THE PROPAGATION OF UNCERTAINTIES IN STELLAR POPULATION SYNTHESIS MODELING II: THE CHALLENGE OF COMPARING GALAXY EVOLUTION MODELS TO OBSERVATIONS

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ABSTRACT

Models for the formation and evolution of galaxies readily predict physical properties such as the star formation rates, metal enrichment histories, and, increasingly, gas and dust content of synthetic galaxies. Such predictions are frequently compared to the spectral energy distributions of observed galaxies via the stellar population synthesis (SPS) technique. Substantial uncertainties in SPS exist, and yet their relevance to the task of comparing galaxy evolution models to observations has received little attention. In the present work we begin to address this issue by investigating the importance of uncertainties in stellar evolution, the initial stellar mass function (IMF), and dust and interstellar medium (ISM) properties on the translation from models to observations. We demonstrate that these uncertainties translate into substantial uncertainties in the ultraviolet, optical, and near-infrared colors of synthetic galaxies. Aspects that carry significant uncertainties include the logarithmic slope of the IMF above $1 M_\odot$, dust attenuation law, molecular cloud disruption timescale, clumpiness of the ISM, fraction of unobscured starlight, and treatment of advanced stages of stellar evolution including blue stragglers, the horizontal branch, and the thermally-pulsating asymptotic giant branch. The interpretation of the resulting uncertainties in the derived colors is highly non-trivial because many of the uncertainties are likely systematic, and possibly correlated with the physical properties of galaxies. We therefore urge caution when comparing models to observations.

Subject headings: galaxies: evolution — galaxies: stellar content

1. INTRODUCTION

Models for the formation and evolution of galaxies have become dramatically more sophisticated over the past decade. These models span a variety of techniques, including the semi-analytic approach, which couples dark matter halo merger trees to analytic recipes for the evolution of the baryons (e.g. White & Frenk 1991; Kauffmann et al. 1999), and cosmologically-embedded hydrodynamic simulations, which numerically follow the evolution of dark matter and baryons self-consistently, with numerical recipes encompassing unresolved physical processes such as star formation, black hole growth, stellar and black hole feedback, etc (e.g. Cen & Ostriker 1992; Katz et al. 1996; Kereš et al. 2005).

The primary predictions of these models include quantities such as the total mass in stars, star formation and metal enrichment histories, and, in some cases, information on cold gas properties. Unfortunately, these quantities are not directly available to extragalactic observers. Instead, these physical quantities are often transformed into observable spectral energy distributions via stellar population synthesis (SPS) techniques (e.g. Tinsley & Gunn 1976; Bruzual 1983; Renzini & Buzzoni 1986; Worthey 1994; Fioc & Rocca-Volmerange 1997; Maraston 1998; Vazdekis 1999). For many applications, SPS thus provides the bridge between models and observations.

Until now, little attention has been paid to the uncertainties in the SPS technique in the context of translating galaxy formation model predictions into observables. And yet uncertainties in advanced stages of stellar evolution, stellar spectral libraries, the stellar initial mass function, and the adopted model for the obscuring effects of interstellar dust can each be significant components of the total error budget on the predictions.

Modeling of the attenuation of starlight by dust is a particularly challenging aspect in the SPS technique. Such models fall into roughly two categories. On the one hand there are approaches that use physical models for the properties of grains (e.g. Weingartner & Draine 2001), coupled to assumptions about the geometry of the dust with respect to the stars (e.g. Silva et al. 1998; Devriendt et al. 1999; Gordon et al. 2001; Tuffs et al. 2004; Jonsson 2006). These models rely on radiative transfer calculations and are therefore computationally expensive. Their computational cost has given rise to the second class of models, which are physically-motivated, but are in essence phenomenological. Models of the second class typically adopt an attenuation curve with a normalization, and, in principle, shape, that depends on the age of the system (e.g. Charlot & Fall 2000). This effective attenuation curve is then applied uniformly to all stars of a given age.

Common to both approaches is the fact that the required inputs are in many cases seriously underconstrained. An accurate dust model requires knowledge of the grain composition and size distribution, and the wavelength-dependence of the grain albedo (Draine 2003), yet these quantities are extremely difficult to constrain in the Galaxy (e.g. Weingartner & Draine 2001), let alone in external systems. It is expected that grain properties will be functions of metallicity and the local intensity of ultraviolet radiation — in addition to other variables — both of which will vary from galaxy to galaxy. The geometry of the dust, including large-scale inhomogeneities and the proximity of the dust to the stars, is not known at all outside of the Local Group, and not known with the requisite precision in our own Galaxy. Yet the geometry of dust has a substantial effect on the net attenuation of starlight. The lifetime of molecular clouds is another important parameter because it controls the length of time that young stars are heavily dust obscured, and yet this timescale is not known to better than an order of magnitude, and will likely depend on quantities...
such as metallicity and local star formation rate (Blitz & Shu 1980; McKee & Ostriker 2007).

Fontanot et al. (2009) have recently compared a physical dust model that employs radiative transfer to simple phenomenological prescriptions. These authors find substantial differences between the analytic calculations and the more complex physical dust model. While comparisons of this type are essential for informing analytic prescriptions, our belief is that the physical dust models themselves are sufficiently uncertain to warrant a flexible approach to the obscuring effects of dust.

Uncertainties in stellar evolution calculations can impact the translation from models to observables (e.g. Tinsley 1980; Charlot et al. 1996; Charlot 1996; Lee et al. 2007; Yi 2003; Conroy et al. 2008). Recently, Tonini et al. (2009) has investigated the impact of the thermally–pulsating asymptotic giant branch (TP–AGB) phase on the observational predictions of a semi–analytic galaxy evolution model. They compare a popular SPS model that does not include the TP–AGB phase of stellar evolution to the model of Maraston (2005) where this important but uncertain phase is handled with care. These authors find that the near–IR colors of model galaxies can differ by as much as two magnitudes between the two SPS models, and that the differences increase with redshift. These results highlight the importance of carefully accounting for uncertain aspects of SPS when translating galaxy formation model predictions into observables.

In the present work we extend the spirit of Tonini et al. by considering a broader array of uncertainties in stellar evolution, uncertainties in the stellar initial mass function (IMF), and the substantial uncertainties associated with the treatment of interstellar dust. We focus on two synthetic galaxies drawn from a recent semi–analytic model of galaxy evolution. These galaxies were chosen to represent a typical bright star–forming galaxy and a typical bright passively evolving galaxy, both at z = 0. For the purposes of this work, the main difference between these two types of galaxies is the presence or absence of young, hot stars.

