Star clusters: basic galactic building blocks
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MASSCLEAN (MASSive CLuster Evolution and ANalysis Package): description, tests, and results

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Abstract. MASSCLEAN is a new, sophisticated and robust stellar cluster image and photometry simulation package. This package can create color–magnitude diagrams and standard FITS images in any of the traditional optical and near-infrared bands based on cluster characteristics input by the user, including but not limited to distance, age, mass, radius and extinction. At the limit of very distant, unresolved clusters, we have checked the integrated colors created in MASSCLEAN against those from other simple stellar population models, with consistent results. Because the algorithm populates the cluster with a discrete number of tenable stars, it can be used as part of a Monte Carlo method to derive the probabilistic range of characteristics (integrated colors, for example) consistent with a given cluster mass and age. We present the first ever mass-dependent integrated colors as a function of age, derived from over 100 000 Monte Carlo runs, which can be used to improve the current age-determination methods for stellar clusters.

Keywords. Galaxy: stellar content, open clusters and associations: general

1. Introduction

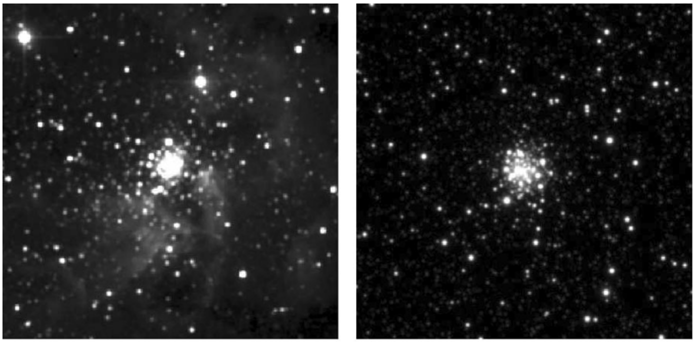
Star clusters are the building blocks of galaxies. To analyze the known population of star clusters, to search for new clusters, and to derive the selection effects of current near-infrared survey searches for Milky Way clusters, we created a simulation package.

The MASSCLEAN package† (Popescu & Hanson 2009; Hanson & Popescu 2007, 2008, 2009) is built using numerous well-established theoretical and empirical models for stars and stellar clusters, starting with the Kroupa–Salpeter initial mass function (IMF) for the stellar mass distribution (Salpeter 1955; Kroupa 2002). The user has the option to choose between two stellar evolutionary models, the Geneva (Lejeune & Schaerer 2001) or the Padova models (Marigo *et al.* 2008). The extinction model is based on Cardelli *et al.* (1989), and a King model is used for the spatial distribution (King 1962). An optional stellar field can be generated using the 'SKY' model (Bahcal & Soneira 1984). MASSCLEAN is built in a modular way and can combine observational data and simulations using an unprecedented level of accuracy.

2. Images: Galactic and extragalactic simulations

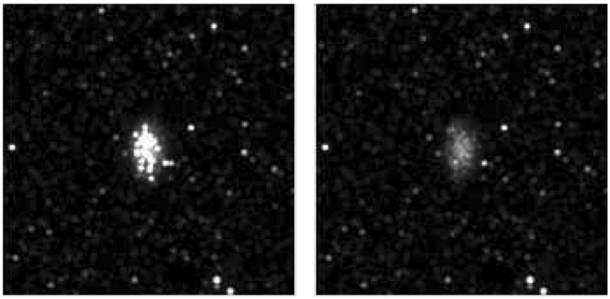
MASSCLEAN generates FITS images, using SkyMaker (Bertin 2009). The simulated J-band image for NGC 3603 is presented in Figure 1b, and the 2MASS‡ image is presented in Figure 1a.

† The package is freely available under GNU General Public License at:
http://www.physics.uc.edu/~bogdan/massclean/
‡ This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and



(a) Real image (2MASS). (b) Simulated image.

Figure 1. NGC 3603 J-band images (4.4×4.4 arcmin^2).



