Systematic Variations of the Stellar Initial Mass Function

Bachelor Thesis

Written by:

Albert Bjerregård Sneppen

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Supervised by:

Charles L. Steinhardt

University of Copenhagen

UNIVERSITY OF COPENHAGEN

FACULTY:	Science
INSTITUTE:	Niels Bohr Institute
AUTHOR:	Albert B. Sneppen
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SUPERVISOR:	Charles L. Steinhardt
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Abstract

In this thesis we will present evidence of systematic variations of the stellar initial mass function from photometric observations of ensembles of galaxies. These variations are interpreted in the context of theoretical predictions of how the temperature of star-forming clouds influences the IMF. We will show that these inferred gas temperatures follow predictions of stellar population feedback and observed dust temperatures. Additionally, we will prove that the spectral features associated with a variable IMF indeed differ between galaxies fitted at different gas temperatures by stacked photometry. Finally, the implications of a variable IMF on other galactic properties will be examined and perspectives for future research outlined.

Contents

1 Introduction

Our current understanding of extra-galactic astronomy is based on the light originally emitted from stars in distant galaxies and sent towards the earth. Everything we have learned within the field rely on the information contained in the magnitude and wavelengths of this stellar light. However, a star twice the mass of the sun will shine more than 10 times brighter yet is only 5 times as rare. Therefore, most of the light in typical galaxies comes from stars more massive than the sun, but most of the mass still comes from stars smaller than the sun. Thus, when examining galaxies, only the massive stars, a small fraction of the total stars, yield information about the whole galaxy. When we wish to measure the star formation rate, the stellar mass or the metallicity, we observe the light from these most massive stars and extrapolate to the galaxy as a whole.

This extrapolation is only possible if we know the relative mass distribution of stars. Thus, the distribution of stellar mass is essential to understanding whole galaxies including the contribution of the undetectable stars. However, this distribution is subtle, because it is only measurable in some parts of the Milky Way and its immediate surroundings and without a theoretical predicted form. Therefore, when we examine other galaxies across the Universe we assume the stellar mass distribution observed locally still applies. The universality of the distribution is neither tested observationally across galaxies or predicted theoretically, but is simply due to the necessity of needing a stellar distribution with mass to extrapolate properties of the whole galaxy.

This extrapolation has been used with great success with everything we know about high-redshift galaxies, the star-forming main sequence and the evolution of galaxies based on this distribution. However, the discoveries also include as yet unresolved tensions between theoretical prediction and observations of downsizing, massive quiescent galaxies and galaxies that are formed impossibly early. This might indicate that the assumption of a universal distribution is flawed especially at the higher redshifts, where the tensions are observed. Indeed as we are going to show in this thesis there are strong theoretical reasons to believe this universality is incorrect and that a stellar mass distribution should depend on temperature. Furthermore, observations even at moderate redshifts show higher temperatures than measured locally in the Milky Way.

Therefore we are motivated in § 2.2 to look for a way to consider a different distribution with a dependence on gas temperature. We construct an experiment, where we reproduce the technique currently used to analyze galaxy-photometry with the exception that we add a new set of models that correspond to a variable stellar mass distribution in § 2.3. In § 3 we will apply these stellar population models to observed photometry from the COSMOS2015 catalog and show that systematically different temperatures are inferred in other galaxies. The gas temperatures found are physically reasonable and conform to measurements of dust temperatures. Finally, we show that varying the stellar mass distribution opens the possibility of reinterpreting many inferred galactic properties and of reexamining potential incongruities in extra-galactic astronomy.

2 Methodology

2.1 The Stellar Initial Mass Function

The stellar initial mass function (IMF) is the distribution of masses for a population of stars at their formation time. This is of central importance to many areas of astrophysics. Understanding the origin of the distribution would provide insights into the physics of star formation, but as mentioned the exact distribution is needed to untangle any property of a stellar population. The low mass distribution of the IMF determines the overall stellar mass scale of galaxies, at intermediate masses the IMF determines the generation of chemical elements and at high stellar masses it determines the number of core-collapse supernovae and thus the kinematic feedback into the ISM [1]. Therefore, a well constrained IMF is required for studying stellar populations and galactic properties [2]. However, despite its profound importance it is only an empirically observed distribution derived from local observations of star forming regions, globular clusters and field stars within the Milky Way galaxy and its immediate surroundings. These direct observations are only available in our immediate neighborhood with selection-biases such as the evolution of stellar populations, dust extinguishing faint stars and the differential migration of different mass stars quickly making direct probes unfeasible. However, these local observations have shown remarkably little variation of the IMF within our Local Group galaxies, while more indirect probes of the IMF from early-type galaxies have shown systematic variations with galaxy mass and velocity dispersion [2].

Several theoretical model have been suggested to explain the physical origin of the IMF distribution drawing from both analytical models derived from the Jeans Equation and from numerical simulations explaining the mass probability distribution in terms of the complicated processes of star formation [3, 4]. The physical origins of the probability distribution are not yet well understood due to the complexity of the collapse of stellar clouds being determined by a complex interaction of thermodynamics, gravity, heat transfer and opacity. A theory has yet to predict an IMF from first principles, the theoretical body of work does suggest that the stellar initial mass function is indeed not a universal property of all galaxies but varies and depends upon local conditions especially the temperature of the star-forming clouds.

Despite the evidence for a varying stellar initial mass function, the prevalent paradigm in astrophysics assumes that the Milky Way IMF is generally applicable to other galaxies. This is the key assumption which we will investigate in this thesis by introducing a dependence on the temperature of the stellar clouds which give birth to new stars and with these new models probe the universality and conformity of initial stellar mass function in galaxies across the universe.

2.2 Temperature Dependence of Star Formation

Over the last 65 years several different expressions have been derived to describe the probability distribution of stellar masses. Edwin Salpeter originally observed the number of stars at a given mass, $\frac{dN}{dm}$, as a function of mass, m, for stars with a mass greater than 1 $M_\odot$ and fitted it with a single powerlaw [5]:

$$\frac{dN}{dm} \propto m^{-2.35} \tag{1}$$

Because the luminosity of stars scale dramatically with mass on the main sequence with $L \propto m^{3.5}$, the power law index discovered by Salpeter has a straightforward implication. The total mass of a stellar population is set by lower mass stars because the mass of the population is the product of the mass of a star and the number of stars at the given mass which drops rapidly as seen in eq. 1. In contrast the luminosity from this stellar population is dominated by the high mass distribution, because the number of stars decreases as a function of mass in a slower manor than the luminosity of individual stars increases with mass[6] [1]. Thus, altering the IMF would alter the mass-to-light ratio and in extension any galactic property derived from this such as star formation rate or mass.

However subsequent measurements have shown that Salpeter's single power law overestimates the number of stars below the 1 $M_\odot$ mass-range originally investigated. Several different probability distributions have since been fitted to follow the observations. The Kroupa IMF is one of the most commonly used and the one chosen in this analysis because previous research has already discussed a physically motivated temperature-dependence [7]. The Kroupa IMF consists of three power laws tied together in two kinks [8]:

$$\frac{dN}{dm} \propto \begin{cases} m^{-0.3} & m < a_1 \cdot \tilde{m} \\ m^{-1.3} & a_1 \cdot \tilde{m} < m < a_2 \cdot \tilde{m} \\ m^{-2.3} & \tilde{m} \cdot a_1 < m \end{cases} \tag{2}$$

Here $a_1 \cdot \tilde{m_0} = 0.08M_\odot$ and $a_2 \cdot \tilde{m_0} = 0.5M_\odot$ are the empirically determined kinks in the Milky Way IMF. Critically the mass scale is set by the mass, $\tilde{m}$, which is the minimum fragmentation mass where a cloud can cool efficiently which depends on the ambient temperature. Intuitively, the scale of the collapsing stellar cloud should depend on temperature as temperature sets the internal pressure of the gas that battles against gravity's attempt to collapse the cloud. A larger temperature implies a larger pressure and thus a cloud stable at larger scales. Therefore, higher temperatures result in larger and more massive clouds collapsing. As the cloud collapses its density grows and so to the internal gravitational attraction, but as long as the cloud remains optically thin and efficiently cools the temperature will remain constant. This implies the cloud will become unstable on even smaller scales. It will fragment into smaller masses which themselves collapse and fragment. However, when the cloud becomes optically thick the temperature will increase stopping this process of fragmentation. These two mass scales whereby the initial cloud collapses and fragmentation stops, set the two kinks in IMF. Importantly they share a temperature-dependence as it is the same process of thermodynamics versus gravity that sets the clouds collapse. Thus, we can express a single mass scale where the clouds stop fragmenting, $\tilde{m}$, that sets the mass scale of the stars created. The specific dependence on temperature requires solving the energy balance and opacity which has already been derived previously from analytical consideration of the Jeans mass (see derivation in [3, 7, 9]):

$$\tilde{m} = \tilde{m_0} f(T) = \tilde{m_0} \left(\frac{T}{T_0}\right)^2 \tag{3}$$