This paper continues with §2 where we discuss the salient ingredients of SPS, including a detailed description of our dust treatment. §3 briefly describes the synthetic galaxies and the semi–analytic model from which they are derived. §4 contains our main results, where we investigate the uncertainties in the predicted UV, optical, and near–IR colors of synthetic galaxies due to uncertainties in SPS. Following this sobering assessment, in §5 we comment on several implications. A summary is provided in §6. All magnitudes are in the AB system (Oke & Gunn 1983).

2. STELLAR POPULATION SYNTHESIS

Our SPS treatment closely follows that of Conroy et al. (2008), to which the reader is referred for details. In brief, the SPS code uses the latest stellar evolution tracks from the Padova group (Marigo & Girardi 2007; Marigo et al. 2008), which follow stellar evolution from the main–sequence through the thermally–pulsating asymptotic giant branch (TP–AGB) phase. Evolutionary calculations exist for metallicities in the range 10^{-4} < Z < 0.030, for ages 10^{6.6} < t < 10^{10.2} yrs, and for initial masses 0.15 ≤ M ≤ 100 M⊙. The stellar spectral libraries are primarily those of the empirically–calibrated theoretical BaSeL3.1 library (Lejeune et al. 1997, 1998; Westera et al. 2002), supplemented with empirical TP–AGB spectra from the library of Lançon & Mouchet (2002). The initial stellar mass function (IMF) of Kroupa (2001) is adopted. Our SPS code is open–source and publicly available at www.astro.princeton.edu/~conroy/SPS/.

We seek to assess the importance of uncertainties in SPS in translating the predictions of galaxy evolution models into observables. In our approach we will focus on two distinct classes of uncertainties. The first class are uncertainties in the single stellar populations (SSP) resulting from isochrone synthesis, including both the stellar evolution tracks and the IMF. The second class concerns the treatment of reddening by interstellar dust.

2.1. SSP uncertainties

2.1.1. Stellar evolution (isochrone) uncertainties

Uncertainties in the isochrones are quantified as in Conroy et al. (2008). The position of TP–AGB stars in the HR diagram is substantially uncertain, both observationally and theoretically. We thus introduce two variables that amount to shifts in log(T_eff) and log(L/Lo) with respect to the default stellar evolution tracks: ΔT and ΔL, respectively. As discussed in Conroy et al. (2008), these variables effectively encompass uncertainties not only in the stellar evolution tracks but also uncertainties in the associated spectral energy distributions and circumstellar dust enshrouding these stars. Since these stars have relatively low effective temperatures, they contribute substantially to integrated spectra only at λ ≥ 7000Å.

Blue straggler (BS) stars and blue horizontal branch (BHB) stars are almost universally neglected when translating galaxy evolution models into observables, although their importance has been demonstrated when modeling observed spectra (e.g. Jimenez et al. 2004; Maraston 2005; Li & Han 2008; 2009; Conroy et al. 2008). We introduce two additional parameters to quantify these uncertain stellar phases: the specific frequency of BSs, S_{BS}, defined as the number of BSs per unit HB star, and the fraction of HB stars that are blue, f_{BHB}. In this context a blue HB star is any HB star extending blueward of the red clump identified in standard stellar evolution tracks. In our treatment this extended blue component is populated uniformly in log(T_eff) from the red clump to T_eff = 10^4 K.

It is important to realize that these parameters can be age–dependent. The most likely candidate for age–dependence is the blue straggler frequency. While the origins of the blue straggler population are contested, a likely mechanism is the coalescence of binary star systems (McCrea 1964; Knigge et al. 2009). If this scenario is correct, or at least the source of a substantial fraction of blue stragglers, then it is reasonable to assume that the blue straggler population in a coeval set of stars would diminish as the system and destroys its binary population. A dearth of a blue straggler signature in galaxies dominated by old stars may thus not imply a dearth in younger systems. We do not allow for any of these parameters to be age–dependent herein, but note that one may interpret a given parameter value as being representative of some effective population age.

2.1.2. IMF uncertainties

We will also explore the importance of the logarithmic slope of the IMF on the derived colors of galaxies. It is widely understood that the IMF has a significant impact on the mass–to–light ratio of galaxies, but it’s impact on the broad–band colors of galaxies is less appreciated (or rather, has become less appreciated with time, see e.g. Tinsley 1980). It is important to consider the influence of the IMF on the translation
between models and observations because of the difficulty in measuring the IMF in the solar neighborhood, let alone in external galaxies.

For example, Kroupa (2001) compiled a number of observations of the logarithmic slope of the IMF in the solar neighborhood and found $\alpha = 2.3 \pm 0.7$ for $m > 1M_\odot$, at 99% confidence, where the IMF is parameterized as $\xi(m) \propto m^{-\alpha}$. It is important to realize that this uncertainty is only statistical. As discussed by Kroupa (2001), corrections due to unseen binary companions will depend on $\alpha$, and will result in an increase in $\alpha$ of the order of 0.3, depending on the details of the binary companions. Further complications arise near $1M_\odot$ because the observational techniques for determining the IMF at this mass regime rely on star counts in the field. At $\sim 1M_\odot$ the stellar lifetime is of order the age of the Galactic disk, and so evolutionary corrections, which are substantial, rely on a detailed knowledge of the star formation history of the disk. The uncertainty on $\alpha$ at $\sim 1M_\odot$ is so large that data points near $1M_\odot$ are often excluded from fits (Kroupa 2001).

The physical conditions of the Universe relevant to star formation were very different at higher redshift, including higher ISM pressures (Liu et al. 2008), lower metallicities (Erb et al. 2006), and higher CMB temperatures. The latter will start to effect the fragmentation and collapse of gas around $z \sim 5$ (Larson 2005). Some authors have suggested that these conditions will result in a top–heavy (or bottom–light) IMF at earlier times, owing essentially to a larger Jeans mass (e.g. Larson 1998, 2005). Recent observational evidence, including the abundance patterns of metal–poor stars in the Milky Way (Lucatello et al. 2003; Tumlinson 2007), evolution in the fundamental plane (van Dokkum 2008), and a comparison between the cosmic mass density evolution and star formation rate density evolution beyond $z \sim 2$ (Davé 2008), is beginning to support this picture, however tentatively (for an alternative, less exotic explanation of the last point, see Reddy & Steidel 2009).

