ASSESSING THE PREDICTIVE POWER OF GALAXY FORMATION MODELS: A COMPARISON OF PREDICTED AND OBSERVED REST-FRAME OPTICAL LUMINOSITY FUNCTIONS AT 2.0 \leq Z \leq 3.3

Danilo Marchesini\(^1\) and Pieter van Dokkum\(^1\)
Accepted for publication in the Astrophysical Journal Letters

ABSTRACT

Recent galaxy formation models successfully reproduce the local luminosity function (LF) of galaxies, by invoking mechanisms to suppress star formation in low- and high-mass galaxies. As these models are optimized to fit the LF at low redshift, a crucial question is how well they predict the LF at earlier times. Here we compare recently measured rest-frame V-band LFs of galaxies at redshifts 2.0 \leq z \leq 3.3 to predictions of semi-analytic models by De Lucia & Blaizot (2007) and Bower et al. (2006), and hydrodynamic simulations by Davé et al. (2006). The models succeed for some luminosity and redshift ranges, and fail for others. A notable success is that the Bower et al. model provides a good match to the observed LF at \(z \sim 3\). However, all models predict an increase with time of the rest-frame V-band luminosity density, whereas the observations show a decrease. The models also have difficulty matching the observed rest-frame colors of galaxies. In all models the luminosity density of red galaxies increases sharply from \(z \sim 3\) to \(z \sim 2.2\), whereas it is approximately constant in the observations. Conversely, in the models the luminosity density of blue galaxies is approximately constant whereas it decreases in the observations. These discrepancies cannot be entirely remedied by changing the treatment of dust, and suggest that current models do not yet provide a complete description of galaxy formation and evolution since \(z \sim 3\).

Subject headings: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — galaxies: high-redshift — galaxies: luminosity function, mass function

1. INTRODUCTION

In the current paradigm of structure formation, dark matter (DM) halos build up in a hierarchical fashion through the dissipationless mechanism of gravitational instability. The assembly of the stellar content of galaxies is instead governed by much more complicated physical processes, often dissipative and non-linear, which are generally poorly understood. To counter this lack of understanding, prescriptions are employed in the galaxy formation models. One of the fundamental tools to constrain the physical processes encoded in these models is the luminosity function (LF), since its shape retains the imprint of galaxy formation and evolution processes.

The faint end of the LF can be matched with a combination of supernova feedback and the suppression of gas cooling in low mass halos due to a background of photo-ionizing radiation (e.g. Benson et al. 2002). Matching the bright end of the LF has proven more challenging. Recent implementation of active galactic nuclei (AGNs) feedback in semi-analytic models (SAMs) has yielded exceptionally faithful reproductions of the observed rest-frame B- and K-band global LFs (Bower et al. 2006; Croton et al. 2006; see also Granato et al. 2004), including good matches to the local rest-frame B-band LFs of red and blue galaxies (although with some discrepancies for faint red galaxies; Croton et al. 2006).

The excellent agreement between observations and models at \(z \sim 0\) is impressive, but partly due to the fact that the model parameters were adjusted to obtain the best match to the local Universe. A key question is therefore how well these models predict the LF at earlier times. The SAMs of Croton et al. (2006), De Lucia & Blaizot (2007), and Bower et al. (2006) have been compared to observations at \(0 < z < 2\) (see Bower et al. 2006; Kitzbichler & White 2007). Although the agreement is generally good, Kitzbichler & White (2007) infer that the abundance of galaxies near the knee of the LF at high redshift is larger in the SAMs than in the observations (except possibly for the brightest objects), in an apparent reversal of previous studies (e.g. Cimatti et al. 2002).

Recently the rest-frame optical LF has been accurately measured in the redshift range 2.0 \leq z \leq 3.3, using a combination of the K-selected MUSYC, GOODS, and FIREs surveys (Marchesini et al. 2007). In this Letter we compare the observed LF to that predicted by theoretical models in this redshift range, in order to test the predictive power of the latest generation of galaxy formation models. We also compare the observed LF to predictions from smoothed particles hydrodynamic (SPH) simulations, which have so far only been compared to data at \(z \sim 6\) (Davé et al. 2006). We note that these comparisons are effectively the rest-frame equivalent of the test proposed by Kauffmann & Charlot (1998). We assume \(\Omega_M = 0.3\), \(\Omega_\Lambda = 0.7\), and \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\). All magnitudes are in the AB system, while colors are on the Vega system.

