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Is the Stellar Initial Mass Function Universal?

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The rich stellar field of the nearby dwarf starburst NGC5253, located at 4 Mpc distance. Even with HST (WFPC2 data form this three-color composite), the IMF cannot be directly measured.

Abstract

Is the stellar Initial Mass Function (IMF) universal or does it depend on environment? Most studies of galaxy formation and evolution assume or require that the stellar IMF is a `universal' function. This assumption is supported by most **direct** measurements, i.e., through counting individual stars (see the review by Kroupa, 2002), although such studies are currently limited to the Milky Way and its satellites, and cover a limited range in properties such as total and specific star formation rate, density/pressure, and galaxy environment. Several recent measurements of large samples of galaxies point to a possible systematic variation of the stellar IMF with galaxy properties, even after accounting for variations in star formation history, extinction, and metallicity. These studies, however, are **indirect**, and rely on the measurement of integrated light. Furthermore, despite its fundamental role, we still lack a theoretical understanding of the stellar IMF. We believe that significant progress in this field requires **direct** measurements of the stellar IMF in a number of diverse environments. This can be best accomplished by a 8-m to 16-m telescope in space with UV/optical capabilities, working in concert with a large (~30-m) ground-based telescope capable of diffraction limited imaging at near infrared wavelengths.

Introduction

The distribution of stellar masses at birth, also called Stellar Initial Mass Function (IMF) is the fundamental parameter, together with the efficiency of star formation, that quantifies the conversion of gas into stars. The IMF designates the fraction of gas and metals returned to the interstellar medium, together with the fraction of the mass forever `locked' into stellar and sub-stellar objects. The IMF enters into any description of the formation and evolution of the luminous baryonic component of galaxies across cosmic time, including the stellar mass assembly and the star formation rate (SFR, Wilkins et al. 2008).

Despite its fundamental role, we still lack a theory for the stellar IMF. Extant models lack predictive power, not only on the specific shape of the IMF, but also on whether it is `universal' or environment-dependent (Elmegreen et al. 2008, Hoverstern & Glazebrook, 2008). Recent results suggest that that dense cloud cores in Milky Way clouds have a mass distribution similar to the stellar IMF (Lada et al. 2008), implying that the shape is driven by gas-phase processes (Elmegreen 2009). However, this result, which is fundamental for guiding theories, still tells us very little about the universality of the IMF.

This problem is compounded by the difficulty of obtaining reliable measurements of the mass distribution of stars at birth (or before significant evolution of the massive stars has taken place) for a large range of parameters (density, pressure, SFR, etc.) and over a significant range of stellar masses. Observational constraints on the IMF are currently limited to the Milky Way (Reid & Hawley 2004, and refs within) and the Magellanic Clouds (Sabbi et al. 2008; Schmalzl et al. 2008; Da Rio et al. 2009), where stellar clusters can be resolved into their individual stars, and mass distributions over the full or a large mass range can be derived. This limitation is imposed by the angular resolution and sensitivities of existing telescopes.

Current Status of the Field

The concept of the stellar IMF was devised by Salpeter (1955) to quantify the rate of stellar creation as a function of mass. Salpeter's data were largely restricted to high-mass stars ($M > IM_{Sun}$), and the results were consistent with a power-law, $dN/dM \sim M^{\alpha}$, with $\alpha=2.35$, the Salpeter index. Improved understanding came with improved technical capabilities. In the late 70s, it became clear that the IMF in the Galactic disk changed slope at $\sim 1M_{Sun}$, flattening to match either a log-normal distribution (Miller & Scalo 1978) or an $\alpha \sim 1$ power-law (Kroupa 1995; Reid & Gizis 1997). These results were refined and extended through deeper surveys, probing the sub—stellar mass régime in the field (Reid et al. 2002; Kroupa 2002; Cruz et al. 2007; Metchev et al. 2008) and young Galactic clusters (Muench et al. 2003; Luhman et al. 2003), showing that the IMF flattens further near the H-burning limit, although the exact form remains ill defined.

HST data have been used to probe the IMF in the Galactic Bulge down to ~0.15 M_{Sun} (Zoccali et al. 2000) and in the halo, both the field (Gizis & Reid. 1998) and the globular clusters (Paust et al. 2009). In each case, the results are broadly similar to the disk IMF. In particular, the globular cluster analysis suggests that the diversity in present-day mass functions is consistent with dynamical evolution, rather than intrinsic variation. Thus, the consensus is that the average IMF in the Milky Way is near-Salpeter at high masses, flattens to α ~1 between ~0.9 and 0.1 solar masses, and turns over, with indeterminate slope, at sub-stellar masses (Figure 1, left). A study of a nearby, metal—poor, dwarf spheroidal galaxy supports the result that the low—mass IMF, down to M~0.3 M_{Sun}, does not appear to depend on metallicity or the local stellar density in a dark—matter—dominated system (Wyse et al. 2002).

