MASSCLEANCOLORS—MASS-DEPENDENT INTEGRATED COLORS FOR STELLAR CLUSTERS DERIVED FROM 30 MILLION MONTE CARLO SIMULATIONS

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ABSTRACT

We present Monte Carlo models of open stellar clusters with the purpose of mapping out the behavior of integrated colors with mass and age. Our cluster simulation package allows for stochastic variations in the stellar mass function to evaluate variations in integrated cluster properties. We find that UBVK colors from our simulations are consistent with simple stellar population (SSP) models, provided the cluster mass is large, $M_{\text{cluster}} \geq 10^6 M_\odot$. Below this mass, our simulations show two significant effects. First, the mean value of the distribution of integrated colors moves away from the SSP predictions and is less red, in the first $10^7$ to $10^9$ years in UBV colors, and for all ages in $(V-K)$. Second, the $1\sigma$ dispersion of observed colors increases significantly with lower cluster mass. We attribute the former to the reduced number of red luminous stars in most of the lower mass clusters and the latter to the increased stochastic effect of a few of these stars on lower mass clusters. This latter point was always assumed to occur, but we now provide the first public code able to quantify this effect. We are completing a more extensive database of magnitudes and colors as a function of stellar cluster age and mass that will allow the determination of the correlation coefficients among different bands, and improve estimates of cluster age and mass from integrated photometry.

Key words: galaxies: clusters: general – methods: analytical – open clusters and associations: general

1. INTRODUCTION

When dealing with the integrated light from extremely massive systems, such as entire galaxies, one can reasonably assume there are enough stars in the system to represent all critical stages of evolution, regardless of stellar mass or age. When studying very massive stellar clusters, 100,000 $M_\odot$ or more, while all members are (typically) of the same age, the isochrones will be fully populated at all ages (e.g., Bruzual & Charlot 2003).

However, typical open star clusters do not have such high masses. Two open star clusters of nearly identical age cannot be expected to have the same integrated light properties. This is because of natural cluster-to-cluster variations in the exact stellar masses found within the cluster, which give way to the cluster’s integrated light properties (e.g., Cerviño & Valls-Gabaud 2009; Buzzoni 1989; Chiosi 1989). In their final evolutionary states, stars become very luminous and/or possess rather extreme red or blue colors. This can cause observable deviations in integrated colors of the cluster as compared to the integrated colors computed in the high mass limit. This effect is particularly great in young- to middle-aged open clusters, where their dying stars are the most luminous and have the most extreme and rapid color changes. This poses a serious problem to astronomers because integrated colors are the primary way in which the age and mass of unresolved stellar clusters are derived (e.g., Larsen 2009).

The fact that integrated colors are affected by the finite value of cluster mass and the fluctuations in the initial mass function (IMF) has been known and studied by many authors (e.g., Bruzual 2002, 2010; Cerviño & Luridiana 2004, 2006; Fagiolini et al. 2007; Lançon & Mouhcine 2000; Lançon & Fouesneau 2009; Fouesneau & Lançon 2009; Brocato et al. 1999, 2000; Buzzoni 1989; Chiosi 1989; Cantiiello et al. 2003; Raimondo et al. 2005; Raimondo 2009; Piskunov et al. 2009; Santos & Frogel 1997; González et al. 2004; González-Lópezlira et al. 2005, 2010; Maíz Apellániz 2009; Pessev et al. 2008). We present a large number of Monte Carlo simulations, which constitute the MASSCLEANcolors database, using the MASSCLEAN (MASSive CLuster Evolution and ANalysis) package1 (Popescu & Hanson 2009). This is a public and open source code. While it was first designed to simulate particular clusters, new additions to the package allow it to run in Monte Carlo mode. Also, all of the tools used to perform statistical analysis described in this work are included, so we are able to directly predict the mean value of the distribution of colors and color dispersion as a function of cluster mass and age.

