130. The initial mass function

THE INITIAL MASS FUNCTION is an empirical description of the *initial* mass distribution of a population of stars resulting from the processes of star formation.

It enters the consideration of many topics in astronomy, notably the theories of star formation, including the formation of the first stars in the Universe, and galaxy formation and evolution more generally.

Characterisation of the stellar initial mass function, or IMF, was first addressed by Salpeter (1955). He found that the mass distribution of high mass ($\gtrsim 1\,M_\odot$) stars in the solar neighbourhood is well described by a power-law function $N(M) \propto M^\alpha$, with slope $\alpha = -2.35$.

Evidence that the mass function for lower-mass stars in the Galactic disk increases less strongly with decreasing mass has led to the wider use of alternative forms, notably the broken power law given by Kroupa (2001), and the log–normal form given by Chabrier (2003).

PREDICTIONS of the form of the initial mass function are founded on theories of star formation. Foremost amongst them is that star formation results from fragmentation and competitive accretion in protostellar clouds (Larson, 1978; Bonnell et al., 2001; Hennebelle & Chabrier, 2008). Detailed models then suggest an IMF dependent on chemical composition, and processes such as collisional excitation and dust cooling.

In an alternative formulation, stars self-regulate their masses, balancing accretion and radiation feedback (e.g. Adams & Laughlin, 1996). In this case, the IMF is influenced by additional processes dependent on (for example) density, angular momentum, and metallicity.

Given these and other complications, it is not surprising that observations have resulted in a confusing picture, with debate over the exact form of the IMF, and how it might apply to the first stars which formed in the Universe (e.g. Abel et al., 2002; Bromm et al., 2002).

Neither is there agreement as to whether the IMF is 'universal' (e.g. Zakharova, 1989; Kroupa, 2002; Portinari et al., 2004; Hennebelle, 2012), or whether it varies across star-forming regions (e.g. Dib, 2014), or galactic environment (Ballero et al., 2007; Hoversten & Glazebrook, 2008; Geha et al., 2013; El-Badry et al., 2017).

In some cases, the IMF has been found to be 'bottom-heavy' in low-mass stars (e.g. van Dokkum & Conroy, 2010; Cappellari et al., 2012), but 'top-heavy' in others (Pouteau et al., 2022; Baumgardt et al., 2023).

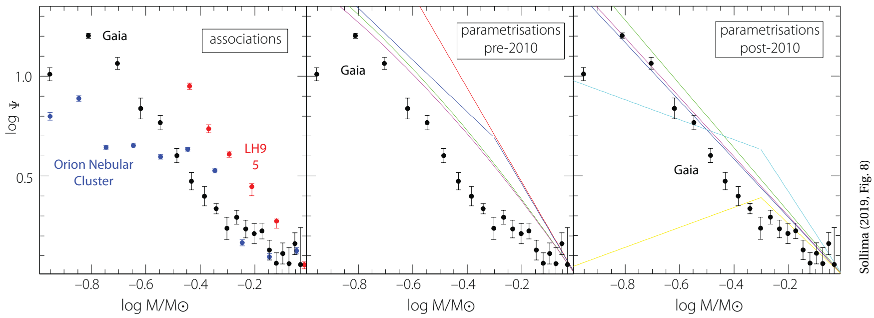
The balance of evidence suggests that the IMF is relatively invariant from one group of stars to another, albeit (perhaps) very different in early galaxies. Indeed, in their review, Bastian et al. (2010) concluded that *'There is no clear evidence that the IMF varies strongly and systematically as a function of initial conditions after the first few generations of stars'.*

OBSERVATIONAL CHARACTERISATION of the initial mass function of a stellar population starts with a determination of the distribution of *observed* stellar masses, viz. the 'present-day mass function'.

But any initial mass distribution is subsequently modified by two main processes, which must be accounted for by detailed models. Stellar evolution results in a present-day mass function depleted in high-mass stars with respect to the IMF, depending on age and star-formation history. In contrast, dynamical evolution resulting from star–star interactions results in a population progressively depleted at its low-mass end.

Neither is the determination of the present-day mass function a simple task: since stellar masses can only be determined rigorously by the application of Kepler's third law to a very small number (some 100) of suitable binary systems, masses are generally estimated by converting absolute magnitudes to masses based on theoretical isochrones (e.g. Chabrier, 2003). The determination of absolute magnitudes relies on knowledge of stellar distances... which is where Gaia can contribute.

SUITABLE POPULATIONS for accurately determining the initial mass function based on accurate Gaia distances include open clusters, which provide large numbers of stars of similar distance, age and initial chemical composition, and the local solar neighbourhood, which is of course particularly amenable to the most rigorous characterisation of the Galaxy's disk population. I will focus on the latter in the following.