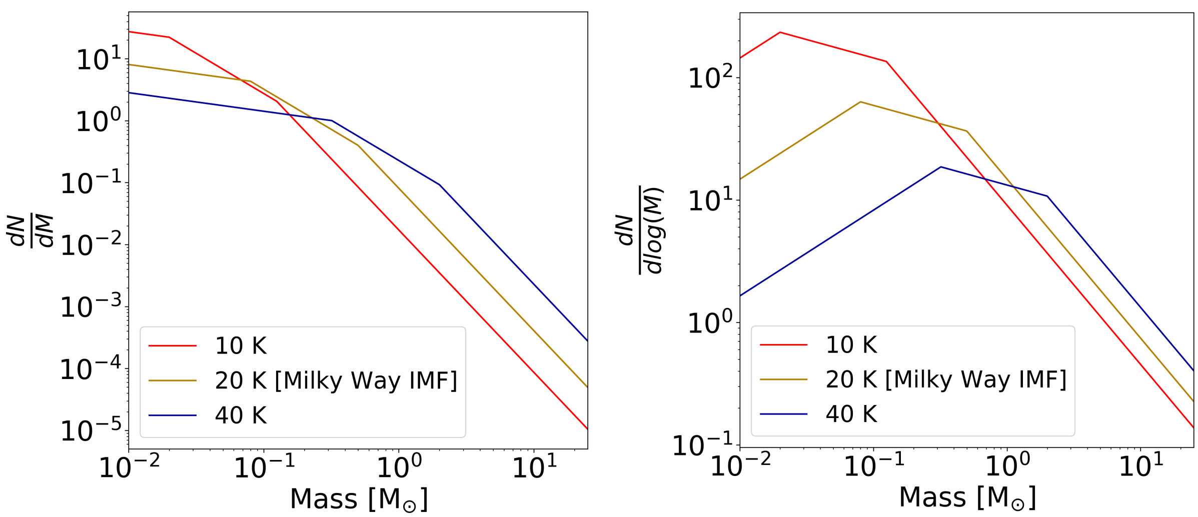
Here m_0 and T_0 is the reference minimum fragmentation mass and temperature observed in the Milky Way. The typical star-forming cloud in the Milky way is about 20 K, so we will set this as our reference temperature, T_0 [10]. Therefore, the fragmentation mass and in extension the locations of the kinks of the IMF become dependent

[1] For a comprehensive analysis of this effect we would need to include both the star-formation history and the specific lifetimes of stars at different masses

on temperature. Inserting the fragmentation mass dependence from literature into the Kroupa IMF yields:

$$\frac{dN}{dm} \propto \begin{cases} m^{-0.3} & m < 0.08M_\odot \cdot \left(\frac{T}{T_0}\right)^2 \\ m^{-1.3} & 0.08M_\odot \cdot \left(\frac{T}{T_0}\right)^2 < m < 0.5M_\odot \cdot \left(\frac{T}{T_0}\right)^2 \\ m^{-2.3} & 0.5M_\odot \cdot \left(\frac{T}{T_0}\right)^2 < m \end{cases} \tag{4}$$

Note that as we change the temperature of the star forming clouds we are moving the transitions between the different power laws. Here decreasing the temperature will lower the frequency of massive stars. This is because the probability of having a given stellar mass declines rapidly at even lower masses. In contrast increasing the temperature implies that the flatter power law is maintained at even larger masses which would make massive stars relatively more likely. Thus, decreasing temperature would lead to more low mass stars (a more bottom-heavy distribution), while an increasing temperature would yield relatively more high mass stars (top-heavy distribution) compared to low mass stars and thus the IMF would be more top-heavy as can be seen in Fig. 1.



(a) Number of stars

(b) Number of stars weighted by their mass

Figure 1: Kroupa Initial Mass Function with described temperature dependence at T = 10 K [red], 20 K [orange], 40 K [blue]. In a) the stellar mass distribution normalized by total number of stars and in b) the mass contribution at a specific mass normalized by total mass. Note that raising the temperature leads to top-heavy or more bottom-light distribution and lowering the temperature leads to a more bottom-heavy distribution. As expected the total mass is dominated by smaller stars.

In the Milky Way, the temperature of cold gas is driven primarily by stellar radiation. A star only heat its immediate surroundings and therefore the temperature of gas is very sensitive to its proximity to stars. As the distribution of stars is very uneven in galaxies when stellar radiation is the main source of heat the temperature might vary between different clouds of gas within a galaxy. This is problematic as we are limited in spatial resolution to an extent where we cannot separate different gas clouds within a given galaxy and parts of the Milky Way. Thus, using a single IMF on the the entire galaxy requires the key assumption that the cold gas temperature in that galaxy is uniform.

However, in galaxies with larger star formation there are correspondingly more supernovae which are the main source of cosmic rays. Therefore, galaxies which produce many massive stars and supernovae might have their temperature set by cosmic rays rather than starlight. Previous work suggests that at $z > 1$ a typical star forming galaxy would have a temperature dominated not by starlight but by the cosmic rays [11]. Indeed observed dust-temperatures in star forming galaxies at most redshifts are systematically higher than the 20 K cold gas in the Milky Way [12]. Cosmic rays permeate the entire galaxy and so galaxies where cosmic rays set the temperature should have a single characteristic temperature for the stellar clouds. Indeed, the temperature-dependence derived above was modelled from star-forming galaxies. In this thesis we will assume a uniform temperature for the star forming clouds in a galaxy out of a principle of simplicity and due to observational necessity, thereby following the standard convention of treating galaxies as monolithic.

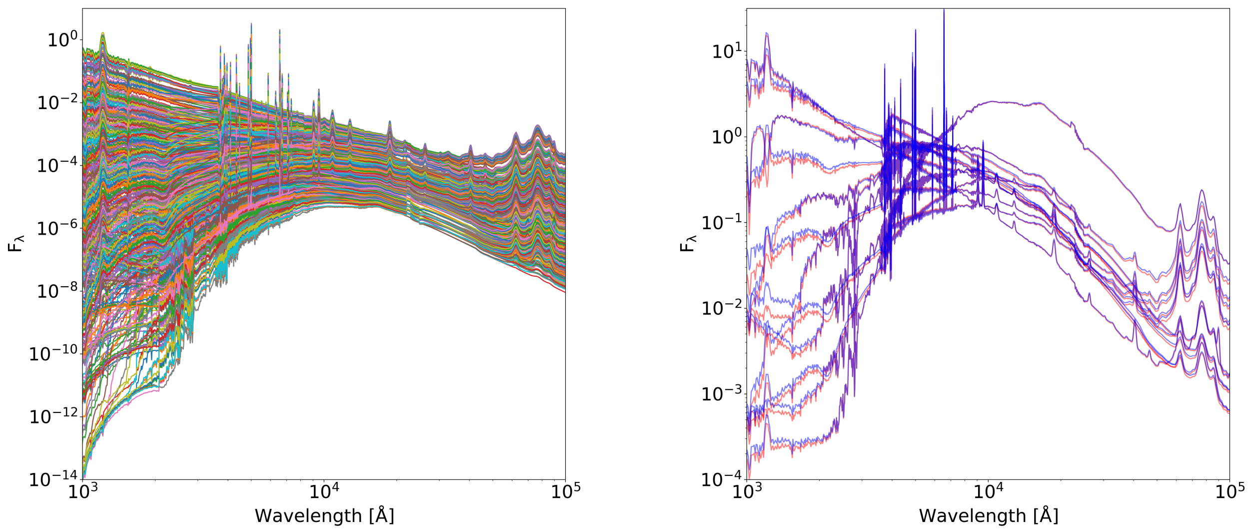
At even earlier times, the Cosmic Microwave Background (CMB) would come to dominate the temperature. The universal nature of the CMB would give all stellar clouds the same temperature. At $z = 6$, beyond the range of redshifts investigated here, the temperature of the CMB would be larger than that of typical Milky Way stellar clouds [7]. Therefore, the effect of a CMB dominated temperature is not relevant on any galaxy yet seen, but JWST may probe this regime.

