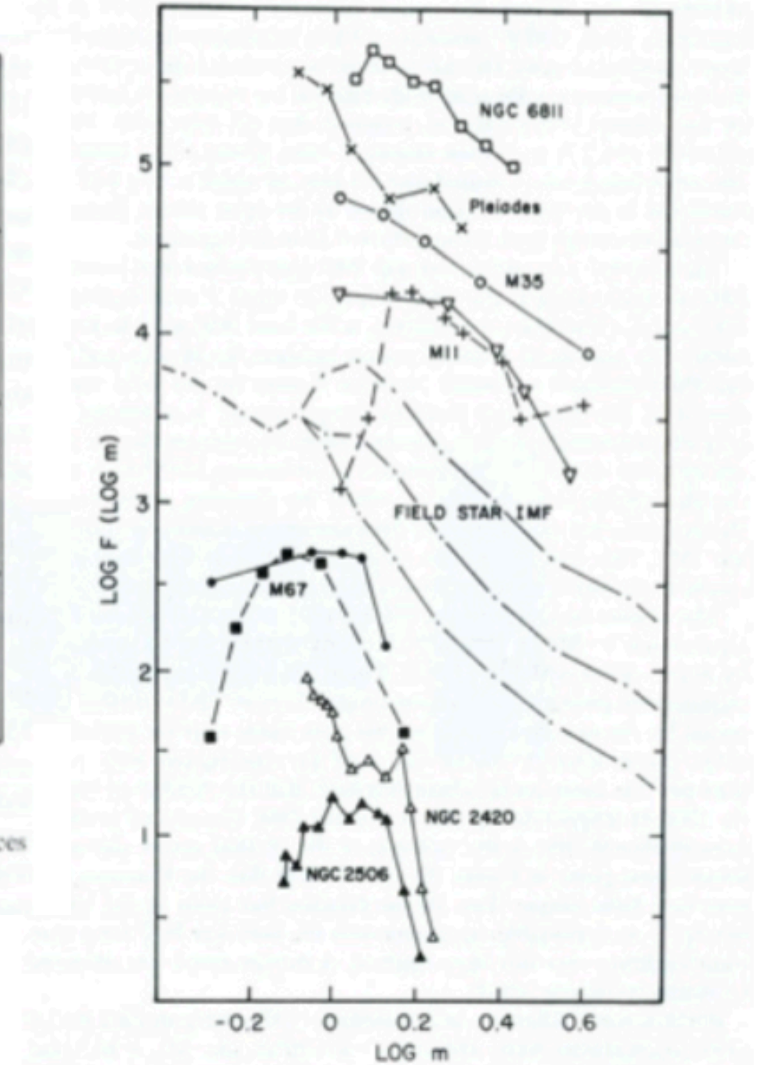


FIGURE 32 IMFs of several of the best-studied open clusters. See text for sources of data.