The Gaia distances for stars in the solar neighbourhood, along with their magnitudes and colours, allows for a major improvement in characterising the present-day mass function and, with appropriate models, the *initial mass function* of the local disk population.

Doing so is, however, not without complications, amongst which are accounting for variations in metallicity and star-formation rate with Galactic latitude, the increasing contamination of the thick disk with time, unresolved multiple systems resulting in erroneously bright magnitudes, and variable extinction.

Mor et al. (2019) used Gaia DR2 magnitudes and parallaxes to derive the star-formation history of the solar neighbourhood and, as a byproduct, constrained the initial mass function using a three-segment power-law with breaks at fixed masses at 0.5 $M_\odot$ and 1.53 $M_\odot$.

With a focus exclusively on characterising the initial mass function of the solar neighbourhood, Sollima (2019) constructed a sample of 120 000 stars in the solar neighbourhood with parallaxes, magnitudes and colours also from Gaia DR2, accounting for the population of unresolved binaries, the metallicity distribution, the star formation history, and their variation across the Galactic disk.

His results, shown here only for masses below $1M_\odot$, as small black circles with error bars, are repeated in three distinct panels: the first compares the Gaia results with those found (independently) in two associations, the others superimposed on various parametrisations of the IMF, separately for pre- and post-2010 studies.

The IMF is well represented by a segmented power-law with two breaks at characteristic masses. It has a maximum at $M \sim 0.15\ M_\odot$ with significant flattening at lower masses, and a slope of $\alpha = -1.34 \pm 0.07$ in the range $0.25 - 1M_\odot$. Above $1M_\odot$ it shows an abrupt decline, with a slope in the range $\alpha = -2.68 \pm 0.09$ to $\alpha = -2.41 \pm 0.11$ (depending on the inferred star formation history).

His conclusions include the following: (a) because of the uncertainties on the mass–luminosity relation at very-low masses, it is not clear whether the deficiency of stars at $M \lesssim 0.15M_\odot$ is significant; (b) the existence of a peak in the IMF is predicted by star-formation theories, although it is not clear whether its position should lie in the stellar or sub-stellar regime; (c) in the mass range $0.15 - 1M_\odot$ the IMF is represented by a power-law with $\alpha = -1.34 \pm 0.07$, in agreement with previous work; (d) above $1M_\odot$, $\alpha = -2.68 \pm 0.09$ is significantly steeper than found in most previous studies; (e) differences with the IMF inferred in other non-collisional environments (galaxies and associations) suggests that the IMF is *not* universal, albeit with no clear trend of slope with either metallicity or environment.

In a study with broadly similar aims and methodologies, Hallakoun & Maoz (2021) used DR2 to determine the IMF in the range $0.2 - 1M_\odot$, and within 250 pc, separately according to kinematics and metallicity.

The dominant thin-disk population (transverse velocities $v_T < 40\,\mathrm{km\,s^{-1}}$) has an IMF similar to other estimates, described by a broken power law with $\alpha = -2.03$ above $0.5M_\odot$, decreasing to $\alpha = -1.34$ for $M \lesssim 0.5_\odot$.

The thick-disk stars ($v_T = 60 - 150\,\mathrm{km\,s^{-1}}$) and those of the high-metallicity 'red-sequence' halo, have a similar low-mass slope $\alpha = -1.14$, but steeper at high-mass, $\alpha = -2.35$. The low-metallicity 'blue sequence' halo stars have a distinct, bottom-heavy IMF, described by a single power law with $\alpha = -1.82$ over most of the mass range.

The IMF of the low-metallicity halo is similar to the Salpeter-like IMF of early-type galaxies, a stellar population that, like the halo stars, has a high α/Fe ratio. Blue-sequence stars are likely the debris from accretion, ~10 Gyr ago, of the Gaia-Enceladus dwarf galaxy. The results hint at a *distinct mode of star formation* common to two ancient stellar populations—elliptical galaxies, and galaxies accreted early-on by our own.

Finally, Li et al. (2023) studied 93 000 spectroscopically observed M-dwarfs, out to 300 pc, to reveal a variable IMF that *does* depend on both metallicity and stellar age. Specifically, the oldest stellar population contains fewer low-mass stars, independent of metallicity. In younger stars, the proportion of low-mass stars increases with stellar metallicity.

Gaia is certainly elucidating details of the local IMF. Further clarity will come with future data releases, with improvements in accuracy, bright star content, and metallicities, reddening, and binary classification.