For starlight, cosmic rays and the CMB driven case, the ambient temperature should in general decrease towards the present time. This is because stellar radiation decreases as the stellar population ages and loses larger stars, the cosmic ray density falls with less star formation and as the universe expands the CMB temperature drops monotonically. Thus, a key prediction from the temperature-dependence introduced is that the IMF typically becomes more top-heavy at larger redshifts. This is also observed in measurements of dust. While the specific dust temperature varies between models, there is a shared decreasing trend toward the present time on the star-forming main sequence [12, 13, 14, 15, 16].

Additionally, it should be noted that other scaling relations between fragmentation mass and temperature have been derived from simulations with $f(T) \propto T$ [17] or $f(T) \propto T^{\frac{3}{2}}$ [18]. This analysis will assume both the Kroupa IMF and the fragmentation mass scaling relation seen in eq. 4. However, the methodology can straight-forwardly be extended to other IMFs and we are agnostic to any particular choice of temperature dependence. Instead we wish merely to examine the need for and consequences of adding a general temperature dependence to the IMF.

2.3 Generating Theoretical Spectra

With this temperature variable IMF we can now generate theoretical spectra with varying temperatures and use these to fit photometric catalogues. Finding the spectra from a population of stars is a complicated process combining the spectra of individual stars weighted together by the current distribution in mass of stars. This in itself depends not only on the IMF but also on the star-formation history and on the isochrones which describe how the stellar population has evolved. Fortunately stellar population modelling is well established with the standard approach being to create model-spectra of galaxies from a physical understanding of how galactic properties impact the spectra. Then by varying the galactic parameters one can create spectra of galaxies which span the space of physical properties. By using the Flexible Stellar Population Synthesis code [19] [20] we can thus model 560 galaxies that hopefully span the space of galaxy spectra and can be seen in Fig. 2a. These spectra are compiled with varying ages, metallicities, star-formation histories, dust attenuation and extinction curves and utilizing two different models of isochrones as seen in Table 1.



(a) 560 FSPS galaxies

(b) 12 basis spectra for EAZY

Figure 2: a) 560 simulated spectra from FSPS galaxy spectra at 20 Kelvin. b) 12 basis spectra for EAZY with 20 Kelvin [red] and 50 Kelvin [blue]. As expected spectral differences with temperature are only seen at wavelengths in the ultraviolet (below 4000 Å). None of the 12 basis spectra is within the set of 560 simulated spectra, but the reduced basis still spans the large variability of the 560 spectra.

These 560 galaxy spectral energy distributions (SED, illustrated in Fig. 2a) have previously been used to create the basis for the EAZY photometry fitting code and as such used to span the space of possible galactic properties [21]. This modelling approach is well established and has yielded great insight into extra-galactic astronomy, but all physical models have relied on a Milky Way IMF. Crucially, we will now add our temperature variations to the IMF varying temperature along with all the other galactic properties. Thereby, we have created 560 templates for any given temperature and we can now compare the templates at different temperatures. In Fig. 3 the difference in SED can be seen for a young [in blue] and old [in red] galaxy with variable IMF. As expected increasing temperature leads to more massive stars and thus more emission in the ultraviolet. In contrast varying temperature does not change emission in the optical noticeably. Note that for the older galaxy there is less variability with temperature. This is also reasonable as massive stars have shorter lifetimes so the variations we introduced to the IMF have decayed for the old galaxy's present stellar mass distribution.

Parameter	Range
Age [Gyr]	0.02-20
τ e-folding time [Gyr]	0.05 - 0.8
Metallicity [$Z_{\odot}$]	0.1 - 1.78
Dust extinction, A_V [mag]	0.01 - 3
Temperature [K]	8 - 50

Table 1: Range of galactic parameters spanned in FSPS spectra, with age of galaxy, τ [the characteristic time for the star-formation rate], Metallicity from the tabular Mist isochrones, A_v is the extinction of dust in magnitudes.

2.4 Applying to Observed Galaxies

To compare the temperature dependent template to photometry we will use the photometric redshift code EAZY [21], which has proven to give reliable photometric redshift [22]. EAZY makes linear combinations of the theoretical spectra and subsequently finds the combination that best-fit photometric observations. However, with 560 basis spectra, attempting to determine possible linear combinations is very degenerate. Possible solutions may fall into different local minima of the chi-square parameter-landscape. Thus, to utilize the potential of EAZY a smaller basis set is needed while still spanning the diversity of spectra. Fortunately, this problems has previously been solved for EAZY by reducing the basis with Non-Negative-Matrix-Factorization (NNMF). NNMF is a computational approximation where we reduce a large positive basis to a smaller positive basis, in such a way that this smaller basis in positive linear combinations approximate to the large basis. Here the choice of NNMF as our dimensionality reducing algorithm is due to the inherent positive nature of the measured fluxes. By reducing to a smaller basis which still adds linearly to our larger basis the basis spectra becomes physically meaningful with the new basis spectra still representing the possible spectra of a galaxy. Therefore galactic parameters from the modelled FSPS spectra can be propagated into the new basis of galaxies.

The approach of fitting the linear combination of a small basis is standard within photometry and the only novel part of our approach is changing the spectral model with the gas temperature. If the Milky Way IMF provides the best physical model this approach will conform and agree with current catalogs. The new reduced 12 basis spectra found from the NNMF coefficients derived for the original EAZY templates can be seen in Fig. 2b. While these coefficients were originally derived for the temperature independent Kroupa IMF, we will use them across the temperature-range. This relies on the assumption that the reduced basis still spans the space of SED at other temperatures.

Another consequence of EAZY is that its approach of fitting observations with linear combinations of our basis allows non-physical combinations to be the best-fit. For example while this body of work builds on the assumption of temperature impacting star formation - EAZY does not enforce this correlation. EAZY might derive a best-fit linear combination with high-temperature and a low star formation rate even though young and massive stars heat the gas. Thus, EAZY opens the opportunity to test the methodology by examining if the solutions remain

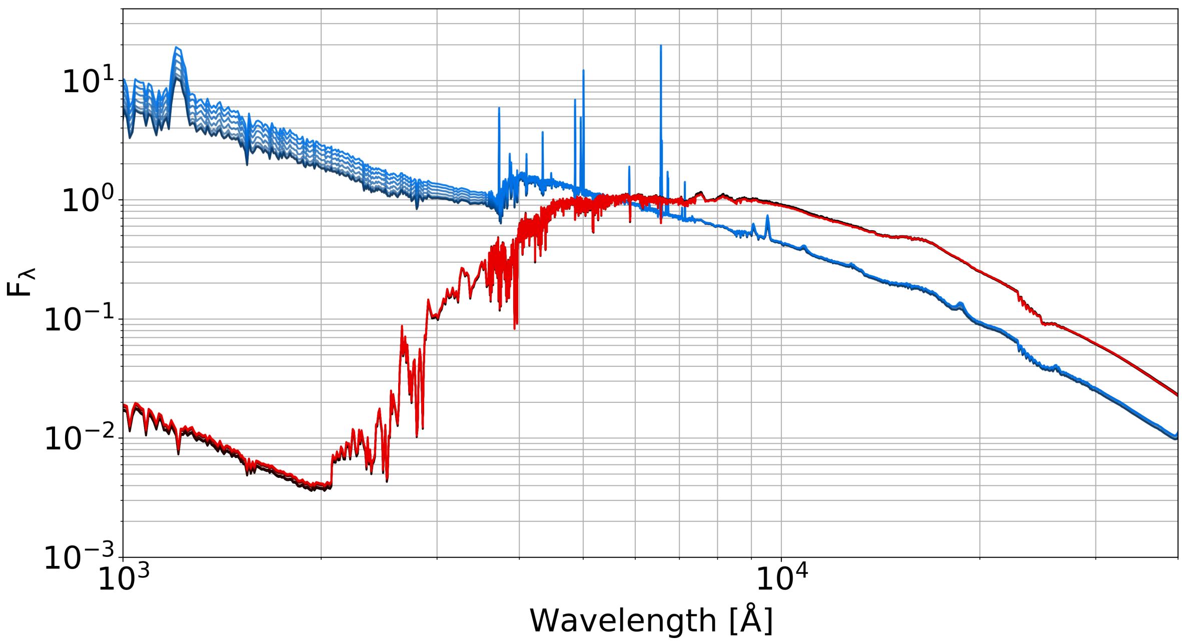


Figure 3: FSPS galaxy spectra normalized at 5600 Å for the same galaxy at an age of 1.3 Gyr [blue] and 20 Gyr [red] with increasing temperature [from 20K to 50 K] shown in progressively brighter hues. Increasing temperature results in larger fluxes in the UV [$\lambda < 4000$ Å] as expected from the additional massive stars shinning in the ultra-violet. Note the large variability in the young galaxy with temperature while the older galaxy is invariant to temperature-variations.

physically reasonable.