MASSCLEAN is a new stellar cluster image and photometry simulation package. It uses an algorithm that populates the simulated cluster with a discrete number of tenable stars and then evolves each individual star following isochrones (Padova: Marigo et al. 2008, or Geneva: Schaller et al. 1992; Meynet et al. 1994 with isochrones obtained using Basel atmosphere libraries as presented in Lejeune & Schaerer 2001). Integrated photometry of the simulated cluster is derived by simply summing up the stellar flux at any point in the cluster evolution. We have tested that at very high cluster mass, the “infinite mass limit” of $M_{\text{cluster}} \geq 10^6 M_\odot$, the integrated colors are consistent with standard simple stellar population (SSP) models when using identical cluster properties of age, IMF, evolutionary code, etc. (Popescu & Hanson 2009). In this Letter, we present results using MASSCLEAN to explore the colors and color ranges of a stellar cluster as the mass drops below this limit, introducing mass as a variable in this investigation.

2. RESULTS FROM 30 MILLION MONTE CARLO SIMULATIONS

We have computed the mean value of $(B-V)_0$, $(U-B)_0$, and $(V-K)_0$ integrated colors as a function of mass and age for a simple stellar cluster. Our results—MASSCLEANcolors

1 http://www.physics.uc.edu/~popescu/massclean/
Figure 1. MASSCLEAN integrated colors for Padova models $Z = 0.19$ using the 0.01 log(age/yr) step. The thick line corresponds to the infinite mass limit ($10^6 M_\odot$ in our simulations). (a) Upper panel: $(B − V)_0$ as a function of mass and age; (b) middle panel: $(U − B)_0$ as a function of mass and age; (c) lower panel: $(V − K)_0$ as a function of mass and age. The Milky Way clusters are from Hancock et al. (2008) and Kharchenko et al. (2009).

database—are based on over 30 million Monte Carlo simulations. Broadly speaking, the simulations provide $UBVRIJHK$ magnitudes as a function of age and mass. For this demonstration we present just $UBVK$, for two metallicities, $Z = 0.019$ (solar) and $Z = 0.008$ (Large Magellanic Cloud, LMC), and employ the two most commonly used stellar evolution models, Padova (Marigo et al. 2008) and Geneva (Lejeune & Schaerer 2001). The simulations were done using Kroupa IMF (Kroupa 2002) with $0.1 M_\odot$ and $120 M_\odot$ mass limits. The age range of $[6.6, 9.5]$ in log(age/yr) was chosen to accommodate both Padova and Geneva models. An average of 5000 clusters were simulated for each mass and age. These results are presented in Figures 1 through 5. Comparison with observational data from LMC and Milky Way clusters is discussed in Section 2.4.
Figure 2. MASSCLEAN integrated colors for Padova models \(Z = 0.008\) using the 0.01 log(age/yr) step. The panels are the same as in Figure 1, except for the data points. Here, the clusters are from the LMC and found in Hunter et al. (2003) and Marigo et al. (2008).

2.1. The “Blueing” of Mean Integrated Colors for Lower Mass Clusters

Figures 1 through 4 are all similarly presented. The mean values for \((B - V)_0\), \((U - B)_0\), and \((V - K)_0\) distributions of integrated colors as generated by MASSCLEAN are given in the top of each of the three panels in each figure. In Figures 1 and 2, we use the Padova evolutionary models with a log(age/yr) step of 0.01, solar and LMC metallicities, respectively. In Figures 3 and 4, we present the mean values using the Geneva evolutionary models with a log(age/yr) step of 0.05, solar and LMC metallicities, respectively. The difference in smoothness seen in the Padova and Geneva sets is due to a smaller log(age/yr) step in the Padova case (0.01 versus 0.05 for Geneva).

The upper graphs in each of the three panels (a) of Figures 1 through 4 show the mean value of the integrated cluster color as a function of age. Thirteen masses are presented starting
at $10^5 \, M_\odot$ (dark solid line, and virtually the same as the SSP codes predictions) and going down to $500 \, M_\odot$ (dotted lines). The dotted lines show a trend away from the SSP predicted values to bluer mean colors, as the cluster mass decreases for young clusters up to an age of as much as $10^8$ years. This occurs with both solar and LMC metallicities and both evolutionary models, Geneva and Padova. More striking, as the mass decreases our simulations show a bluing of the integrated $(V-K)_0$ color for all cluster ages simulated (bottom panel).