(a) $\log(\text{age/yr}) = 6.0$. (b) $\log(\text{age/yr}) = 8.0$.

Figure 2. 10^5 $M_\odot$ simulated cluster at the distance of M31 and the resolution of *HST*/ACS.

In Figure 2 we present a simulated 10^5 $M_\odot$ cluster at the distance of M31 and the resolution of *HST*/ACS. The images show the cluster at ages of 1 and 100 million years.

We are using MASSCLEAN to help us derive the selection effects of current near-infrared survey searches for Milky Way clusters (Hanson *et al.* 2009, in prep.). As a proof of concept, we present an example image simulation of 45 randomly generated clusters of various ages, masses, concentrations, and extinction values. The V and K-band images are shown in Figures 3a and b, respectively (note that no stellar field is included). The positions of the clusters along with the scaled angular size of their cores is shown in Figure 3c.

3. Integrated colors and ages

MASSCLEAN follows the evolution of every star in the cluster, providing full photometry at all ages. We have tested that at the infinite-mass limit the integrated colors are consistent with standard simple stellar population (SSP) models. A log(age/yr) step of 0.05 has been used to allow comparison with all other models. The integrated colors generated by MASSCLEAN using Padova 2008 evolutionary models for solar metalicity are presented in Figure 4a. The results from other SSP codes (Marigo *et al.* 2008; Bruzual & Charlot 2003; Maraston 2005; Kotulla *et al.* 2009) are also displayed, along with the

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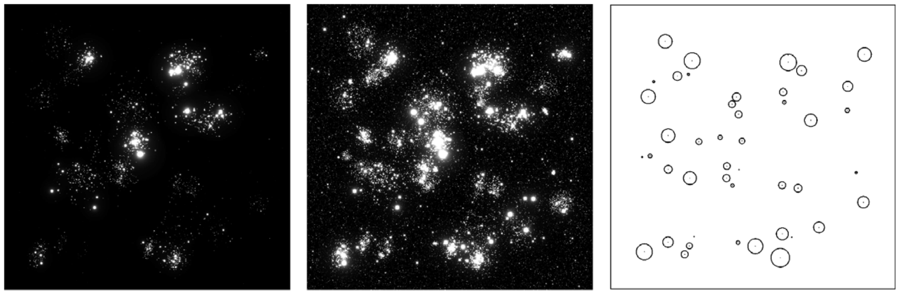
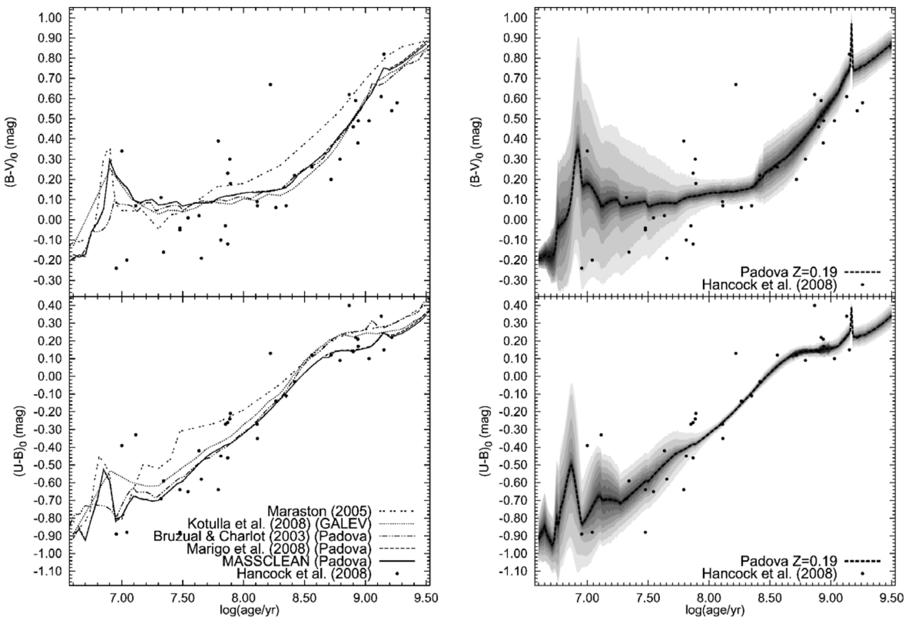


(a) V-band image. (b) K-band image. (c) Positions.