2. THE OBSERVED LUMINOSITY FUNCTIONS

The observed rest-frame optical LFs at \(z \geq 2\) have been taken from Marchesini et al. (2007). Briefly, they presented the galaxy LFs in the rest-frame B-band (at \(2.5 < z < 3.5\) and \(2 < z < 2.5\)), V-band (at \(2.7 < z < 3.3\)), and K-band (at \(2 < z < 2.5\)), measured from a K-selected sample constructed from the Multiwavelength Survey by Yale-Chile (MUSYC; Quadri et al. 2006), the ultra-deep Faint InfraRed Extragalactic Survey (FIREs; Franx et al. 2003), and the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004; Chandra Deep Field South). This K-selected sample, comprising a total of \(\sim 990\) galaxies with \(K_{\text{tot}} < 25\) at \(z < 3.5\), is unique for its combination of surveyed area (\(\sim 380\) arcmin\(^2\)) and large range of luminosities.

In this Letter we limit our comparison between observed
and predicted LFs to the rest-frame $V$-band, at the two redshift intervals $2.7 \leq z \leq 3.3$ (directly taken from Marchesini et al. 2007) and $2 \leq z \leq 2.5$ (derived in the same way as described in Marchesini et al. 2007). The results are qualitatively similar for other rest-frame bands.

3. THE MODEL-PREDICTED LUMINOSITY FUNCTIONS

The Bower et al. (2006) SAM is implemented on the Millennium DM simulation described in Springel et al. (2005). The details of the assumed prescriptions and the specific parameter choices are described in Cole et al. (2000), Benson et al. (2003), and Bower et al. (2006). We have also used the outputs from the SAM of Croton et al. (2006), as updated by De Lucia & Blaizot (2007). This model differs from the SAM of Bower et al. (2006) in many ways. The scheme for building the merger trees is different in detail, as are many of the prescriptions adopted to model the baryonic physics, most notably those associated with the growth of and the feedback from SMBHs in galaxy nuclei and the cooling model (see Kauffmann & Haehnelt 2000; Springel et al. 2001; De Lucia et al. 2004; De Lucia & Blaizot 2007 for details). Finally, we have compared the observed LFs with the predictions from the cosmological SPH simulations of Oppenheimer & Dave (2006) for galaxy evolution. Differences between the various models, and discrepancies between model predictions and data, are still as large as a factor of $\sim 5$ for certain luminosity and redshift-ranges.

At $2.7 \leq z \leq 3.3$, the global LF predicted by the SAM of Bower et al. (2006) agrees well with the observed LF, although the SAM slightly underpredicts the density of galaxies around the knee of the LF. However, while at $2 \leq z \leq 2.5$ the shape of the observed LF is broadly reproduced by the SAM, the predicted characteristic density $\Phi^*$ is $\sim 2.5$ times larger than the observed value. The SAM of De Lucia & Blaizot (2007) has difficulty with both the normalization and the slope of the LF, which is too steep. At $2.7 \leq z \leq 3.3$, the De Lucia model matches the faint end but underpredicts (by a factor of $\sim 2$) the bright end. At $2 \leq z \leq 2.5$, instead, the predicted LF matches the bright end but overpredicts the faint end by a factor of $\sim 2$. The SPH simulations of Finlator et al. (2007) predict LFs that are qualitatively similar to those predicted by the two SAMs, although the former are characterized by larger uncertainties, due to the much smaller simulated volume.

We quantified these results by determining the luminosity density $j_V$ (obtained by integrating the LF) for the observations and models. The luminosity density is a more robust measure than $M^*$, $\Phi^*$, and the faint-end slope $\alpha$, because the errors in these parameters are highly correlated. The ob-

---

2 Available at http://www.mpa-garching.mpg.de/Millennium Lenson 2006; see also footnote 6.

3 To derive the model-predicted LF in a specific redshift interval, we averaged the number of galaxies as function of rest-frame $V$-band magnitude (with dust modeling included) of all redshift snapshots in the targeted redshift interval.
served $j_V$ ($j_V^{\text{obs}}$) has been estimated by integrating the best-fit Schechter function down to $M_V = -19.5$, which is the faintest luminosity probed by the K-selected sample\(^4\). To estimate $j_V$ from the SAM ($j_V^{\text{SAM}}$), we have fitted the predicted LFs with a Schechter function, leaving $M^*$, $\Phi^*$, and $\alpha$ as free parameters, applying the same limits as to the data.