With these reduced sets we can now compare our temperature dependent templates to photometry by varying the temperature and then fitting the best linear combinations (ie. fitting all other galactic properties).

3 Results

Fitting linear combinations of our basis spectra through EAZY with our temperature parameterized IMF allows us to compare the goodness of fit at any temperature. By comparing the chi-squares of EAZY fits at different temperatures we can determine whether the temperature-independent Kroupa IMF truly is the best fit for other galaxies. As can be seen in Fig. 4 this is not the case and many galaxies are fit at other temperatures with other Initial Mass Functions than traditionally assumed.

In general, two distinct populations of IMFs are apparent within the temperature-range, one at an IMF similar to the Milky Way at around 23K and a top-heavier IMF at $\sim$ 35K. This bimodality of observed IMFs is suggestive that two different processes are driving the temperature of stellar clouds.

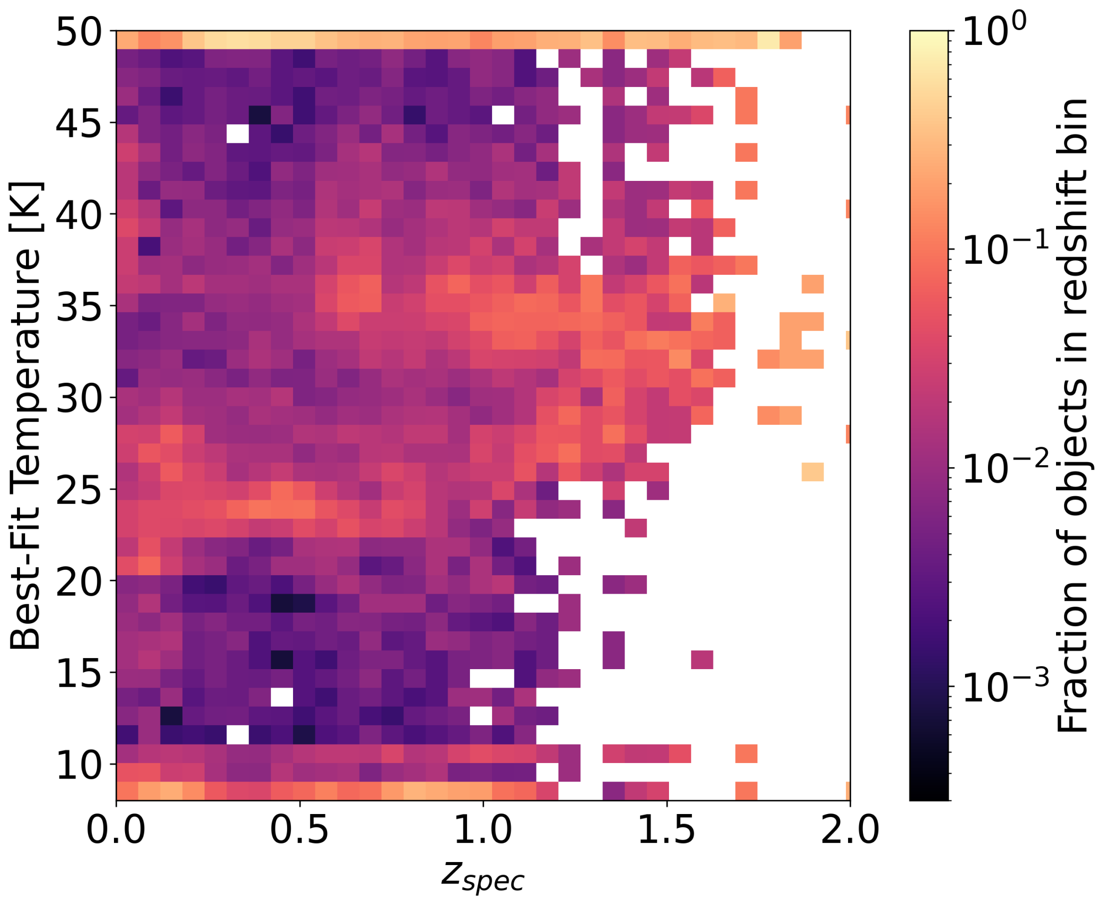


Figure 4: Best fit temperature from 8-50 K versus spectroscopic redshift from a sample of 23,000 COSMOS2015 galaxies with known spectroscopic redshifts [23]. One group of galaxies is fitted with a Milky Way IMF (around 23 K) and another group of galaxies has a top-heavier IMF (approx. 35 K) as the best fit. With increased redshift fewer galaxies are fitted at lower temperatures and the cooler branch of galaxies is fitted at progressively higher temperatures.

A majority of galaxies converge within the temperature range investigated. However, there is a significant population of galaxies where the minimum of the chi-square landscape appears on the boundary of the temperature range. The lower bound of the temperature range we have investigated is 8 K where the steepest power law goes from $0.08 M_{\odot}$ and upwards. Note that below approximately $0.08 M_{\odot}$ the objects are no longer stars in the sense that fusion can no longer take place, so to create an even bottom-heavier IMF we would need to change the slope (which has previously been suggested from theoretical considerations [4]). Extending the temperature range upwards to 100 K leads to little qualitative difference as the best-fit temperatures still appear at the bounds. This is suggestive that the modifications we introduced to the IMF may be incomplete, which we will elaborate on in § 3.2.

3.1 Predictions

Notably the relation between best-fit temperature and redshift seems to exhibit a few key predictions made previously from theoretical consideration and observational evidence. It seems evident that galaxies at low redshift are likely to exhibit a best-fit temperature around 20-25 K. This is quite encouraging as the best fit predicts a Milky Way IMF as being typical locally which is also the only IMF which has been observed locally.

With increasing redshift fewer galaxies display a Milky Way IMF or a bottom-heavier IMF. Additionally, the typical temperature increases towards higher redshift (see Fig. 5) with the population of galaxies that locally fits to a Milky Way temperature tending towards having a higher best-fit temperature with increasing redshift. This also agrees with observational evidence. Although gas temperatures are themselves difficult to directly observe, dust temperature have been probed within other galaxies. Although the trend seen in Fig. 4 and elaborated in Fig. 5 might be due to complex selection biases it does agree with observational evidence that dust temperature increases with redshift [12]. These observations suggest that the characteristic dust temperature of galaxies on the star-forming main sequence decrease from approximately 35 K to 25 K from $z = 2$ toward the present time. Note that if the temperatures of dust and cold gas clouds are similar, we can constrain the theoretical temperature dependence introduced to the IMF. Unfortunately, this comparison is only approximate as different models of dust yield different dust temperatures. However, in principle a reliable dust-temperature could be used to constrain the temperature-dependence of the IMF.

For instance a linear temperature dependence in the fragmentation mass would imply the mean best fit temperature should be even higher. At $z = 1$ the linear temperature dependence would fit the mean temperature at 45 K, significantly hotter than typical dust at that redshift. To match dust-temperatures with our best-fit temperatures (seen in Figure 5) we would need a temperature-dependence in the IMF between $\tilde{m} \propto T^{3/2}$ and $\tilde{m} \propto T^{2}$. However, the dust temperature is not necessarily equal to the gas temperature of star-forming clouds as there may not be adequate cross-section or time for the two to equilibrate. An additional discrepancy is that dust temperature is luminosity averaged, so any inferred dust temperature will be dominated by hotter dust. However, the gas temperature is not as it is inferred from IMF. Therefore, the gas temperature is mass averaged as it comes from the relative abundance of stars. Despite the discrepancies between the approaches the novel methodology of introducing temperature variations in the stellar mass probability distribution is entirely independent of dust still agrees with measurements of it.