Recent observational results in the local Universe has also pointed toward an IMF that varies with environment. Meurer et al. (2009) recently demonstrated that the ratio between H$\alpha$ flux and near-UV luminosity varies systematically with galaxy surface brightness. This ratio should be constant for a universal IMF. The data can be explained by an IMF slope at high masses that varies over the range $1.5 < \alpha < 4.0$, or by a systematically varying upper mass cut–off over the range $\approx 20 < M_{\text{up}} < 100M_\odot$.

We follow Kroupa (2001) in the parameterization and best–fit logarithmic slopes of the IMF. In the following sections we will explore the effects of varying the IMF only for masses $> 1M_\odot$.

2.2. Dust treatment

We now turn to the treatment of dust in the SPS technique. Since we are interested in restframe wavelengths bluer than 2.4$\mu$m, we do not model the reprocessing of radiation by dust; we only attempt to model its obscuring effects.

The light emerging from a galaxy can be modeled as

$$F_\lambda(t) = \int_0^\infty \Psi(t-t')S_\lambda(t', Z(t-t')) e^{-\tau_\lambda(t')} dt',$$

where $\Psi$ is the SFR, $S_\lambda$ is the SSP spectrum, $F_\lambda$ is the resulting composite spectrum, $\tau_\lambda$ is the optical depth, and the integration variable is the age of stellar populations. Note that this formulation allows for metallicity evolution with time.

The obscuring effects of dust are encompassed in the optical depth $\tau_\lambda(t)$. A toy model for the effective optical depth was presented in Charlot & Fall (2000) and has since become quite popular. The physical motivation for their model is the following. Stars are born in molecular clouds and thus the light from young stars is heavily attenuated by dust in the cloud. At later times the stars will no longer experience attenuation due to their birth cloud, either because they will have wandered out of the cloud, or because the cloud will have evaporated. Stars are thus subject to attenuation that varies with time — young stars are obscured by the dense molecular clouds in which they form, while the light from older stars is attenuated by the diffuse ISM. Motivated by this physical picture, the optical depth is parameterized as:

$$\tau_\lambda(t) = \begin{cases} \tau_1(\lambda/5500\AA)^{-\delta_1} & t \leq t_{\text{esc}} \\ \tau_2(\lambda/5500\AA)^{-\delta_2} & t > t_{\text{esc}}, \end{cases}$$

where $t_{\text{esc}}$ is the timescale over which young stars reside in their natal clouds. While there is ample evidence that the extinction curve slope depends on environment (e.g. Mathis 1990), herein we fix $\delta_1 = \delta_2 = \delta$, which has become a common assumption (e.g. Charlot & Fall 2000). Charlot & Fall (2000) advocate $\delta = 0.7$, $\tau_1 = \tau_2 = 7.0$, $\tau_1 = 1.0$, and $\tau_2 = 0.3$, although it is clear from their own figures that these parameters may plausibly vary over a wide range. We choose to leave these parameters free with a range motivated by a variety of data (see discussion in [23]).

In reality each of the parameters $\tau_1, \tau_2, \delta, \text{and } t_{\text{esc}}$ will take on a range of values for a given galaxy. For example, $\tau_1$ will depend on the location of the young star cluster with respect to the molecular cloud within which it’s embedded. If the stars are born near the edge of the cloud, as is often observed within the Galaxy (Israel 1978), then $\tau_1$ will depend strongly on the relative orientation of the observer with respect to the star cluster—cloud configuration. A more accurate dust model would therefore allow for a distribution in each of these quantities. Owing to the non–linear relation between these parameters and the resulting galaxy spectrum, the use of distributions rather than a mean values will have important consequences. These issues will be considered in detail in future work; in the present work we consider only mean values.

The optical depth associated with the diffuse ISM, $\tau_2$, will be handled separately. Many treatments of dust attenuation adopt the reasonable assumption that the optical depth of dust is proportional to the column density of metals (e.g. Guiderdoni & Rocca-Volmerange 1987). Of the parameters listed above, $\tau_2$ is therefore the parameter most readily predicted by galaxy evolution models. In our main results, we therefore choose not to marginalize over this important parameter. It must be noted, However, that this parameter is not at all easily or reliably predictable in the majority of galaxy evolution models owing to the enormous dynamic range required to adequately resolve the relevant physical processes leading to the production of metals. And, even if the quantity and spatial distribution of metals are accurately predicted, the relationship between metals and dust is in reality quite

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1 This is one of the dust models provided in the popular Bruzual & Charlot (2003) SPS code, and therefore is a standard dust model for many investigators.

2 In future work we will investigate this assumption in detail. For the present work, we are interested in quantifying the uncertainties associated with the dust model, and so it matters little if we vary $\delta_1$ and $\delta_2$ separately or in conjunction.
complex owing to the variety of heating and cooling processes in the ISM relevant for dust formation and destruction.

The attenuation law required in our formulation represents the net fraction of starlight photons removed by dust, as seen by a distant observer. It is different than true extinction, which quantifies the fraction of photons removed along the line of sight to a single star. The difference is due to both true absorption and scattering, while attenuation is primarily true absorption. In other words, while photons from a single star may be scattered out of the line of sight to an observer, when viewing an entire galaxy those scattered photons will on average (depending on geometry) be seen by a distant observer. We measure extinction in the Milky Way and Magellanic Clouds, but require attenuation when applying dust corrections to external galaxies, and therefore require accurate knowledge of the net scattering effects of dust. See Calzetti (2001) for detailed discussion of these and related issues.

It is well-known that the Milky Way and Magellanic Cloud extinction curves are approximately a one parameter family (Cardelli et al. 1989; Fitzpatrick 1999). In the optical and near-IR these curves are well-characterized by a power-law. The net attenuation in local starburst galaxies is also approximately a power-law from the far-UV to $\approx 1\mu$m (Calzetti et al. 1994, 2000). Motivated by these observational results, we have adopted a power-law attenuation law in our dust model. For the purposes of this paper it is not essential that our parameterization provide the most accurate reflection of the underlying attenuation curve; rather, it is important only that the parameterization be flexible enough to encompass the uncertainties, or variations, in the attenuation law. Or, put differently, for our purposes we are primarily interested in an accurate parameterization of the variance, and not the mean, of the attenuation law.

There is an additional feature in the Galactic and Magellanic Cloud extinction curves that deserves mention. The strong, broad absorption feature at 2175Å is ubiquitous in the Galactic and LMC extinction curves, and has even been detected at $\approx 2$ (Noll & Pierini 2005; Elíasdóttir et al. 2008; Noll et al. 2009). It is however conspicuously absent in local starbursts (Calzetti et al. 1994) and through most sightlines of the SMC (Pei 1992). It is thought that this feature is due to polycyclic aromatic hydrocarbons (Draine 2003), and that it may vary with local environment and star formation rate (Gordon et al. 2003).