### 2.2. The Increased Range in the Observed Integrated Colors of Low Mass Clusters

The color dispersion (presented as 1σ—standard deviation—about the mean) for different values of mass in the $500–100,000 \, M_\odot$ interval is presented in the lower graphs of each panel. Here, we use differing levels of gray-scale tone to represent the cluster masses. The most massive clusters show their 1σ range in the darkest gray scale, while lower mass clusters are shown with increasingly lighter shades. Recall, the mean

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**Figure 3.** MASSCLEAN integrated colors for Geneva models $Z = 0.20$ using the 0.05 log(age/yr) step. The panels are the same as in Figure 1, including the Milky Way clusters shown.
Figure 4. MASSCLEAN integrated colors for Geneva models $Z = 0.008$ using the 0.05 log(age/yr) step. The panels are the same as in Figure 1, except for the data points which are from the LMC.

The expected number of stars in any given evolutionary phase is fractional. This fact is not relevant if the cluster has enough stars (is massive enough) so variations of $+/−$ one in a given evolutionary phase have no impact. However, when the mass of the cluster decreases, this number becomes lower than 1 in the red, luminous evolutionary phases, so most of the clusters in the simulation will have no luminous red stars at all, since the number of stars in a given phase must be an integer. This produces a bluer mean color. However, a few clusters will have one (or a few) luminous red stars, so the result will be an excess in both sides (blue and red) (Lançon & Mouchine 2002; Cerviño & Luridiana 2004; Fagiolini et al. 2007). In this situation, it is difficult to obtain a clear correlation of a particular (real) cluster-integrated color with mass for a single age (Santos & Frogel 1997; Cerviño & Luridiana 2004, 2006; Fagiolini et al. 2007). While the correlation between the mean value (of the distribution of integrated colors) and mass is apparent in our plots, an accurate quantitative description could be obtained only using a larger number of simulations. However, we hope the predicted increased color range with lower mass should be a strong enough signal with a realistically observable number of
clusters. In order to verify this result with observations, perhaps hundreds of clusters would be needed and they must have well constrained mass and age.

2.3. The Effect of Low Cluster Mass on the UBV Color–Color Diagrams

The color–age diagrams of Figures 1 through 4 are not typically used by researchers because age is often not known for unresolved stellar clusters. In fact, the great utility of SSP models has been to provide a way to derive cluster ages based on the easily observed integrated magnitudes and their location in a color–color diagram (Searle et al. 1980; Girardi et al. 1995). In Figure 5 we show such diagrams. Here, we have re-plotted the simulations already shown in Figures 1 through 4, including the mean color lines and the gray-scale 1σ ranges of those colors, just like our earlier figures. Here, the four panels represent the two evolutionary models (Padova and Geneva), with each of those using LMC and Milky Way metallicities. We include the same real data shown in Figures 1 through 4 for the LMC and Milky Way. Again we provide both mean colors as a function of age, and the 1σ range of that mean color. A similar color scheme for the range is employed, the darkest gray scale representing the most massive cluster simulated, while lighter shades represent lower mass clusters. It is easy to see the very large dispersion of the lower mass clusters, particularly in the blue, young portion of Figure 5. While it is rather crowded, we have attempted to demonstrate the location of the mean color as a function of mass through the use of differing line styles in the plot. As one might expect from our four earlier figures, most of the predicted mean variation occurs in the upper left portion of the diagram, corresponding to the youngest clusters.