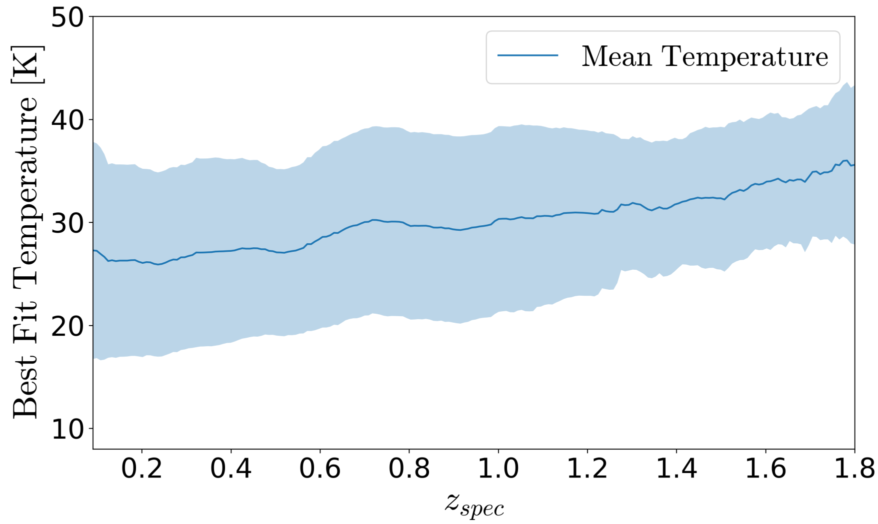


Figure 5: Boxcar smoothed mean with standard deviation of best-fit gas temperature at different spectroscopic redshift [with mean determined from objects in 0.2 width redshift bins and not including high temperature outliers]. The mean temperature increases from ~ 26 K to ~ 34 K from $z = 0$ to $z = 1.8$, while the spread decreases.

This decrease in temperature towards the present time also follows theoretical predictions described in § 2.1. In short, both cosmic rays and the ultraviolet light of larger stars contribute to heating the gas within galaxies, but with decreasing redshift the cosmic ray density falls while stellar populations age and lose their most massive stars leading to progressively cooler star-forming clouds [11].

There is an additional complexity in inferring best-fit temperatures from the stellar mass distribution. The temperature inferred is not the current temperature of the cold gas but the ambient temperature of the stellar clouds at the time of star formation. For instance a local galaxy might have formed its stellar population when its stellar clouds were hotter, which complicates any direct comparison to dust temperatures or indeed to any mapping of best-fit temperatures across different redshifts. Notably, the spread in temperature seen in Fig. 5 decreases towards higher redshift. This could be indicative of local observations convolving hotter and older with cooler and younger stellar populations while at higher redshifts only the hotter galaxies remain. However, the increased spread might also be a result of the different mechanisms driving the temperature of star forming clouds. For example stellar radiation displays larger variance between galaxies than for example a CMB driven temperature as the latter is universally shared across galaxies at a given redshift. Indeed the difference in the spread might potentially yield a way to distinguish whether stellar radiation, cosmic rays and CMB is setting the gas temperatures. At present either cosmic rays or stellar radiation might determine the gas-temperature in a galaxy. Cooler and quiescent galaxies exist at the same redshifts as hotter and star-forming galaxies. Thus, the spread in temperature is larger locally than when compared to higher redshifts where cosmic rays are the typical cause of gas temperature.

3.2 Significance of improvements

While the best-fit to the photometric observations improves with our variable IMF we have not yet clarified the significance of these fits. To do this we can examine the chi-square landscape as a function of temperature for individual galaxies as seen in Figure 6. As can clearly be seen no individual galaxy is tightly constrained in its temperature with relatively wide and shallow χ^2-minima. This is to be expected as our alteration to the IMF only subtly influences the spectra as seen in Fig. 3. For the whole set of galaxies tested the difference between the extreme values of the χ^2 varies from 0.1 to 5 for typical galaxies over the temperature range 8-50 K.

Furthermore, the non-convex nature seen in some of the chi-square landscapes might be indicative that a single temperature IMF is to simplistic. As can be seen in the latter two galaxies of Fig. 6 both a very top-heavy and Milky Way IMF fit the observations better than the intermediate 35 K IMF. This implies that while making IMF more top-heavy improving the fit at some wavelengths it worsens at other wavelengths where the cooler IMF succeeded. Perhaps indicative that there is not a single IMF in these galaxies, but in reality several different temperatures within the galaxies different star-forming clouds.

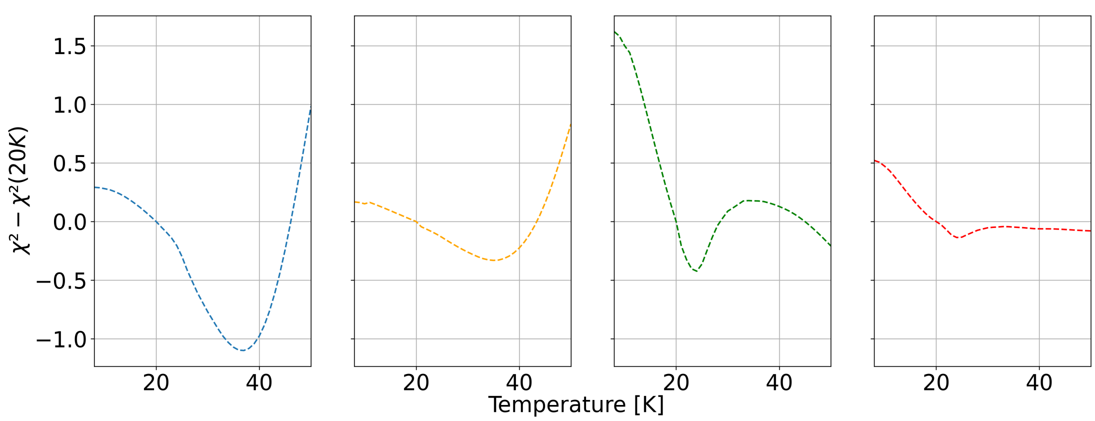


Figure 6: Example chi-square landscapes for 4 different galaxies bench-marked against 20 K. In general all chi-square landscapes are shallow and the gas temperature is not well constrained for any individual galaxy. Furthermore, some chi-square-landscapes are non-convex with several local minima.

Another independent test of the fit quality is that the redshift scatter does not increase with the additional parameter. Improvements to the fits might occur at the cost of the correct redshift, but the accuracy of the photometric redshift fitted remains unchanged with a slight albeit not statistically significant decrease in redshift-scatter when compared to spectroscopic redshifts. That the scatter does not vary significantly is presumably due to photometric redshifts being mainly determined by breaks in the spectrum, such as the Lyman break or Balmer break, which is independent of the IMF.

It is noteworthy that photometry of individual galaxies so poorly constrains the IMF, which is presumably why this photometric approach has not been tested previously. However, in an era of big data astronomy we can instead test and see patterns by inspecting ensembles of galaxies.

3.3 Stacking Spectra

We have now shown that fitting an IMF from photometric observations of galaxies yields a wide range of best-fit stellar initial mass functions. However, to ensure that these observations are actually fitted at a higher temperature because of features within their spectrum we would need too inspect their spectral energy distribution.

To do this we have created a composite SED by using the fluxes in different wavelength-bands at different redshifts to sample the galaxies rest-frame spectrum. The underlying idea is that the flux from a galaxy in a specific band can be turned into an approximate flux at a specific wavelength using the passband of our telescope. Additionally, we have galaxies spanning a range of redshifts. This means that different parts of their spectra are redshifted into the wavelength-range which the bands observe. Thus combining galaxies across the redshift range gives approximate fluxes across a range of wavelengths ie. a spectral energy distribution.