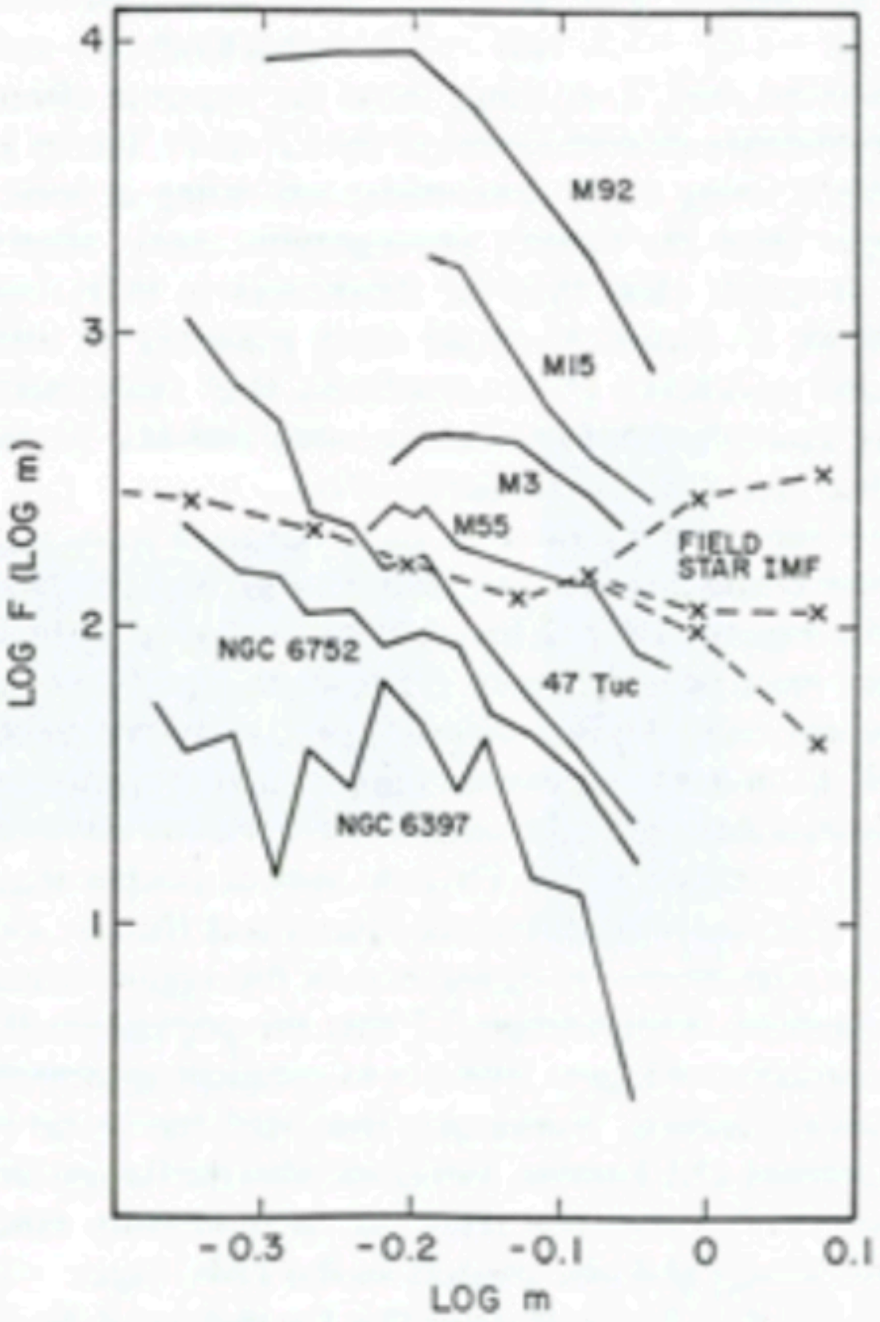


FIGURE 38 Estimated IMFs for globular clusters. See text for sources of data.

Star Cluster IMF Conclusions - (3.9)

1. Gamma ~ -1.5 to -1.8 for 1 <= m <= 10, just like field stars
   - But some evidence of flattening at high mass to Gamma ~ 1.2
   - Unclear whether this difference is real
2. IMF variations between clusters? Still unresolved.
   - ‘turnovers’ in some clusters are peculiar, but not related to any obvious physical parameter
   - Majority of clusters appear similar to one another
3. Most globular clusters have similar IMFs from 0.5 < m < 0.9
   - Somewhat steeper than field stars here
   - Hard to tell if this comparison is meaningful
   - Smaller masses are hard to get at because of incompleteness of data

Conclusions

Applications of f(m)B(t) - (1.4)

- SFR is related to f(m)B(t) where B(t) is total rate of stellar birth
- Total number of stars/volume is integral of f(m)B(t) wrt both t and m
- Supernova rate at a given time T is integral f(m)B(T-tau(m)) dm, where tau is the characteristic star lifetime
- Frequency distribution of masses of stars in a particular evolutionary stage N(m) is integral f(m)B(t) dt bounded by the time interval over which the star is in that phase
- f(m)B(t) also plugs into equations for
  - chemical evolution of clusters and galaxies (ejection of mass, enrichment, etc)
  - radiation from stars
  - Most other galactic evolution problems

Conclusions I (8)

- Local IMF
  - peaks at M ~ 0.3 m_sun and declines at smaller masses
  - likely bimodal, second peak at 1.2 m_sun
  - Power law from 2 <= m <= 10 might have Gamma ~-1.7
  - Extremely uncertain above 10 m_sun
  - Disk and halo field stars have very similar IMF, at least from 0.3-0.8 m_sun -> no evidence for Z dependence

Conclusions II (8)

- Clusters
  - Conclusions severely limited by observational difficulties
    - Membership, mass segregation, small numbers, mass assignment
  - *Composite* cluster studies say Gamma ~ -1.7 for 1.5 <= m <= 10
  - Evidence for significant flattening of slope above 10 m_sun esp. from studies of individual young clusters
  - Most individual cluster studies point to agreement, and peculiarities are difficult to confirm
    - Some authors still believe large IMF variations in clusters are possible, though
  - Globular cluster IMFs appear similar
    - Possible steeper IMF slope at m~0.6-0.8 than in open clusters and field stars
      - But segregation may cause systematic error

Conclusions III (8)

- Extragalactic
  - Surprisingly similar in galaxies of different metallicities, morphologies, luminosities
  - Even with different methodologies, Gamma differs by <= +/- 0.5 between studies.
  - No systematic trends with morphology or metallicity across studies
    - Universal IMF shape suggested from 10 <= m <= 20
    - Less data below 10 m_sun, but several regions in the LMC agree with field star results down to ~2 m_sun

Conclusions IV (8)

- Indirect
  - Problematic – yield indeterminate or ambiguous results
  - Indications show high-mass Gamma in range -1.5 to -2
  - Choice of upper mass limit affects results and should be treated as an additional parameters
  - Burst of star formation <-> larger mass lower limit or larger mode (maybe)
    - That is, IMF turns over at fairly large masses in regions disturbed by hydrodynamics
    - Spiral arms, starburst galaxies
  - Chemical evolution arguments that suggest IMF variations are ambiguous, explicable through other means

Conclusions V - Variable M_0 Models (8)

- Idea: in a large-scale star forming region the IMF has a form independent of local or global conditions for masses well in excess of a characteristic mass m_0. The IMF is assumed to terminate/turn over at m_0. Then assume $m_0(t)$ is an increasing function of the star formation rate $B(t)$
  - Bimodality could arise in an isolated spiral galaxy: arms vs interarm regions
  - Dwarf galaxies have similar high mass IMFs but multimodal features at smaller mass representing superposition of bursty SF episodes
  - Galaxy collisions would also cause increase in m_0
- This or similar model could explain many observed features
- However the shapes are observed to be consistent with universality

“Unfortunately the uncertainties in empirical estimates are large, and theorists appear capable of deriving agreeable IMF slopes using a wide range of physical ideas”