Figure 3. 45 simulated clusters.



(a) Comparison with modern SSP codes. (b) Mass-dependent integrated colors.

Figure 4. MASSCLEAN integrated colors.

Milky Way clusters from Hancock *et al.* 2008. The MASSCLEAN integrated colors follow Marigo *et al.* (2008), since they both use the same evolutionary models for their input.

Of course, real star clusters have a finite mass. They do not have fully populated isochrones at all ages and their integrated colors may not always correspond to the ones computed in the infinite-mass limit (Bruzual 2002; Cerviño & Luridiana 2004, 2006; Fagiolini *et al.* 2007; Lançon & Mouhcine 2000; Lançon & Fouesneau 2009). The dispersion of the integrated colors (1σ) due to different values of mass and fluctuations in the IMF is presented in Figure 4b. $(B-V)_0$ versus log(age/yr) and $(U-B)_0$ versus log(age/yr) are presented for a few values of the cluster's mass. The step in log(age/yr) is 0.01. The color dispersion for clusters with masses in the $2\times10^3 - 2.5\times10^5$ $M_\odot$ range is based on about 100 000 Monte Carlo runs (which corresponds to about 15 million cluster models). We present, for the first time, mass-dependent integrated colors for clusters. The entire set

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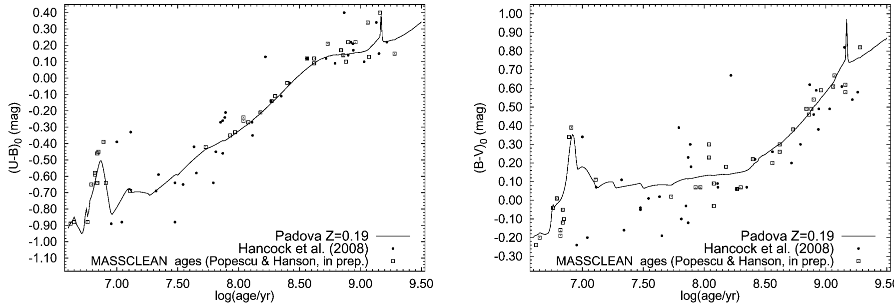

(a) $U - B$ colors as a function of age. (b) $B - V$ colors as a function of age.

Figure 5. Real clusters, with masses of just a few thousand solar masses, are expected to be redder than SSP models predict using the 'infinite-mass assumption,' particularly in the age range $10^6 - 10^8$ yr. We are testing this result using integrated colors of Milky Way clusters with well-constrained ages (Popescu & Hanson, in prep.).

of mass-dependent integrated colors using both Padova and Geneva models and different metallicities will be publicly available soon (Popescu & Hanson, in prep.).

Age determination of clusters using integrated colors is usually based only on the infinite-mass limit. Using our mass-dependent integrated colors and magnitudes, we expect to provide a more realistic model. As an initial demonstration, we present new age determinations based on MASSCLEAN integrated colors for numerous Milky Way clusters in Figure 5 (Popescu & Hanson, in prep.).

4. Summary

We have developed a sophisticated cluster image and photometry simulation package which we are using to test against current search algorithms. We predict that clusters over certain age ranges (particularly when the red-supergiant phase is just starting) and clusters with low stellar densities (even though possibly of very high total mass) are being missed by the current searches, particularly when combined with high extinction. Our mass-dependent integrated colors for clusters should provide a better description for known clusters and a more accurate age determination.

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