The (Non?) Universality of the IMF

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Overview

• A crash course in IMF models
  – The isothermal conundrum and two solutions
• The IMF from Non-Isothermal Fragmentation
• Implications
Isothermal Fragmentation

- Gas clouds fragment due to Jeans instability

\[ M_J \approx \sqrt{\frac{c_s^3}{G^3 \rho}} \]

\[ \approx 0.34 \frac{W_\infty}{100 \text{K}} \left( \frac{T}{100 \text{K}} \right)^{3/2} \left( \frac{m}{10^5 \text{amu}} \right)^{-1/2} \]

- Problem: GMCs have \( T \sim \) constant, but \( n \) varies a lot
Isothermal Gas is Scale Free

\[ \mathcal{M} = \frac{\sigma}{c_s} \propto \sigma \]
\[ \beta = \frac{8\pi \rho c_s^2}{B^2} \propto \rho B^{-2} \]
\[ n_J = \frac{\rho L^3}{c_s^3 / \sqrt{G^3 \rho}} \propto \rho^{3/2} L^3 \]
\[ \mathcal{M}_A = \mathcal{M} \sqrt{\frac{\beta}{2}} \]
\[ \mu_\Phi = \frac{M}{M_\Phi} = \sqrt{\frac{\pi \beta}{2}} n_J^{1/3} \]
\[ n_{J,\text{turb}} = \frac{n_J}{\mathcal{M}^3} \]
\[ \alpha_{\text{vir}} = \frac{5\sigma^2 L}{2GM} = \frac{5}{6\pi} \left( \frac{\mathcal{M}}{n_J} \right)^2 \]

All dimensionless numbers invariant under \( \rho \rightarrow x \rho, \)
\( L \rightarrow x^{-1/2} L, \) \( B \rightarrow x^{1/2} B, \) but \( M \rightarrow x^{-1/2} M \)

Non-isothermality **required** to explain IMF peak!
Option 1: Galactic Properties

• GMCs embedded in a galaxy-scale non-isothermal medium

• Set IMF peak from Jeans mass at mean density (e.g. Padoan & Nordlund 2002, Hopkins 2012, Narayanan & Dave 2012)

• ... or from linewidth-size relation (e.g. Hennebelle & Chabrier 2008, 2009; Hopkins 2012)
Problem 1: MW Cluster IMFs

Figure 3
The derived present-day mass function of a sample of young star-forming regions (Section 2.3), open clusters spanning a large age range (Section 2.2), and old globular clusters (Section 4.2.1) from the compilation of G. de Marchi, F. Paresce, and S. Portegies Zwart (submitted). Additionally, we show the inferred field star initial mass function (IMF) (Section 2.1). The gray dashed lines represent “tapered power-law” fits to the data (Equation 6). The black arrows show the characteristic mass of each fit ($m_p$), the dotted line indicates the mean characteristic mass of the clusters in each panel, and the shaded region shows the standard deviation of the characteristic masses in that panel (the field star IMF is not included in the calculation of the mean/standard deviation). The observations are consistent with a single underlying IMF, although the scatter at and below the stellar/substellar boundary clearly calls for further study. The shift of the globular clusters characteristic mass to higher masses is expected from considerations of dynamical evolution.

2.3. Young Clusters and Associations
2.3.1. Primordial and dynamical mass segregation.

An additional complication in IMF studies comes from the spatial distribution of stars within a cluster or association. The most massive stars in large, young clusters are often located in a cluster’s innermost regions. This phenomenon is
Problem 2: Choice of Scale

Map of the Perseus molecular cloud (Heiderman+ 2010)

Linewidth-size relation low and high mass star-forming regions (Shirley+ 2003)
Problem 3: Simulations

Left: fragmentation in an isothermal simulation (Martel+ 2006)
Right: IMF at 3 different resolutions for isothermal simulations
Option 2: Small Scale Non-Isothermality

- Fragmentation by small-scale non-isothermality (e.g. Larson 2005, Jappsen+2005, Elmegreen+ 2008)
- Most important source: stellar accretion luminosity

Temperature vs. radius before (red) and after (blue) star formation begins in a 50 $M_\odot$, 1 g cm$^{-2}$ core (Krumholz 2006)
Setting the IMF Peak

(Krumholz 2011)

\[ P \approx \frac{GM^2}{R^4} \]

\[ T = \left( \frac{3^{2/3} L}{\pi^{1/3} (\rho M)^{2/3} \sigma_{SB}} \right)^{1/4} \]

\[ L = \epsilon_L \epsilon_M \sqrt{2G\rho M} \sqrt{\frac{GM_*}{R_*}} \]

\[ M_{BE} = 1.18 \sqrt{\left( \frac{k_B T}{\mu m_H G} \right)^3 \frac{1}{\rho}} \]
Mass-Radius Relation and the IMF

- Accreting stars burn D: D + 2 H → He
- Burning keeps $T_{\text{core}} \sim 10^6$ K; calculable from fundamental constants
- Fixed $T_{\text{core}}$ → fixed $M_*/R_*$
- No metallicity dependence

$$M_* = 0.4m_H \Theta_c^{-4/3} \left( \alpha G \Theta_c \approx 12.4 \right) \left( \alpha_25 \right)^{8/3} \left( \frac{P}{k_B} \right)^{-1/18} \left( \frac{10^6}{10^6 \text{ K cm}^{-3}} \right) \left( \frac{P_{\text{Pl}}}{c^7/\hbar G^2} \right)^{8/3} M_\odot$$
Checking this Story
Simulations with varying metallicity show very little change in fragmentation, as long as the gas remains optically thick (Myers+ 2011).
Simple Collapsing Cluster Simulation
(Krumholz+ 2011)

Column density

Temperature

1000 M☉ cloud (roughly the size of the ONC), isolated, no protostellar outflows
Doesn’t Work!

\[ \frac{t}{t_{ff}} = 0.60 \]
\[ M_* = 6.0 \, M_\odot \]
\[ K\hat{S} = 0.000 \]
Why it Fails

Krumholz, Dekel, & McKee 2012
A More Realistic Simulation
(Krumholz+ 2012)

Cloud embedded in a larger, turbulent medium; simulation includes protostellar outflows
A Good IMF at Last

SmNW

TuW

\[ t/t_{ff} = 0.60 \]
\[ M_* = 6.0 \, M_\odot \]
\[ KS = 0.000 \]

\[ t/t_{ff} = 0.60 \]
\[ M_* = 21.4 \, M_\odot \]
\[ KS = 0.002 \]
Why it Works
Implications

What does the IMF depend on?

Krumholz 2011
Possible Explanation for Ellipticals?

Giant elliptical galaxies have high pressure, high metallicity; NB: $\sigma$ is a (rough) proxy for pressure

van Dokkum & Conroy (2010)
Summary

• IMF set by the thermodynamics of fragmenting gas on small scales, not galaxy scales
• The invariance of the peak comes from stellar feedback + fundamental physics
• Weak variation from radiation-matter coupling: peak moves to slightly lower mass at high P, Z. Simulations to test this are underway.