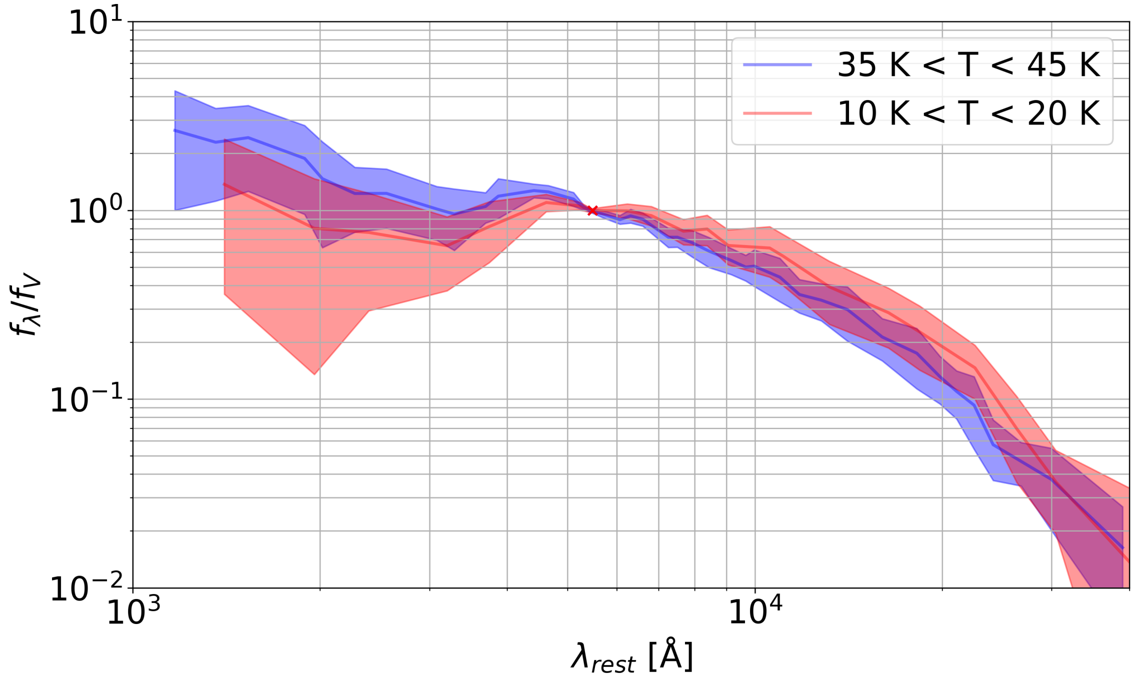


Figure 7: Composite SED normalized at 5600 Å for galaxies with best-fit temperature in 10-20 K range [red] and 35-45 K range [blue] with standard deviation in shading. The cooler galaxies are systematically below the hotter galaxies at all wavelengths of the ultraviolet [$\lambda < 4000$ Å]. Cooler galaxies look more quiescent than the hotter galaxies, which share spectral features with more star-forming galaxies.

In Fig. 7 this stacked photometry can be seen for galaxies with different best-fit temperatures. As can be seen these two populations of galaxies yield significantly different results. While the two populations of spectra conform at larger wavelengths they disagree in the ultraviolet and lowest wavelengths of the optical. This is precisely the wavelength-range sensitive to the IMF alterations as seen in Fig. 3. Massive stars shine at higher temperatures and thus a lower wavelengths, so we would expect that increasing temperature which creating a top-heavy IMF would lead to a larger flux in the UV. This is exactly what is seen in Fig. 7 with the hotter galaxies having larger fluxes in the ultraviolet [$\lambda < 4000$Å] than the galaxies with cooler star forming clouds. This stacked photometry thus suggests that the best fits are not merely spurious but indicative of systematic features within their spectrum.

3.4 ULIRGs

Galaxies which have undergone similar physical processes should have star-forming clouds in similar conditions. Therefore examining a group of galaxies with similar properties should yield similar fitted temperatures. Since spectral features originate from physical properties it is assumed that galaxies that look like a distinct group in terms of their color must have similar properties and have undergone similar processes. One such group of galaxies is the ultra-luminous infrared galaxies (ULIRGS) which is a class of bright galaxies with luminosities greater than $10^{12}L_{\odot}$. These are typically galaxies with a burst of star formation conventionally believed to be caused by mergers of gas-rich galaxies [24].

Applying our methodology, ULIRGs exhibit a few notable discrepancies from their less luminous counterparts. First, they are systematically hotter (around 30 K) and therefore top-heavier than the Milky Way IMF. This follows the naive expectation that photons from luminous galaxies also heat the galaxy's own stellar clouds. Second, the population of ULIRGs appear to trace the population of galaxies with a top-heavier IMF seen in Fig. 4. This further highlights that real physical processes are separate galaxies at different best-fit IMFs. Finally, the typical best-fit temperature seems nearly independent of redshift. For ULIRGs higher redshifts do not imply typically hotter star-forming clouds. This is especially interesting as the correlation between temperature and redshift is based on ageing stellar populations and a falling cosmic ray density. Therefore, the correlation with redshift is more a proxy of the dependence on the galactic age where ULIRGs are galaxies selected across redshifts but at a similar time in their evolution. Thus, the temperature dependencies introduced and tested on a specific subsample of ultra-luminous galaxies still yield physically intuitive fits.

3.5 Galactic properties

We will now turn our attention towards how a variable IMF would impact inferred galactic properties. The theoretical spectra created with FSPS contains galactic parameters as inputs. Extracting these parameters, propagating them into the new basis, and propagating it through the linear combinations EAZY derived allows the determination of the best fit galactic properties of all the photometric observations. Mapping these across the temperature variations, we can investigate how varying the IMF would change inferred quantities which can be seen in Fig. 9.

First of all, the current star formation rate monotonically decreases as the IMF becomes progressively top-heavier. Star formation happens at all stellar masses, but because larger stars have shorter lifespans a larger current star formation rate increases the ratio of O-stars to less massive stars. Another way to create relatively more O-stars is by using a top-heavier IMF. Therefore, an increase in temperature requires less star formation to fit the observations. Conceptually the relation between SFR and temperature is to be expected as a hotter cloud of gas has a larger pressure. If the internal pressure of the cloud is larger, then it is less likely to collapse and fewer stars will be formed. Additionally, as can be seen in Fig. 9 the range in SFR between the lower and upper quartile

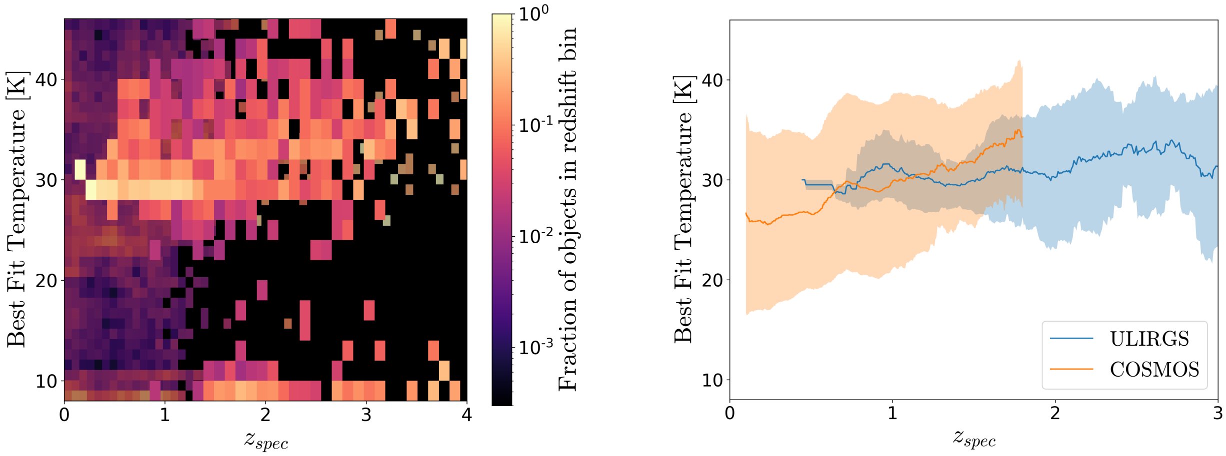


Figure 8: Left: Best fit temperature from 8-50 K versus spectroscopic redshift for a sample of ULIRGs overlayed on previously analysed galaxies. Note that ULIRGs are generally top-heavier than a Milky Way IMF with temperatures similar to the population of galaxies with a top-heavy IMF (seen in Fig. 4). Right: Mean and spread of best-fit temperatures at different spectroscopic redshift for ULIRGs and COSMOS galaxies. ULIRGs have no clear redshift dependence in contrast to the COSMOS galaxies examined previously. The ULIRGs seem to be a distinct population of galaxies in the best-fit gas temperature versus redshift diagram.

is very narrow compared to other galactic properties. This illustrates the tight correlation between the IMF and the SFR with the star formation rate dependence on temperature being constrained.