This feature happens to lie within the GALEX NUV band for low-redshift galaxies. Its presence or absence can change the attenuation in the NUV band by a magnitude or more. We do not consider the uncertainties associated with this feature herein, but simply note that including it would likely double the resulting uncertainties in the NUV band. Future work will consider this issue in further detail.

2.2.1. Large-scale dust distribution

The prescription described above assumes that stellar populations are obscured by a uniform screen of dust. In reality, one expects the large-scale diffuse ISM to exhibit considerable variation. This effect is important because a clumpy ISM will result in a lower effective optical depth compared to a uniform screen, for the same total amount of gas and dust. Moreover, the effect of clumpiness is wavelength-dependent, implying that the clumpiness of the ISM cannot be treated as a simple modulation of $\tau_{2}$ (Natta & Panagia 1984; Witt & Gordon 1996). An accurate accounting of the large-scale inhomogeneities of the ISM is therefore a crucial element of any dust model (e.g. Bruzual A., et al. 1988; Witt et al. 1992; VárÓsi & Dwek 1999; Witt & Gordon 2000; Gordon et al. 2001; Jonsson 2006). We now describe our treatment of a clumpy ISM.

We define $n$ as the density enhancement of the ISM along a given sightline, relative to a uniform screen. Then Equation[1] becomes:

$$F_{n}(t) = \int_{0}^{t} \int_{0}^{\infty} P(n) e^{-\tau_{2}(t')} \Psi(t-t') S_{\lambda}(t', Z(t-t')) dt' dt,$$

where $P(n)$ is the probability that an SSP is behind a column of dust enhanced by a factor $n$ relative to the uniform screen. The above relation holds as long as the optical depth is proportional to the column density of dust.

We do not modify the treatment of obscuration around young stars where $t < t_{esc}$. Therefore:

$$P(n) = \begin{cases} \delta(n-1) & t \leq t_{esc} \ \text{yr} \\ \frac{P_{2}}{P_{2}} & t > t_{esc} \ \text{yr}, \end{cases}$$

where $\delta(x)$ is the Dirac delta function.

There is a constraint that must be satisfied for $P_{2}$:

$$\int \ n \ P_{2} \ dn = 1.$$

This equation ensures that the clumping of dust does not alter the total amount of dust in the galaxy.

The parameter $\tau_{2}$ takes on a somewhat different meaning in the context of a clumpy ISM. Formally, it describes the attenuation that would be experienced, were the ISM smoothed to a uniform screen. Physically, $\tau_{2}$ can be thought of as simply controlling the total dust mass in the galaxy — e.g., keeping $\tau_{2}$ fixed while varying $P_{2}$ implies that the total amount of dust is held constant, and only its spatial distribution is changed.

There are very few direct observational constraints on the column density distribution of gas and dust in the Galaxy, let alone in external systems. Berkhuisen & Fletcher (2008) have used pulsed emission and dispersion measures to probe the PDF of diffuse atomic gas in the solar neighborhood. They find that the distributions of column densities is consistent with lognormal with a dispersion of $\sim 0.3$. A lognormal distribution of column densities also naturally arises from simulations of turbulence in an isothermal ISM (Vázquez-Semadeni 1994; Scalo et al. 1998; Nordlund & Padoan 1999; Ostriker et al. 2001), with a width that scales with the Mach number. Fischer et al. (2003) attempt to fit the observed attenuation law derived by Calzetti et al. (2000) with a model that includes a clumpy ISM. Their best-fit values for the dispersion range from $0.6 < \sigma < 2.2$.

Motivated by these results, we adopt a lognormal PDF for the distribution of column densities (i.e. $P_{2}$ in Equation[5] is a Gaussian in the variable $log(n)$). Equation[5] implies a constraint on the relation between the mean and variance of a lognormal PDF that we fit with a fifth-order polynomial:

$$\mu \approx 0.0709 \sigma_{\text{clump}}^{2} + 1.68 \sigma_{\text{clump}}^{2} + 1.56 \sigma_{\text{clump}}^{3} + 1.96 \sigma_{\text{clump}}^{4} + 0.886 \sigma_{\text{clump}}^{5},$$

where $\mu \equiv \mu_{\log n}$ is the logarithmic mean and $\sigma_{\text{clump}}^{2}$ is the logarithmic variance. Note that our default assumption of a uniform distribution of dust is recovered in the limit where
Parameter ranges and priors

This section describes and motivates the adopted priors on each parameter. In all cases we will assume, for simplicity, that the prior distribution is flat between the minimum and maximum of the range.

- $\sigma_{\text{clump}} = 0$ (i.e. in this limit $P_2 = \delta(n-1)$). The dispersion characterizing the lognormal PDF is therefore the single variable controlling the clumpiness of the ISM in our model.

In reality one might expect the distribution of column densities to be more complex than lognormal. In the limit that dust lies at the mid–plane of a galactic disk (e.g. Dalcanton et al. 2004), fully one half of the disk stars will experience no attenuation. For galaxies that contain both a stellar bulge and disk, the majority of the bulge stars will also experience little or no attenuation, again under the assumption that most of the dust lies at the mid–plane of the disk. While we do not include these more realistic geometries in our general analysis, we will demonstrate in §4.1 that they can have a very important effect on the derived colors of synthetic galaxies.

2.3. Parameter ranges and priors

This section describes and motivates the adopted priors on each parameter. In all cases we will assume, for simplicity, that the prior distribution is flat between the minimum and maximum of the range.

- $\Delta_L$: Shift in log($L_{\text{bol}}$) with respect to the default evolutionary tracks of TP–AGB stars. There is a lack of data on the TP–AGB phase outside of the Galaxy and the Magellanic Clouds, making it very difficult to even specify a reasonable prior range for this parameter. We adopt the following conservative estimate: $-0.2 < \Delta_L < 0.2$, and refer the reader to Conroy et al. (2008) for motivation of this range.

- $\Delta_T$: Shift in log($T_{\text{eff}}$) with respect to the default evolutionary tracks of TP–AGB stars. As above, observational constraints are lacking for this parameter. We adopt the conservative range: $-0.1 < \Delta_T < 0.1$, and refer the reader to Conroy et al. (2008) for details.