2.4. Comparison with Real Cluster Data

In Figures 1 through 4, we show data taken from Marigo et al. (2008) and Hunter et al. (2003) for the LMC, and from Kharchenko et al. (2009) and Hancock et al. (2008) for the Milky Way. In Figure 5, we provide data from Hunter et al. (2003) for the LMC and from Hancock et al. (2008) for the Milky Way only. The other data sets did not include U band. In Figure 5, there appears to be just as large of a variation of observed colors along the portion of the color–color diagram for the LMC clusters, where old clusters are expected to be found (in the lower right) as there is among young clusters (in the upper left). This seems incongruous with the rather tight fit of panels (a) and (b) in Figures 2 and 4. Also, in Figure 5, we see that the youngest clusters from the LMC are found to lie almost
entirely within the gray-scale error range when they do not do so in Figures 1 through 4. The first is due to a selection effect of the data. Clusters deviating greatly from the expected SSP curve in the UBV color–color diagram of Figure 5 are not typically aged, and thus will not appear in Figures 2 and 4, cleaning up those diagrams considerably. To understand why the younger clusters lie almost entirely within the gray scale of Figure 5 and not Figures 1 through 4, one needs to recognize that in the blue range, the lines representing the mean double back on themselves make the region very complex. A quick check shows that the greatest range of gray scale in Figure 5 never extends beyond the greatest range seen in Figures 1 through 4.

Looking at the figures, one notes the data do not appear to be distributed in a manner consistent with our 1σ ranges. In fact, one could say, the colors of real clusters shown often extend to values much redder than our 1σ range given in the figures (more often than 1σ would indicate for the data). This is because of the way in which we have shown the color range with mass. To provide a 1σ range is most useful when the distribution is Gaussian. Unfortunately, the distribution of observed colors is far from a well-behaved Gauss about the mean for early ages and low mass clusters. The distribution of colors with age in Figures 1 through 4 becomes increasingly bimodal as mass decreases. This is consistent with the fluctuations described by Lançon & Mouhcine (2000), Cerviño & Valls-Gabaud (2003), and Cerviño & Luridiana (2004, 2006). We will show that our simulations are consistent with these very red colors observed in low mass systems (B. Popescu & M. M. Hanson 2010, in preparation). We are running additional simulations and eventually will present more than 50 million clusters to better constrain the exact behavior of the colors as a function of mass and age.

3. DISCUSSION AND CONCLUSIONS

While it is entirely expected that integrated colors computed by the modern SSP codes in the infinite mass limit will work best when applied to very massive systems, it has been difficult to ascertain the error involved when one applies their predictions to lower mass systems. Our new stellar cluster simulation routine, MASSCLEAN, provides a means to determine this through Monte Carlo simulations of realistically modeled stellar clusters.

We used MASSCLEAN to simulate 30 million stellar clusters over a mass range typical of open stellar clusters and for ages in the [6.6, 9.5] log(age/yr) range. Our results indicate that cluster mass decreases, the mean value of the distribution of colors in the first tens (to hundreds) of millions of years will not reach to such high red values as predicted by SSP models. Most of this very red color is brought on by very luminous red stars. Lower mass clusters will have fewer highly luminous red stars to pull the colors so red. However, the stochastic variation of stars in these very luminous, quickly evolving phases, and thus very red colors, makes it still possible just not as likely. Thus, we also find that the typical range of colors observed increases significantly as the cluster mass decreases. This is because the color depends so strongly on the most luminous stars, and a single star has the potential to produce greater deviations in the color of smaller clusters. Our results indicate a bluer mean value of the distribution of colors for lower mass clusters compared to SSP predictions in the infinite mass limit.

We continue to simulate still more clusters and expand the MASSCLEANcolors database to provide a complete sampling of colors and absolute magnitudes as a function of cluster age and mass (the work presented in this Letter was done during a 6 month period, using multiple computers). When complete, this database will provide a probabilistic grid from which a statistical inference code will be based to aid researchers in deriving cluster characteristics from their observed integrated photometry. We have completed some preliminary work to provide proof of concept (Popescu & Hanson 2010). With additional simulations (B. Popescu & M. M. Hanson 2010, in preparation), we will be able to obtain the correlation coefficients among different bands.

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