The comparison between $j_V^{\text{obs}}$ and $j_V^{\text{SAM}}$ of \cite{Bower2006} is shown in Fig. 2 (lower panels) by the black lines and data points. The Bower SAM matches the observed luminosity density at $z \sim 3$. However, the model does not match the evolution of $j_V$. In the model the luminosity increases with cosmic time, by a factor of $\sim 1.6$ from $z \sim 3$ to $z \sim 2.2$. By contrast, the observed luminosity density decreases with time, by a factor of $\sim 1.8$ over the same redshift range. Results for the De Lucia SAM are similar, but for this model the difference between observed and predicted density is a strong function of the adopted faint-end integration limit.

5. COLORS

We investigated the cause of the discrepancies by splitting the sample into blue and red galaxies, using their rest-frame colors. Here we focus on the Bower model, as it provides the best match to the shape of the global LF and a wide range of rest-frame colors are available. Interestingly, the results depend strongly on the choice of color: splitting the sample by $U - V$ color (as done in \cite{Marchesini2007}) produces very different results than splitting by $B - V$ color.

To define red galaxies, we first use the criterion $U - V \geq 0.25$, as done in \cite{Marchesini2007}. As shown in the bottom left panel of Fig. 2 the Bower model reproduces the densities of red and blue galaxies at $z \sim 3$ extremely well. The model overpredicts the densities of red and blue galaxies at $z \sim 2.2$, although it predicts the correct ratio between the two (roughly 1:1).

Next, we use the criterion $B - V \geq 0.5$.\(^5\) As can be seen in the top panels of Fig. 2, this criterion leads to very similar observed densities of red and blue galaxies as the $U - V$ criterion. However, the predicted densities are in severe disagreement with the observations, particularly at $z \sim 3$ (see bottom right panel of Fig. 2). The red galaxy density at $z \sim 3$ underpredicts the observed density by a factor of $\sim 8$. Qualitatively similar results are obtained when $j_V^{\text{SAM}}$ from the SAM of \cite{DeLucia2007} is used in the comparison.\(^6\)

Irrespective of the color criterion that is used, we find that the predicted evolution of the red and blue luminosity densities in the De Lucia & Blaizot (2007) is used in the comparison.

6. DISCUSSION

The main results of our comparison between the observed and model-predicted $V$-band LFs of galaxies at $z \geq 2$ are: (1) the SAM of \cite{Bower2006} reproduces well the observed LF at $z \sim 3$; (2) the models predict an increase with time of the rest-frame $V$-band luminosity density, whereas the observations show a decrease; (3) the models predict strong evolution in the red galaxy population, whereas in the observations most of the evolution is in the blue population; (4) the models greatly underpredict the abundance of galaxies with $B - V \geq 0.5$ at $z \sim 3$.

The different results obtained for $U - V$ and $B - V$ colors are interesting, as they may hint at possible ways to improve the models. We further investigate the disagreement between observed and predicted colors in the SAM of \cite{Bower2006} in Fig. 3 which shows the comparison of observations and predictions in the $B - V$ versus $U - B$ diagram. While the SAM seems to broadly reproduce the observed $U - B$ distribution, it predicts galaxies that are systematically bluer in $B - V$ compared to the observed galaxies. We have plotted evolutionary tracks of stellar population synthesis models constructed with the \cite{Bruzual2003} code, assuming three different prescriptions for the star-formation history (SFH): a constant SFH (CSF), an exponentially declining in time SFH characterized by the parameter $\tau = 300$ Myr ($\tau = 300$), and an instantaneous burst model (SSP). We selected the “Padova 1994” evolutionary tracks, solar metallicity, the \cite{Chabrier2003} initial mass function with lower and upper mass cutoffs 0.1 $M_\odot$ and 100 $M_\odot$, and modeled the extinction by dust using the attenuation law of \cite{Calzetti2000}. A new burst of star formation lasting 100 Myr and contributing 20% to the mass is also added at $t = 2.1 \times 10^9$ Gyr ($t = 2.9 \times 10^9$ Gyr) at $z \sim 3 (z \sim 2.2)$ to explore more complex SFHs.