- $f_{\text{BH}}$: Fraction of HB stars that are blueward of the red clump. It is well known that metal–poor globular clusters ([Fe/H] $\lesssim -1.4$) have extended HB morphologies (Harris 1996). In addition, there are several less metal–poor globulars ([Fe/H] $\approx -0.6$) with blue horizontal branches (Rich et al. 1997), and the most metal–rich Galactic star cluster known, NGC 6791, has $f_{\text{BH}} \approx 0.3$ (Kalirai et al. 2007). In our Galaxy, several percent of stars are metal–poor (Zoccali et al. 2003, 2008; Schoerck et al. 2008), while in elliptical galaxies the fraction may range from 1–10% (Worthey et al. 1996; Maraston & Thomas 2000). Dorman et al. (1995) demonstrated that the observed UV upturn in elliptical galaxies can be explained by 5–20% blue (extreme) horizontal branch fractions. Based on these results, we adopt $0 < f_{\text{BH}} < 0.2$.

- $S_{\text{BS}}$: Specific frequency of blue straggler stars, defined as the number of blue stragglers per unit horizontal branch star. Typical values for $S_{\text{BS}}$ range from 0.1–1.0 for globular clusters (Piotto et al. 2004). While much more challenging to measure, the frequency of blue stragglers in the field may be as high as five (Preston & Sneden 2000). We adopt the following range for $S_{\text{BS}}$, which will be high if blue stragglers only exist in globular clusters, but conservative if they originate from binary star systems, which are ubiquitous in the field: $0 < S_{\text{BS}} < 2$.

- $\alpha_{\text{IMF}}$: Logarithmic slope of the IMF above $1M_\odot$. Kroupa (2001) quote $\alpha_{\text{IMF}} = 2.3 \pm 0.7$ for $M > 1M_\odot$. The quoted uncertainties are $\pm \alpha$, statistical. However, as pointed out by Kroupa, the corrections to $\alpha$ due to unseen binary companions depends on $\alpha$ and is of the order of $0.3 - 0.4$. Moreover, direct constraints on the IMF come only from the Milky Way and Magellanic Clouds, while we require the IMF for star clusters of all ages and metallicities. In addition, there is increasing indirect evidence that the IMF was substantially different when the Universe was younger and in different environments at low redshift (for a summary, see Preston & Sneden 2000). For these reasons we adopt the range advocated by Kroupa, but we re–interpret his quoted uncertainty as a more modest $\pm 1\alpha$ range.

- $\delta$: Power–law index of attenuation curve. In a comparison to properties of local starbursts, Charlot & Fall (2000) find that the observations can be well–fit with $0 < \delta < 1.3$. The upper limit also corresponds to the Milky Way extinction curve in the optical and near-IR (Fitzpatrick 1999), while the lower limit roughly approximates the optical region of an extinction curve with $R = A_V/E(B-V) \approx 6$. Extinction curves with such high values of $R$ are seen along dense sightlines in the Galaxy. The attenuation law for local starbursts can be characterized by a power–law index of 0.9 from the UV to $\approx 1\mu\text{m}$ (Calzetti et al. 2000).

- $t_{\text{esc}}$: For star clusters, the transition timescale from birth clouds to the diffuse ISM. This transition occurs either because the birth cloud is destroyed (i.e. photoevaporated by O–type stars), or because the stars wander out of the cloud. The relative importance of these two processes is uncertain but will depend on the mass of the cloud, in addition to the local star
A variety of observational estimates both in the Galaxy and the Local Group suggest this parameter to be in the range $6.5 < \log(t_{\text{esc}}/\text{yrs}) < 7.5$ (Israel 1978; Williams & McKee 1997; Blitz & Shu 1980; Blitz et al. 2007; McKee & Ostriker 2007).

- $\tau_1$: Optical depth around young stars (where $t \leq t_{\text{esc}}$). Charlot & Fall (2000) found that a variety of data from starburst galaxies are bracketed by $0 \lesssim \tau_1 \lesssim 2$. Humphreys (1978) tabulated $V$–band optical depths for hundreds of supergiants and O–type stars in the Galaxy and found a rough range of $0.4 \lesssim \tau_1 \lesssim 3$. Observations of extragalactic HII regions find similar results (Israel & Kennicutt 1980; van der Hulst et al. 1988). We therefore adopt a range of $0.3 < \tau_1 < 1.5$ as a conservative range for this parameter.

- $\tau_2$: Optical depth around old stars (where $t > t_{\text{esc}}$). In the context of our dust model, this parameter may be considered as a proxy for the dust mass in a galaxy. In our total uncertainty budget, this parameter is not allowed to vary because, as discussed in §2.2, it may, with some degree of faith, be predicted in galaxy formation models from the surface–averaged column density of metals. We vary this parameter in Figure 2 only to provide intuition for its importance.

- $\sigma_{\text{clump}}$: Dispersion of the lognormal PDF characterizing the distribution of column densities of the ISM. Owing to the absence of constraining data beyond the solar neighborhood, we allow the $\sigma_{\text{clump}}$ to vary between $0.0 < \sigma_{\text{clump}} < 1.3$. The upper limit is set by the practical consideration that the effect of $\sigma_{\text{clump}}$ on colors tends to saturate near this value, and so allowing larger values has no effect on observables (see §4 for details). A value of 0.0 corresponds to a uniform screen of dust.

3. SYNTHETIC GALAXIES

As described in the Introduction, our goal is to investigate to what extent uncertainties in the SPS technique hamper the translation of synthetic galaxies into observables. The outputs of galaxy evolution models typically include star formation and metallicity–enrichment histories of galaxies, and, increasingly, information about the spatial distribution of gas as well.

We make use of the publicly–available milli–Millennium simulation database to query the outputs from the semi–analytic galaxy formation model of De Lucia & Blaizot (2007). This model couples analytic recipes for gas cooling, star formation, supernova feedback, AGN heating, galaxy merging and metal enrichment, to a large, cosmological, dissipationless $N$–body simulation (the ‘Millennium Simulation’ 3)

3 http://www.mpa-garching.mpg.de/millennium/
The details of their model do not concern us here — we are merely interested in extracting a realistic star formation and metal–enrichment history for a typical passive and star–forming galaxy. Note that spatial information on the scale of a galaxy is not available for the galaxy evolution model we consider, in particular the spatial distribution of the gas with respect to the stars is not a prediction of the model. This is generic to the class of models known as semi–analytic, and in contrast to modern cosmological hydrodynamic simulations. Of course, without this detailed spatial information it is extremely difficult to accurately account for the attenuation of starlight by dust.