Almost all of these analyses, however, are dominated by stars that formed in dense, average— Milky—Way, environments. A handful of observations suggest that different environments may produce different results. Specifically, the low density star-forming regions in Taurus (Bejar et al. 2001) and NGC 6611 (Oliveira 2008) have IMFs that peak near ~0.7 M_{Sun} , with a corresponding deficit of low-mass stars. Conversely, the scant observations currently available for the Galactic Center indicate that the IMF may be flatter than Salpeter in those very high density regions (see Elmegreen 2009 for a review).

Key unsolved problems therefore center on two main issues:

- 1. what is the form of the IMF at sub-stellar masses, and is there a lower mass cutoff?
- 2. is the IMF universal and, if not, what are the key factors that drive variation?

The first issue is discussed in other science white papers submitted to the decadal panel, notably those led by A. Burgasser and K. Cruz. Here, we focus on the second issue, which is crucial to interpreting observations of unresolved stellar populations in galaxies beyond the Local Group.

Science Case

While direct measurements of the IMF in the Milky Way and a few of its satellite galaxies indicate that the IMF does not vary strongly with metallicity or environment, there have been a number of recent studies suggesting that the IMF does in fact, vary from galaxy to galaxy. These are primarily based on indirect techniques of the integrated light from galaxies, but cover a broader range in star formation rate, galaxy luminosity and environment, and metallicity.



inferred IMF for Low Surface Brightness galaxies (M09, Meurer et al. 2009); the high-end IMF required to reconcile the cosmic SFR with the galaxy mass assembly at high redshift (W08, Wilkins et al. 2008). The vertical dashed lines mark the lower-mass limits reached by 8-m & 16-m UV/optical space telescopes and the upper-mass limit of a 30-m ground-based telescope (with MCAO in NIR) for galaxies at 2 Mpc distance. The UV capabilities of a large space telescope will also enable the determination of the high-end of the IMF, down to ~5 M_{Sun}, out to ~20 Mpc. (**Right**) The ratio of the SFRs determined from the UV and H α emission as a function of the H α luminosity for model galaxies with constant IMF, constant SFR, and *environment—dependent cluster mass function* (Pflamm-Altenburg et al. 2009). For low SFRs, the number of ionizing photon light is suppressed relative to the UV light emitted by stars. Therefore, H α measurements underestimate the SFR in this regime, and mimic bottom—heavy stellar IMFs (reproduced with data kindly provided by J. Pflamm-Altenburg 2009, private comm.).

Several recent works have suggested that the stellar IMF becomes steeper (i.e. increasingly bottom-heavy) in low luminosity and low surface brightness galaxies. Hoverstern & Glazebrook (2008), from an analysis of $\sim 10^5$ SDSS galaxies, found that while luminous galaxies have integrated properties consistent with a standard IMF, fainter galaxies are consistent with a steeper IMF (i.e., appear to be deficient in massive stars). Similarly, Meurer et al. (2009) compared UV and Ha fluxes for ~ 100 HI—selected galaxies (Figure 2), and found that lower surface brightness galaxies have a steeper IMF, and that this trend is not due to variations in star formation history, metallicity, or dust extinction (Figure 1, left). The extended UV disks observed in many local, large star-forming galaxies also show a deficiency in the expected number of ionizing photons (Thilker et al. 2005, 2007), analogous to the results of Meurer et al. (2009), although it is possible that ionizing photons escape the low-density environment in these

outer disks. Current observations suggest that the IMF may evolve with cosmic time, and becomes more 'top heavy' (i.e. flatter) in galaxies at high redshift (Figure 1, left; Wilkins et al. 2008). If high redshift galaxies are the low—mass fragments of today's massive galaxies, this trend is in the opposite sense of that suggested for low luminosity galaxies in the Local Universe.

The observational effects described above can also be produced by a combination of a `universal' stellar IMF plus an environment—dependent mass function of star clusters. Stars in galaxies form in groups, clusters, and associations, rather than in isolation. Most of these clustered stellar systems disperse within a few 100 Myr, contributing their stars to the general (unclustered) field population. The observational effect of a steep IMF can be produced if the stellar IMF within clusters has a universal shape but its upper mass cutoff depends on the mass of the cluster (Figure 1, right; see Pflamm-Altenburg et al. 2009). In this case the ability of a galaxy to form massive clusters drives the upper mass end of the observed stellar IMF. While the two mechanisms (variation in the stellar IMF or in the cluster mass function) lead to the same observational results, the underlying physics is significantly different and would significantly impact any theory of star formation.