As can be deduced from Fig. 3, the differences between observed and predicted colors could be due to larger amount of

---

\(^4\) As in \cite{Marchesini2007}, the 3-$\sigma$ error on $j_V$ was calculated by deriving the distribution of all the values of $j_V$ within the 3-$\sigma$ solutions of the Schechter LF parameters from the maximum-likelihood analysis, including in quadrature a 10% contribution from photometric redshift uncertainties. Using a brighter integration limit of the LF ($M_V = -20.4$) does not change the results of the comparison significantly.

\(^5\) For observed galaxies in the Marchesini et al. (2007) sample, $U - V = 0.25$ roughly corresponds to $B - V = 0.5$.

\(^6\) The De Lucia model provides $B - V$ colors, but no $U - V$ colors.
dust and/or to more complex SFHs in the observed galaxies. The ad hoc treatment of dust absorption is a significant and well-known source of uncertainty in the models. Modifications to the specific dust model could partly resolve the differences between observations and SAM predictions. By simply multiplying the $A_V$ in the SAM by a fixed factor, we were able to better reproduce the observed LFs at $z \sim 2.2$ (although making the faint-end slope of the red galaxy LFs quantitatively too steep) and to have a better agreement between observed and predicted colors. However, at $z \sim 3$ this simple remedy is not able to solve the disagreement between the predicted and the observed number of $B-V \geq 0.5$ galaxies. We conclude that, while ad hoc modifications of the dust treatment might help to alleviate some of the found disagreements, it does not seem to be sufficient to accommodate the problem with global colors at $z \sim 3$.

While our ability to simulate galaxy formation has greatly improved in the past few years, our results imply that the present understanding of the physical processes at work in galaxy formation and evolution is still far from being satisfactory. On the observational side, more accurate redshift and color estimates would benefit studies of this kind. The lack of spectroscopic redshifts is particularly worrying, as systematic errors in redshift will lead to systematic errors in colors and luminosities (e.g., Kriek et al. 2004 and in preparation).

We are grateful to G. De Lucia (the referee) and G. Lemson for assistance with the Millennium Simulation database and helpful clarifications. We thank K. Finlator and R. Davé for making available their SPH simulations, and R. Bower for his help with obtaining the Bower et al. (2006) predictions. DM is supported by NASA LTSA NNG04GE12G. The authors acknowledge support from NSF CARRER AST-0449678. The Millennium Simulation databases used in this paper and the web application providing online access to them were constructed as part of the activities of the German Astrophysical Virtual Observatory.

REFERENCES

Benson, A. J., Bower, R. G., Frenk, C. S., Lacey, C. G., Baugh, C. M., & Cole, S. 2003, ApJ, 599, 38
Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., Frenk, C. S. 2002, MNRAS, 333, 156
Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, MNRAS, 370, 654
Brammer, G. B., & van Dokkum, P. 2007, ApJ, 654, L107
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R.C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Chabrier, G. 2003, PASP, 115, 763
Cimatti, A., et al. 2002, A&A, 391, L1
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
Croton, D. J., et al. 2006, MNRAS, 365, 11
Davé, R., Finlator, K., & Oppenheimer, D. 2006, MNRAS, 370, 273
De Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2
De Lucia, G., Kauffmann, G., & White, S. D. M. 2004, MNRAS, 349, 1101
Finlator, K., Davé, R., & Oppenheimer, B. D. 2007, MNRAS in press

Franceschini, M., et al. 2003, ApJ, 587, L79
Giavalisco, M., et al. 2004, ApJ, 600, L93
Granato, G.L., De Zotti, G., Silva, L., Bressan, A., & Danese, L. 2004, ApJ, 600, 580
Kauffmann, G., & Charlot, S. 1998, MNRAS, 297, L23
Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576
Katz, B. M., & White, S. D. M. 2007, MNRAS, 376, 2
Kriek, M., et al. 2006, ApJ, 649, L71
Lemson, G., and the Virgo Consortium 2006, astro-ph/0608019
Marchesini, D. et al. 2007, ApJ, 656, 42
Oppenheimer, B. D., & Davé, R. 2006, MNRAS, 373, 1265
Quadri, R., et al. 2006, AJ accepted (astro-ph/0612612)
Springel, V., & Hernquist, L. 2003, MNRAS, 339, 312
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Springel, V., et al. 2005, Nature, 435, 629