The star formation and metal–enrichment histories for the two galaxies that we will consider are shown in Figure 1. Notice that the passive galaxy experienced the bulk of its star formation in the distant past (and has experienced no star formation in the past \( \approx 4 \) Gyr), while the star–forming galaxy has experienced multiple episodes of intense star formation super–imposed on a relatively quiescent level of star formation. Assuming a Kroupa (2001) IMF, the passive (star–forming) galaxy has a stellar mass at \( z = 0 \) of \( \log(M) = 11.1(10.9)M_\odot \).

4. RESULTS: UNCERTAINTIES IN TRANSLATING SYNTHETIC GALAXIES INTO OBSERVABLES

This section demonstrates the difficulty of translating the synthetic galaxies produced from galaxy evolution models into observables. Discussion is focused around three colors, one of each sensitive to the ultraviolet, optical, and near–infrared regions of the spectrum. We will first investigate the dependence of these colors on the parameters in our dust model, and then the parameters controlling the SSPs. We will then combine all uncertainties to demonstrate their net effect on the derived colors. Discussion is focused on broad–band filters available from the GALEX (Martin et al. 2005), SDSS (York et al. 2000), and 2MASS (Jarrett et al. 2000) surveys. For reference, the filters and their effective wavelengths are \( NUV = 2300\text{Å}, g = 4700\text{Å}, r = 6200\text{Å}, \) and \( K = 2.2\mu m \).

4.1. Dependence of synthetic galaxy colors on uncertain SPS ingredients

4.1.1. Dust uncertainties

Figure 2 shows the colors of two synthetic galaxies as a function of the parameters of our dust model. For each panel, only one parameter is varied. The fiducial set of parameters is: \( \delta = 0.7, \tau_1 = 1.0, \tau_2 = 0.3, t_{esc} = 7.0, \sigma_{clump} = 0.0, \Delta_I = 0.0, \Delta_\tau = 0.0, f_{BH} = 0.0, S_{BS} = 0.0, \) and \( \alpha_{IMF} = 2.3 \). Several important trends are apparent. First, the effect of \( \tau_2 \) on the colors is the strongest of the parameters explored. This is not surprising as \( \tau_2 \) controls the total amount of attenuation. The slope of the attenuation curve, \( \delta \), and the timescale for escape from the birth cloud, \( t_{esc} \), are similar in that they have a substantial effect in the UV, with increasingly diminishing importance toward the IR. The parameters \( \tau_1 \) and \( t_{esc} \), which control the attenuation around young stars, have no effect on the passive galaxy because that galaxy has no young stars. The parameter \( \tau_1 \) saturates at high values for the star–forming galaxy because, as one completely extinguishes the light from young systems (where \( t \leq t_{esc} \)), the colors will asymptote to the colors of the older population, which in this case are still relatively blue. Finally, it is clear that the clumpiness of the ISM, controlled by \( \sigma_{clump} \), has the effect of making colors bluer, and its effect tends to saturate at \( \sigma_{clump} \sim 1.3 \).

The importance of the clumpiness of the ISM is explored further in Figure 3. This figure is similar to the far–right column of Figure 2, except here we show results only for the star–forming galaxy, for varying values of \( \tau_2 \) (notice also that the range of the \( y–\)axes are different). It is clear that modest increases in \( \tau_2 \) result in a substantially stronger dependence of colors on the clumpiness of the ISM. This trend is due to the fact that increasing \( \sigma_{clump} \) decreases the effective dust opacity to approximately it’s limiting value of zero (as can be seen by comparing columns three and five in Figure 2). Since variation of \( \sigma_{clump} \) can be interpreted as a variation of the effective dust opacity from \( \tau_2 \) to \( \approx 0.0, \) increasing \( \tau_2 \) will clearly increase the effect of \( \sigma_{clump} \) on the derived colors.

\[ \text{Springel et al.} \ (2005) \]
The implications of Figure 5 should not be underestimated. For galaxies that are moderately dusty ($\tau_2 \gtrsim 1$), the geometry of the dust is enormously important when translating physical properties into observations, and visa versa. Note also that the dependence of colors on $\sigma_{\text{clump}}$ is strongest for modest deviations from a uniform distribution of dust. Observations suggest that in the Milky Way $\sigma_{\text{clump}} \sim 0.3$ (Berkhuijsen & Fletcher 2008), where the dependence of color on $\sigma_{\text{clump}}$ is strongest. This suggests that the detailed distribution of dust with respect to the stars must be known with great precision. Given this sensitivity, it is reasonable to suspect that deviations from a lognormal distribution of column densities will also be important.

In Figure 4 we explore further the importance of the large-scale spatial distribution of the dust with respect to the stars. In this figure we modify our default dust model by allowing for a fraction of starlight to be unobscured by dust. As discussed in (2.2), realistic galaxies will likely have a substantial fraction of starlight unobscured by dust. Consider again the example of a galaxy composed of a disk and a bulge with a majority of its cold gas and dust at the midplane of the disk. At any viewing angle, roughly one half of the disk stars, and the majority of the bulge stars, will be unobscured by dust. Unobscured light fractions as high as 50% will therefore be common in galaxies containing dust. Figure further demonstrates that fruitfully comparing galaxy models to observations requires a detailed understanding of the relation between dust and stars.

4.1.2. Stellar evolution and IMF uncertainties

Figure 5 shows the colors of two synthetic galaxies as a function of the parameters controlling the SSPs, i.e. parameters governing late stages of stellar evolution and the logarithmic slope of the IMF at high masses ($> 1 M_\odot$). It is clear that the TP–AGB parameters, $\Delta L$ and $\Delta T$, have little or no impact in the UV and optical, but a large effect in the near–IR. The effect is larger for the star–forming galaxy because this galaxy has a larger fraction of intermediate age stars, and the TP–AGB phase contributes substantially to the bolometric luminosity of intermediate age populations.

The morphology of the horizontal branch and the frequency of blue straggler stars, parameterized by $f_{\text{BH}}$ and $S_{\text{BS}}$, respectively, only impact the colors of the passive galaxy. These parameters have no effect on the star–forming galaxy because this galaxy has young, hot stars that outshine the hot, but less luminous, blue straggler and horizontal branch stars. The impact of these parameters on the UV color for the passive galaxy is quite strong. Even a modest number of blue horizontal branch or blue straggler stars can produce changes in the UV of several tenths of a magnitude. The impact of these exotic stars on the UV spectrum of passive galaxies has been discussed for decades as a possible explanation for the UV upturn phenomenon in elliptical galaxies (Burstein et al. 1988; Dorman et al. 1995; Han et al. 2007).