The inferred mass also drops with increasing temperatures, but surprisingly plateaus after 25 K. The decrease of mass with temperature also makes sense, as respectively the luminosity and mass is dominated by the upper and lower end of the mass distribution. Making the IMF more top-heavy increases the luminosity relative to the mass. Thus, for a measured luminosity less mass is inferred. It should be noted that the galactic parameters are inherently very degenerate, so perhaps the plateau is a feature of the rapidly decreasing SFR.

Metallicity decreases with temperature up to around 25 K and beyond this point the metallicity varies widely with most galaxies increasing in metallicity. Metallicity influences the SED in complicated ways which might explain the great variability in Z(T). In general increasing the metallicity contributes to an overall reddening of the SED [25]. Making the IMF more top-heavy and therefore more blue can be offset with increased metallicity. Furthermore, physically massive stars lead to more metals being produced more rapidly and because of the short lifetimes of large stars, these star quickly throw the metals produced out into the interstellar medium. Therefore, a top-heavier IMF should result in an increased metallicity.

The dust extinction, measured as the absorption of electromagnetic radiation of dust in magnitudes, declines slightly. As dust is constrained by the luminosity in infrared [25], not the optical and ultraviolet wavelengths that our variable IMF changes, dust extinction is not very sensitive to the IMF. Finally, the age remains constant throughout the temperature range. This is encouraging as galaxies within the sample extend to an age of about 10 billion years, thus possible making anything significantly older exceed the current age of the universe. However, as

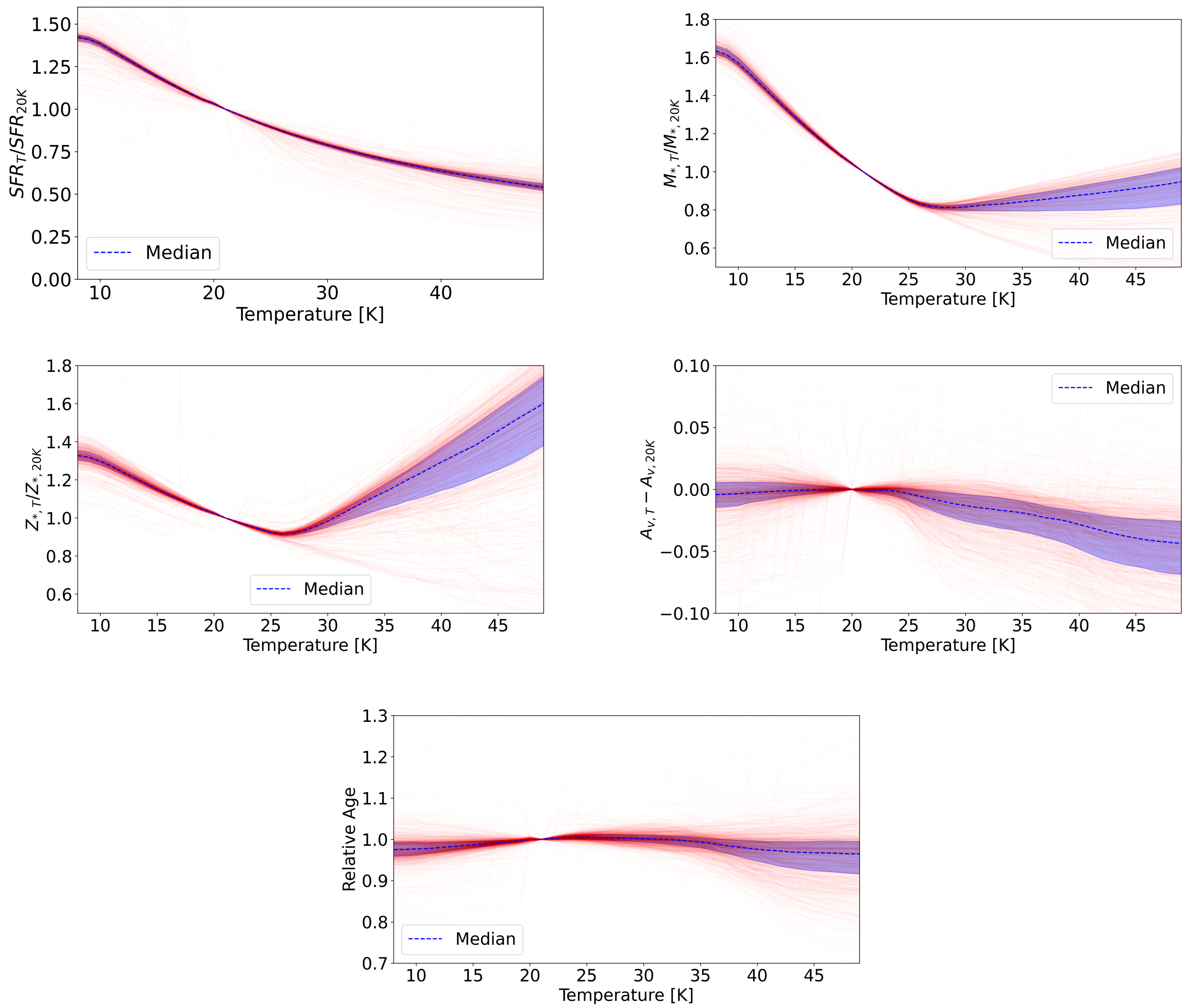


Figure 9: Best fit star formation rate (SFR), stellar mass (M), metallicity (Z), dust extinction (A_v) and age of the individual fitted galaxies [in red] as a function of temperature relative to 20 K. The blue dashed line is the median with shading indicating 1st and 3rd quartile. SFR decrease monotonically with increasing temperature as we would expect from a top-heavier IMF, while stellar mass plateaus at 25 K indicative of a possible co-variance between mass and SFR. Additionally, the inferred age and dust extinction remain relatively stable.

seen in 9 the new fits are not creating additional impossible old galaxies.

Probing the IMF with another basis for EAZY that is worse at spanning the space of spectra yields similar results as in §§ 3.1, 3.2 and 3.3. However, the inferred galactic properties differ from Fig. 9 with the stellar mass decreasing monotonically and no systematic changes in all other inferred properties. While this other basis reveals the robustness of previous results it also underscores the degeneracy between all other inferred parameters. In short, the inferred gas temperature displays complicated co-variances with other galactic parameters though the dependencies occur in a physically predictable fashion.

4 Discussion

The approach presented in this thesis provides the first step in a new methodology testing the universality of the IMF by using ensembles of galaxies. With this we have presented a new probe of the IMF, but understanding this variance requires examining our assumptions.

The paradoxical nature of attempting to disprove the universality of a Milky Way IMF is that we need to make the key assumption that a single IMF can describe individual galaxies. As discussed in § 2.2 assuming a monolithic nature within galaxies is standard within astronomy simply because we do not have the spatial resolution to separate star forming regions in galaxies. Further, increasing the complexity of this issue is that the temperature determining the IMF is the temperature at the time of star formation which might vary with time. For instance as stellar population ages or the cosmic ray density falls there will be less heating of the cold gas. As the gas cools the IMF will become progressively bottom-heavier. The importance of the temporal variations in IMF will naturally depend upon the speed stellar clouds change temperature but also the timescale in which star formation takes place. Both these temporal and spatial variations could and should be explored in further works.

However, it should also be stressed that the spectral features indicating a variable IMF may not originate only from variations in temperature. Although this thesis is based on previous theoretical predictions on relations between the Jeans mass and temperature, simulations have predicted an additional dependence on density of star-forming clouds in the fragmentation mass [1]. This is intuitive as a larger density exerts a larger gravity with clouds collapsing at smaller scales. With the methodology presented here there is no way to break the degeneracy between density and temperature. However, we did see in section 3.1 that a series of independent predictions of a temperature variable IMF were present.

That inferred gas temperatures follow the predictions of stellar population feedback and observed dust temperatures should be explored in further research. For example, do galaxies above and below the star-forming main sequence exhibit respectively higher and lower gas temperatures similar to measurements of dust [12]? Do quiescent, star-forming or starbursty galaxies exhibit systematically different temperatures as might be expected from their different large-scale evolution? These sub-samples will reveal potential selection-biases within the catalog used in this thesis, while using physical sub-samples will not only test the physics of our variable IMF, but also probe the different mechanisms causing these variation.

