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SLUG: A new way to Stochastically Light Up Galaxies

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Abstract. We present SLUG, a new code to "Stochastically Light Up Galaxies". SLUG populates star clusters by randomly drawing stars from an initial mass function (IMF) and then following their time evolution with stellar models and an observationally-motivated prescription for cluster disruption. For a choice of star formation history, metallicity, and IMF, SLUG outputs synthetic photometry for clusters and field stars with a proper treatment of stochastic star formation. SLUG generates realistic distributions of star clusters, demonstrating the range of properties that result from finite sampling of an IMF and a random distribution of ages. The simulated data sets provide a quantitative means to address open problems in studies of star formation in galaxies and clusters, such as a test for IMF variations that are suggested by the systematic deficiency in the Hα/UV ratio in outer disks or in dwarf galaxies. SLUG will be made publicly available through the website `http://sites.google.com/site/runslug/`.

1. Motivations

The continuous build up of observations is enriching our view of how galaxies form and evolve, but not without introducing new riddles. The availability of *Galex* UV data, together with ground-based Hα imaging, has recently uncovered a systematic deficiency of hydrogen recombination line emission normalized to UV fluxes below star formation rates (SFRs) of $\lesssim 0.1$ M$_\odot$ yr^{-1}. A debate around the origin of this Hα deficit has opened, questioning some of the basic assumptions in star formation studies, such as a constant initial mass function (IMF) (e.g. Meurer 2009; Lee 2009).

Support to this interpretation comes from the apparent inability of spectral energy distribution (SED) modeling with different star formation histories (SFHs) (e.g. Hoversten & Glazebrook 2008) or stochastic sampling of canonical IMFs with a constant SFR (e.g. Lee 2009) to fully account for the observed deficiency of Hα. Furthermore, semi-empirical models of a galactic IMF that depend on the SFR appear to reproduce the observed trends (e.g. the IGIMF theory; Pflamm-Altenburg et al. 2009). However, uncertainties on dust corrections, stellar models, star formation histories, or escape fraction of ionizing radiation limit our ability to unambiguously interpret these observations (e.g. Boselli et al. 2009, but see Meurer et al. 2009).

Beside the intrinsic difficulties of understanding this effect, a straightforward comparison of independent studies is made even harder by the inhomogeneity in the various data sets and in the stellar models used for theoretical predictions. To help addressing the fundamental problem of the IMF variation or more generally other open issues in studies of star formation, we present SLUG, a new code to "Stochastically Light Up Galaxies". Among its applications, SLUG can be used to extensively test the null hypothesis of incomplete sampling of the upper end of the IMF for low star formation rates as well as to the test for environmental effects (e.g., metallicity) on the observed Hα/UV ratio.

2. The SLUG code

A schematic representation of the SLUG code is shown in Figure 1. A more extensive description will be presented in da Silva et al. (in preparation). As inputs, SLUG accepts an arbitrary SFH, metallicity, and a choice of IMF (Chabrier, Kroupa, Salpeter or IGIMF). From these parameters, the code creates a collection of star clusters and field stars, representative of a portion of a galaxy. A more realistic galaxy can then be assembled by combining different outputs tuned to best match the SFH and metallicity properties across the objects of interest.

In more detail, the code starts by drawing a cluster mass from a given cluster mass function of the form $dN/dM \propto M^{-\beta}$, extending from $M_{\rm cl,min}$ to $M_{\rm cl,max}$ (by default $\beta = 2$, $M_{\rm cl,min} = 20 M_{\odot}$, and $M_{\rm cl,max} = 10^7 M_{\odot}$). The birth of a cluster represents a new event in the galaxy SFH at time t and therefore the age of the galaxy is incremented as implicitly defined by

$$M_{\rm galaxy}(t) = \int_0^t SFR(t')dt' \ . \tag{1}$$

The next step is to populate the cluster with stars randomly drawn from the chosen IMF. The combination of these two random draws (for clusters and stars) allows for a proper treatment of stochastic star formation.

Once the cluster has been filled, the photometric properties (far UV and near UV in the *Galex* passbands, bolometric luminosity, and Hα) of individual stars are computed for a series of time steps, up to a maximum age defined by the user. To this purpose, SLUG uses libraries of theoretical evolutionary tracks (Schaller et al. 1992) combined with model spectral energy distributions (Lejeune & Schaerer 2001; Girardi et al. 2004)[1]. Next, the code outputs the integrated cluster photometry by summing over all the star luminosities in each cluster.

Clusters dissolve after $\sim$ 1 Myr from their formation at a rate $\propto t^{-1}$ (Fall et al. 2009) and SLUG reproduces this empirical disruption rate by evaluating at each time step the probability that a cluster survives. If the cluster is disrupted, the code continues to follow the evolution of the individual stars, but the stellar integrated luminosities are added to a field where all the former cluster-member stars are accumulated.

These operations are repeated iteratively for the subsequent star clusters, until the age of the galaxy as defined by equation (1) reaches the maximum age specified by the user. As a last step, SLUG writes a series of binary files containing the mass, age, photometry, number of stars and the maximum stellar mass for each cluster at each

[1]Additional stellar models will be provided in the public version of the code or can be added by the user.