The final column of Figure 5 shows the effect of the logarithmic slope of the IMF on the derived colors of synthetic galaxies. The slope is only allowed to vary for stellar masses $> 1 M_\odot$. The explanation of the trends seen in the figure are qualitatively different for the two galaxy types. The trends seen for the passive galaxy are explained by inspection of the IMF–dependence of the SSPs (see Conroy et al. 2008, for details). For wavelengths $\lesssim 5000 \text{Å}$, the SED is sensitive to stars at a particular mass (i.e. stars near the main–sequence turn–off mass). However, at wavelengths $\gtrsim 5000 \text{Å}$, the SED is sensitive to both the red giant branch (RGB) and asymptotic giant branches (AGBs), and in particular the TP–AGB phase. For a coeval set of stars, these two phases of stellar evolution are inhabited by stars of different masses (stars along the AGB are more massive than stars along the RGB), and therefore the relative weights given to these phases will depend on the IMF. In essence, a steeper IMF favors the RGB over the AGB, and since the AGB is at lower effective temperature, a steeper IMF results in bluer near–IR colors.

The trends of $\alpha_{\text{IMF}}$ with color for the star–forming galaxy are both much stronger and, in the optical and near–IR, in the opposite sense compared to the passive galaxy. These trends are due to the fact that the colors of a star–forming galaxy are sensitive to stars of a range of masses. This can be understood from the following example. Imagine that a galaxy consists of two SSPs: an old and a young population. As mentioned above, the light from each component is dominated by stars of a given (different) mass, and so the relative importance of each young and old component is determined by both the star formation history, which specifies the fraction of mass formed in each component, and the IMF, which specifies the relative weights given to the mass intervals that dominate the
two components. One can see this another way by considering:

\[ F_\lambda \sim \Phi(M_1)\Psi(t_1)S_\lambda(M_1,t_1) + \Phi(M_2)\Psi(t_2)S_\lambda(M_2,t_2), \]

which is qualitatively analogous to Equation (1) without dust. This equation is approximate insofar as we are assuming that the old population, born at time \( t_1 \), is dominated by stars of mass \( M_1 \), while the young population born at time \( t_2 \) is dominated by stars of mass \( M_2 \). The logarithmic slope of the IMF determines the ratio \( \Phi(M_2)/\Phi(M_1) \), and it is therefore clear that the IMF directly effects the emergent flux for a fixed star formation history.

In the context of the above example, increasing \( \alpha_{\text{IMF}} \) results in a redder SED because the young (blue) component is sensitive to high–mass stars, while the old (red) component is sensitive to low–mass stars, and a steeper IMF favors low–mass over high–mass stars. This simple example serves to qualitatively explain the trends observed in the far–right column of Figure 5.

4.2. Total uncertainties in UV, optical, and near–IR colors

In the previous section we explored the dependence of synthetic galaxy colors on various uncertain aspects of the SPS technique, including uncertainties in the dust model, stellar evolution, and the IMF. We are now in a position to investigate the combined effects of these uncertainties on the broad–band colors of synthetic galaxies.

Figure 6 shows the distribution of colors and \( K \)–band magnitudes for two synthetic galaxies. The distributions were obtained by marginalizing over the uncertain aspects of SPS discussed in the previous section. All quantities are plotted as differences with respect to our default model. We marginalize over all parameters shown in Figures 2 and 5 except for \( \alpha_{\text{IMF}} \) and \( \tau_2 \). We choose to fix \( \tau_2 \) because, if we interpret this parameter as probing the total dust mass, then we may hope that galaxy evolution models are able to predict this quantity, if not at present then in the future. In other words, our aim in this work is to marginalize over aspects of SPS that must be assumed when translating models into observations. If one or more parameters discussed in the previous section is readily predicted by such models, then such parameters should obviously not be marginalized over.

We choose to fix \( \alpha_{\text{IMF}} \) simply because its effect on the resulting colors is so large that it would dominate the error budget in all cases. The uncertainties in broad–band colors inferred from Figure 6 can thus be safely interpreted as lower limits to the true uncertainty.

Figure 6 shows results for different values of \( \tau_2 \). For both galaxies we consider our default value of \( \tau_2 = 0.3 \). For the star–forming galaxy we also consider \( \tau_2 = 1.0 \), while for the passive galaxy we consider \( \tau_2 = 0.0 \). We vary \( \tau_2 \) for the star–forming galaxy to demonstrate the fact that the relationship between \( \sigma_{\text{clump}} \) and the resulting colors itself depends on \( \tau_2 \) (cf. Figure 3). Larger values of \( \tau_2 \) imply that variation of \( \sigma_{\text{clump}} \) will have a progressively larger impact on the derived
colors, as is evident in the broader distributions in Figure 6 for $\tau_2 = 1.0$.

Passive galaxies are often observed to contain little dust ($\tau_2 \lesssim 0.1$; see e.g. Goudfrooij et al. [1994], Ferrari et al. [1999], Temi et al. [2004], Draine et al. [2007]). We thus also include $\tau_2 = 0.0$ in Figure 6 for the passive galaxy, which implies that the parameters $\sigma_{\text{clump}}$ and $\delta$ are not included in the marginalization. The removal of dust decreases the uncertainties only slightly. This is because, for the passive galaxy, uncertainties are dominated by the uncertainties in stellar evolution.

5. DISCUSSION

5.1. How do we interpret these uncertainties?

We have demonstrated that the broad–band colors of synthetic galaxies carry significant uncertainties due to uncertain aspects of SPS. These uncertainties must thus be incorporated into any analysis that attempts to compare models to observations. But how are these uncertainties to be interpreted?

Unfortunately, it is not clear whether or not one should treat these uncertainties as statistical or systematic. Uncertainties associated with the dust model, including the attenuation curve and large–scale geometry of the ISM, can probably be interpreted as statistical uncertainties. These aspects depend in very complex and uncertain ways on the geometry of the stars with respect to the dust, the local population of O–type stars, the gas–phase metallicity, and other physical properties of the ISM.

Uncertainties associated with stellar evolution are more likely systematic, although there may be a statistical component. One might imagine that the fraction of blue stragglers or horizontal branch stars, or the evolution of TP–AGB stars, would not vary stochastically from galaxy to galaxy since stellar evolution is believed to depend on a small number of variables. However, even within globular clusters there appears to be a need for stochastic mass–loss along the RGB in order to explain the observed broad range in temperatures along the horizontal branch (e.g. Dorman et al. [1995], Kalirai et al. [2007]). Thus, in addition to the systematic variation of these post–main sequence stars with global quantities such as metallicity and age, one might indeed expect a statistical uncertainty as well.