A temperature-dependent IMF would provide a potent probe of galactic features. The specific functional form of the variations would yield powerful theoretical insights into star formation. However any variable IMF requires that many observed and inferred properties [as shown in section 3.5] need to be revised including especially star-formation rate and stellar mass. Thus, as suggested in previous research [7] this might alleviate the tension of the impossible early galaxies, which is a population of very early and very luminous galaxies revealed in recent high-redshift surveys. Photometry infers that these galaxies masses should be greater than seen in simulations with halos too massive to have formed on the timescale available at their redshifts [26]. However, the inferred mass is set by the luminosity which comes from more massive stars, while the actual mass is set by the low mass stars. A top-heavier IMF would have more O-type stars relative to smaller stars than expected from a Milky Way IMF and therefore a smaller mass than inferred. However, if the inferred mass truly plateaus after 35 K, this would not resolve the tension. Indeed as we saw in § 3.5 typically the predicted age does not change with temperature, thus the impossible early galaxies should remain unsolved. However, further potential research could investigate the consequences of the IMF variations we have tested on specifically the impossible early galaxies.

Finally, a temperature-dependent IMF might yield complex feedback mechanisms with the stellar population as a whole. A hot and top-heavy IMF would produce more massive stars which heat gas more than less massive stars. This would result in an even top-heavier IMF, which would heat up the gas further and so forth. However, this runaway solution competes with another effect. Higher temperatures might result in overall fewer collapsing clouds and thus fewer stars. Therefore a hotter gas might drive down star-formation, which in turn results in fewer stars and less heating of the clouds. The gas will then cool and star formation can once more take place. This equilibrium solution has previously been suggested to be the cause of the star-forming main sequence [11]. Thus, understanding star-formation, the feedback of gas-temperatures and the role of the IMF might yield important steps towards understanding the remarkably similar properties of galaxies on large scales.

5 Conclusion

In conclusion, we have shown that theoretical predictions for a temperature-dependent stellar initial mass function yield superior fits on photometric observations with every available diagnostic indicating the viability of these new fits. The χ^2 decreases, the photometric redshifts remain reliable and other inferred galactic parameters behave in physically predictable manner. Furthermore, we have proven that the spectral features associated with a variable IMF indeed differ between galaxies fitted at different temperatures by stacking the photometry. Thus, this thesis questions the global universality of the stellar IMF suggesting that IMF becomes progressively top-heavier with increased temperature.

Indeed mapping the best-fit temperature for 23.000 COSMOS-galaxies up to a redshift of 1.8 indicates that the typical temperature of star forming clouds grows with increasing redshifts. This agrees both with theoretical predictions of the feedback mechanism of stellar populations and observations of dust temperatures. However, this redshift-dependence is not observed in a sample of luminous galaxies as these galaxies are at similar stage in their evolution. Additionally, it predicts a Milky Way IMF as being typical in the most local universe. Lastly, we have shown that changing the initial mass functions impacts many inferred galactic properties. A top-heavier IMF leads to a smaller star formation rate and inferred mass, while changes to the IMF do not significantly change either the age or dust extinction of a galaxy.

The methodology presented in this thesis opens new opportunities in studying the IMF. With further research potentially unlocking the secrets of star-formation, changing inferred properties and exploring the macroscopic galactic similarities of galaxies. Therefore, this methodology should be verified, extended and tested further, so we can constrain these systematic variations of the stellar initial mass function.

References

[1] Bonnell, I. A., Larson, R. B. & Zinnecker, H. The Origin of the Initial Mass Function. In Reipurth, B., Jewitt, D. & Keil, K. (eds.) *Protostars and Planets V*, 149 (2007). `astro-ph/0603447`.

[2] Conroy, C. & van Dokkum, P. G. The Stellar Initial Mass Function in Early-type Galaxies From Absorption Line Spectroscopy. II. Results. **760**, 71 (2012). `1205.6473`.

[3] Low, C. & Lynden-Bell, D. The minimum Jeans mass or when fragmentation must stop. **176**, 367–390 (1976).

[4] Bonnell, I. A. *Competitive Accretion and the IMF*, vol. 327 of *Astrophysics and Space Science Library*, 425 (2005).

[5] Salpeter, E. E. The Luminosity Function and Stellar Evolution. **121**, 161 (1955).

[6] Böhm-Vitense, E. *Introduction to Stellar Astrophysics* (1992).

[7] Jermyn, A. S., Steinhardt, C. L. & Tout, C. A. The cosmic microwave background and the stellar initial mass function. **480**, 4265–4272 (2018). `1809.03502`.

[8] Kroupa, P. On the variation of the initial mass function. **322**, 231–246 (2001). `astro-ph/0009005`.

[9] Jeans, J. H. The Stability of a Spherical Nebula. *Philosophical Transactions of the Royal Society of London Series A* **199**, 1–53 (1902).

[10] Schnee, S., Li, J., Goodman, A. A. & Sargent, A. I. Dust Emission from the Perseus Molecular Cloud. **684**, 1228–1239 (2008). `0805.4215`.

[11] Steinhardt, C. L., Jermyn, A. S. & Lodman, J. Thermal Regulation and the Star-forming Main Sequence. **890**, 19 (2020). `1909.12303`.

[12] Magnelli, B. *et al.* The evolution of the dust temperatures of galaxies in the sfr-mane up to z 2. *A&A* **561**, A86 (2014). URL `https://doi.org/10.1051/0004-6361/201322217`.

[13] Béthermin, M. *et al.* Evolution of the dust emission of massive galaxies up to z = 4 and constraints on their dominant mode of star formation. **573**, A113 (2015). `1409.5796`.

[14] Casey, C. M. Far-infrared spectral energy distribution fitting for galaxies near and far. **425**, 3094–3103 (2012). `1206.1595`.

[15] Cortzen, I. *et al.* Deceptively cold dust in the massive starburst galaxy GN20 at z $\sim$ 4. **634**, L14 (2020). `2002.02974`.

[16] Magdis, G. E. *et al.* Dust and gas in star-forming galaxies at z 3. Extending galaxy uniformity to 11.5 billion years. **603**, A93 (2017). `1705.06296`.

[17] Hopkins, P. F. The stellar initial mass function, core mass function and the last-crossing distribution. **423**, 2037–2044 (2012). `1201.4387`.

[18] Jappsen, A. K., Klessen, R. S., Larson, R. B., Li, Y. & Mac Low, M. M. The stellar mass spectrum from non-isothermal gravoturbulent fragmentation. **435**, 611–623 (2005). `astro-ph/0410351`.

[19] Conroy, C. & Gunn, J. E. The Propagation of Uncertainties in Stellar Population Synthesis Modeling. III. Model Calibration, Comparison, and Evaluation. **712**, 833–857 (2010). `0911.3151`.

[20] Conroy, C., Gunn, J. E. & White, M. The Propagation of Uncertainties in Stellar Population Synthesis Modeling. I. The Relevance of Uncertain Aspects of Stellar Evolution and the Initial Mass Function to the Derived Physical Properties of Galaxies. **699**, 486–506 (2009). `0809.4261`.

[21] Brammer, G. B., van Dokkum, P. G. & Coppi, P. EAZY: A Fast, Public Photometric Redshift Code. **686**, 1503–1513 (2008). `0807.1533`.

[22] Dahlen, T. *et al.* A Critical Assessment of Photometric Redshift Methods: A CANDELS Investigation. **775**, 93 (2013). `1308.5353`.

[23] Laigle, C. *et al.* The COSMOS2015 Catalog: Exploring the 1 < z < 6 Universe with Half a Million Galaxies. **224**, 24 (2016). `1604.02350`.

[24] Lonsdale, C. J., Farrah, D. & Smith, H. E. *Ultraluminous Infrared Galaxies*, 285 (2006).

[25] Conroy, C. Modeling the panchromatic spectral energy distributions of galaxies. *Annual Review of Astronomy and Astrophysics* **51**, 393–455 (2013). URL `https://doi.org/10.1146/annurev-astro-082812-141017`. `https://doi.org/10.1146/annurev-astro-082812-141017`.

[26] Steinhardt, C. L., Capak, P., Masters, D. & Speagle, J. S. The Impossibly Early Galaxy Problem. **824**, 21 (2016). `1506.01377`.