FIGURE 2: Color composites of two representative galaxies in the Local Volume (from Meurer et al. 2009). Direct IMF measurements need to be made in galaxies like these, to establish whether the IMF is universal or dependent on environment.



Lack of a theory for the IMF has hindered progress in a number of extragalactic areas. Over the past ~3 decades, non—standard IMFs have been invoked to account for a wide range of `puzzling' observational results, including the low mass—to—light ratio of starburst galaxies (Rieke et al. 1980), the enhanced alpha—element abundances of ellitptical galaxies (Nagashima et al. 2005), or the metal—enrichment of the intracluster medium (Loewenstein 2006), just to name a few. In all cases, mechanisms alternative to a non—standard IMF have also been suggested (Satyapal et al. 1997, Fulbright et al. 2007, Renzini 2004). However, in many of these cases none of the suggested mechanisms unambiguously excludes the other, and a resolution of these questions requires definite determinations of any variation of the stellar IMF.

Methodology and Requirements

Answering the fundamental question, 'Is the stellar IMF universal?', will require **direct** measurements of stars over a large range in mass, in as many environments as possible. Galaxies

within the Local Group, which include only 3 spirals and a few dozen dwarfs (the dwarfs are mostly satellite galaxies), do not span the full parameter space of gas density/pressure, total SFR, specific SFR, and galaxy environment. The Local Volume within ~20 Mpc contains the Virgo Cluster, a number of galaxy groups, and many starburst galaxies and Low Surface Brightness galaxies; this volume expands on those parameters by an order of magnitude toward the faint/low end and about 1—2 orders of magnitudes at the bright/high end. Expanding the coverage of this multi—dimensional parameter space by the above factors is the next frontier.

In order to directly observe stars and construct the IMF, one ideally needs a recently formed coeval stellar population, where little evolution of the most massive stars has occurred. Such young, coeval populations are found in stellar clusters; they can also be extracted from field populations using standard CMD techniques to separate age, metallicity, and extinction. Individual stars need to be resolved, which requires high angular resolution. Measuring stellar luminosities requires multi-wavelength capabilities, as the peak emission from stars moves from the UV, for the most massive ones, to the infrared, for the lowest masses, plus photometric stability and a high Strehl ratio for the point spread function. We will not dwell on the further complication of converting stellar luminosities to masses, or of separating binaries. All these steps are complex, but can be accomplished with the appropriate facilities.

Most of the limitations of the work possible with HST and current ground—based telescopes are due to a combination of angular resolution and/or sensitivity limitations, which prevent a direct determination, *over the full range of stellar masses*, of the IMF beyond the Milky Way and its satellites (the local few tens of kpc). At present, IMF constraints at larger distances either probe just the high—mass range of the IMF or are largely based on galaxy—averaged indirect arguments, which compare the light emission at a variety of wavelengths. These indirect arguments suffer from a number of degeneracies, including leakage of ionizing photons and, for small samples, star formation histories. Currently, there are no planned facilities that can perform these fundamental measurements, since JWST and ground 30-m AO lack the necessary UV imaging capabilities.

A reference 16-m space UV/optical telescope (Figure 1, left) will reach V~35 mag in sensitivity, equivalent to a 1 M_{Sun} star at 10 Mpc distance. IMF studies will be limited by the ability to isolate stars in crowded locales, and stars with sub—solar masses (~0.5 M_{Sun}) will only be identified and measured within the nearby ~2 Mpc Volume. Stars with even lower masses (emitting the bulk of their light in the NIR) will be sampled by future 30-m ground telescopes with NIR AO. IMF determinations down to masses ~5 M_{Sun} will be enabled by our baseline UV/optical space telescope out to the representative ~20 Mpc Volume.

Recommendation

To directly measure the stellar IMF for every galaxy out to ~2 Mpc requires a 8-m to 16-m space telescope with UV/optical sensitivity (to access the high-mass to solar-mass range of the IMF) working in concert with a large (~30-m) ground-based telescope capable of diffraction-limited performance in the NIR (to access sub—solar mass stars. The same capability will determine the stellar IMF down to ~5 M_{Sun} in galaxies within the local ~20 Mpc Volume. This will broaden the range of environments in which the IMF is known by more than 2 orders of

magnitude, and will finally provide the required observational foundation for a comprehensive theory of star formation.

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