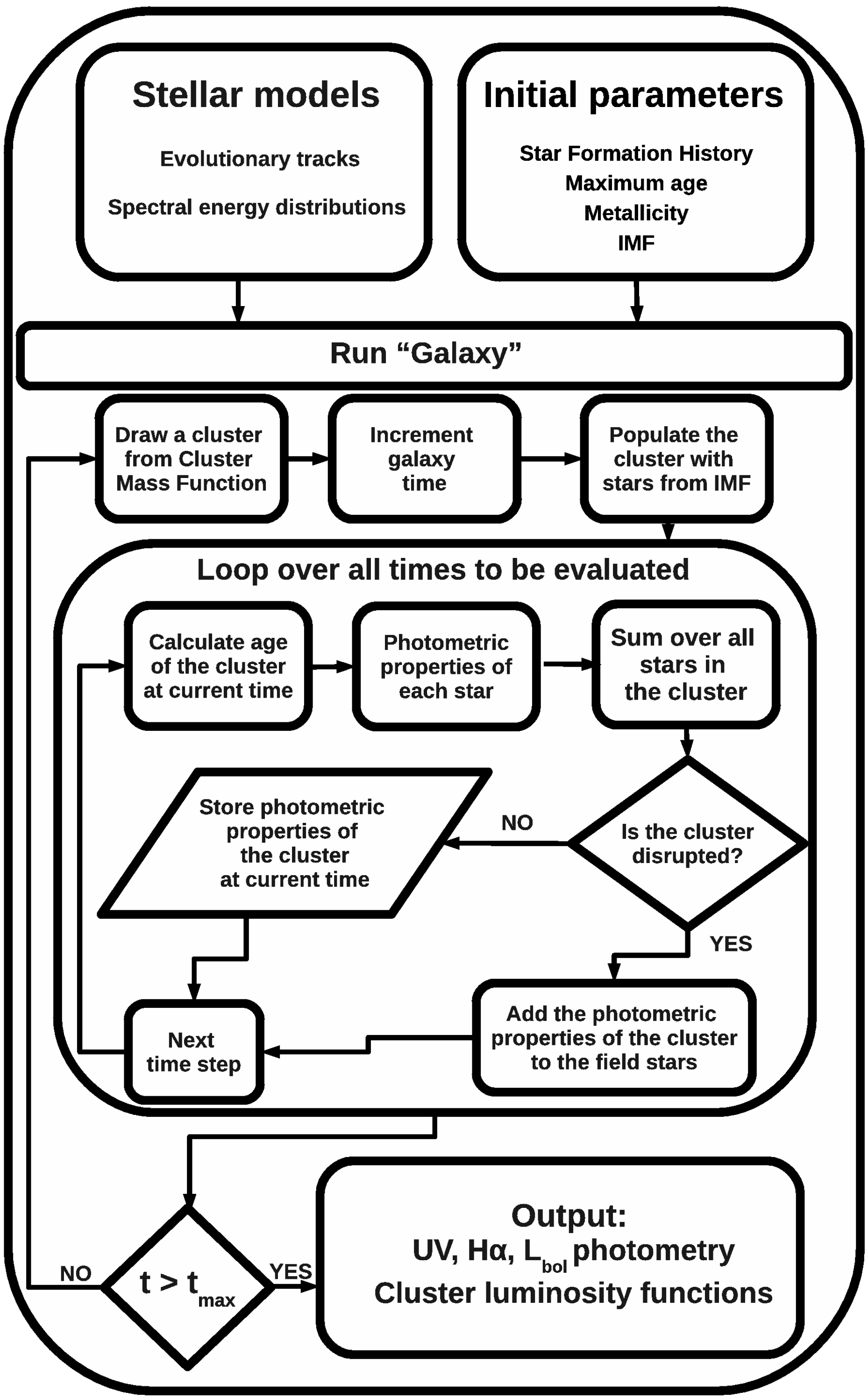

Figure 1. Schematic representation of the SLUG code. See Section 2 for a description.

time step. Also, the photometric properties of all the stars from disrupted clusters are recorded in histograms. With a suite of IDL codes[2], useful statistics such as the cluster luminosity functions or probability distribution functions can easily be generated.

3. Applications and future developments

An immediate application of SLUG is to verify whether stochastic star formation may explain the observed decrease in the UV/Hα ratio at low SFRs. Indeed, incomplete sampling of the IMF combined with stellar evolution and cluster disruption produces populations that are deficient in high mass stars, even if the underlying stellar IMF is universal and independent of the star formation rate. SLUG will enable an extensive and homogeneous comparison between observations and theoretical predictions over a large parameter space (SFHs, metallicity, IMFs, ages, stellar models). Particularly useful will be a comparison of outputs from various stellar models to quantify uncertainties in theoretical predictions, particularly relevant to test modest variation in the IMF.

SLUG can also be used to generate synthetic distributions for the cluster mass and the maximum mass of cluster-member stars (e.g. Weidner & Kroupa 2006), or to test and develop new analysis techniques which are based on probabilistic formulations (e.g. Cerviño & Luridiana 2006), or more generally for applications related to photometric distributions of clusters. In future versions of the code, we aim to output additional broad-band photometry and spectral properties of clusters and field stars, suitable to simulate color-magnitude diagrams from random sampling of the IMF.

SLUG will be publicly available at `http://sites.google.com/site/runslug/`. It is easy to use and modify, and users can include physical processes relevant for specific applications.

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[2]The IDL procedures will be distributed as part of SLUG.