Uncertainties in the IMF may be plausibly be either statistical or systematic, depending on the dominant mechanisms responsible for the shape of the IMF (i.e. is gas–phase metallicity or ISM pressure more important?). Whether or not the resulting color uncertainties are predominantly statistical or systematic obviously has very different implications for their interpretation. For the statistical errors, the interpretation is straightforward. Systematic uncertainties are rather more troubling in this context because systematics will almost certainly be correlated with galaxy properties such as age, metallicity, and/or mass. For example, if future observations of TP–AGB stars imply that $\Delta L = 0.3$, then the colors will shift in an age–dependent (and because mass correlates with age, a mass–dependent) way. Thus, systematic uncertainties will tend to introduce not only overall shifts but also tilts in observational quantities derived from models such as the color-magnitude diagram and luminosity functions.

With the preceding discussion in mind, we return to Figure 6. It should be clear that the distributions shown in this figure are not to be interpreted as PDFs for colors given a star formation history. Consider a simple example. If we had chosen to marginalize over nine parameters that had almost no effect on a particular color and one parameter that
had a large effect, then the distribution in colors would be very strongly peaked at $\Delta$(color) $\approx 0$, with broad wings at low frequency, because each parameter is sampled equally. Even with a strongly peaked distribution, one would not conclude that the uncertainty on the color is small, since that one important parameter produces such large uncertainties. The implication is that the only robust way to interpret these distributions is to consider their entire width as a simple measure of the resolution with which one may accurately predict colors given star formation and metal enrichment histories.

5.2. Why the IMF matters

It is often assumed that results are insensitive to the IMF so long as both modelers and observers use the same IMF to translate between fluxes and physical parameters. This assumption is incorrect. Galaxy evolution models predict star formation histories that are independent of the IMF. Upon integration, these SFHs provide total stellar masses for model galaxies. In this context, the IMF enters only in the estimation of the fraction of mass returned to the ISM via winds and supernovae.

In contrast, since the IMF has a direct effect on the colors of star–forming galaxies, it will affect the SFRs and stellar masses inferred from observations, and will affect modelers’ ability to translate and compare their models to observations. It is important to realize that this is true even if the low-mass end of the IMF — which has a negligible effect on the integrated light from galaxies — is fixed. It is the slope of the IMF at masses $> 1M_\odot$ that most affects the colors of star–forming galaxies.

The IMF is thus extraordinarily important when attempting to compare models to observations. As we have demonstrated herein, the measured uncertainty in the IMF in the solar neighborhood is sufficiently large to adversely effect comparisons between models and observations. A more pessimistic assessment of our knowledge of the IMF in external galaxies (and at earlier epochs), will only exacerbate this problem.

5.3. What is to be done?

Despite the magnitude of the uncertainties presented herein, there is, we believe, a clear way to proceed in the comparison between models and observations.

As emphasized in the present work, the principle difficulty in translating models into observables is the array of important aspects of SPS that are neither well–constrained observationally nor well–understood theoretically. We are thus forced to adopt rough ranges for these uncertainties — rough because uncertainties are difficult to quantify. However, this does not imply that each observed galaxy can be equally well–fit by the full range of parameters. In other words, it is precisely because these parameters impact the broad–band colors of galaxies that they may be constrained, to some extent, directly by the data.

We therefore advocate using the SPS technique to estimate the basic physical properties of observed galaxies, including star formation rates and stellar masses. The SPS technique must include a marginalization over the uncertain aspects discussed herein. The derived properties will therefore be robust, though they will carry larger errors. Such an approach requires a pan–chromatic view of a large number of galaxies at multiple epochs. The physical properties of observed galaxies can then be directly compared to galaxy evolution models, so long as proper attention is given to the impact of the associated uncertainties. We believe that this approach will afford a more accurate and stringent constraint on models than the approach of converting models into observables.

This recommendation is guided largely by the manner in which modelers, in practice, compare their predictions to observations. Models are often tested against observed luminosity functions, color–magnitude diagrams, and luminosity–dependent clustering. We instead suggest that models should be tested against observationally–constrained physical relations including mass functions, mass–dependent clustering, and SFR–mass correlations. As these observational results have become available in the past few years, modelers have begun to use them as constraints. We believe that this is the better way to proceed, as long as two conditions are met: 1) the observational results contain an accurate accounting of all the relevant uncertainties, including the correlations between derived products, and 2) the comparison between model and observations takes careful account of the resulting uncertainties on the derived physical properties.

6. SUMMARY

We have investigated some of the uncertainties associated with translating synthetic galaxies into observables, focusing on broad–band UV through near-IR photometry available from the GALEX, SDSS, and 2MASS surveys. The uncertainties associated with stellar evolution and dust are important and effect passive and star–forming galaxies in different ways.

For star–forming galaxies, both uncertainties in dust and in the TP–AGB phase of stellar evolution result in substantial uncertainties in UV, optical, and near–IR colors. Uncertainties in the spatial distribution of dust with respect to stars play an especially important role, as do uncertainties in the dust attenuation law.

The uncertainties in the colors of passive galaxies are dominated by uncertainties in stellar evolution, including the TP–AGB phase, blue stragglers, and the morphology of the horizontal branch. The uncertainties in the dust model have a minor effect because the total dust content of passive galaxies is observed to be low, though non–zero (e.g. Goudfrooij et al. 1994; Ferrari et al. 1999; Draine et al. 2007).

We have also explored the impact of the IMF on the derived colors of galaxies, although we have not included this source of uncertainty in the total error budget. Varying the logarithmic slope of the IMF has different effects for passive and star–forming galaxies. The magnitude of the effect is much larger for star–forming galaxies, and needs to be taken seriously by both modelers and observers. The importance of the IMF in this regard has been known since at least the work of Tinsley (1980) — we have explored it here primarily to (re)call attention to its importance when comparing models to observations.

The ranges of uncertainties investigated here are largely optimistic, and yet their influence on our ability to fruitfully compare models to observations is substantial. Many of these uncertainties are systematic, further complicating their interpretation. The comparison of models to observations can be done with confidence only once these uncertainties are carefully included in the analysis. The results from this work highlight the urgent need for observations capable of diminishing the various uncertainties discussed herein.

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