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Generating LSB-optimised synthetic images for simulated galaxies

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ABSTRACT

We introduce an emission–biasing scheme in the `SKIRT` radiative transfer code that enables efficient generation of synthetic galaxy images optimized for low-surface-brightness (LSB) science. Standard Monte Carlo radiative transfer simulations achieve high signal-to-noise in bright regions but require prohibitively many photon packets to reach reliable depth in galaxy outskirts. By assigning stellar particles bias factors that scale with their smoothing lengths, our method boosts photon emission from low-density regions while conserving energy through weight corrections. Tests on a Milky-Way-like galaxy from the TNG50 cosmological simulation show that bias factors proportional to the smoothing length substantially extend the reliable LSB regime, providing an inexpensive improvement for deep synthetic imaging of simulated galaxies.

Keywords: radiative transfer — dust: extinction — galaxies: structure

1. INTRODUCTION

Cosmological hydrodynamical simulations are essential tools for studying galaxy evolution. Synthetic observations bridge the gap between simulations and real data by allowing simulated galaxies to be analysed within the same observational framework as their observed counterparts. The `SKIRT` Monte Carlo radiative transfer code (M. Baes et al. 2011; P. Camps & M. Baes 2015, 2020) is a widely used tool for generating realistic dust-aware synthetic data products across a broad range of cosmological simulations (e.g., J. W. Trayford et al. 2017; P. Camps et al. 2018; V. Rodriguez-Gomez et al. 2019; M. Baes et al. 2024; C. Bottrell et al. 2024).

Low-surface-brightness (LSB) structures, such as stellar halos, tidal streams, and diffuse outer disks, offer powerful constraints on galaxy assembly histories and dark matter distributions. However, synthetic images produced with standard Monte Carlo radiative transfer are typically not optimised for LSB science: photon packets naturally concentrate in high-surface-brightness (HSB) regions, yielding excellent signal-to-noise (SNR) there but poor performance in faint outskirts. Achieving high SNR in LSB regions requires launching extremely large numbers of photon packets, resulting in prohibitively long runtimes.

In this Research Note, we describe a new emission-biasing feature in `SKIRT` designed to improve LSB sensitivity without increasing computational cost.

2. THE GENERATION OF LSB-OPTIMISED IMAGES

In a Monte Carlo radiative transfer simulation, a large number of photon packets are launched stochastically from a source. In the case of simulated galaxies, the source consists of a set of stellar particles. After emission, each photon packet propagates through the dusty interstellar medium, may undergo interactions, and is eventually detected once it exits the system.

The first step is to randomly select a particle m from which a photon packet is launched. As the number of photon packets launched from a particle should be proportional to that particle's contribution to the galaxy's total luminosity, the appropriate probability density function (pdf) is

$$p(m) = \frac{L_m}{\sum_n L_n} \quad m = 1, \ldots, M. \tag{1}$$

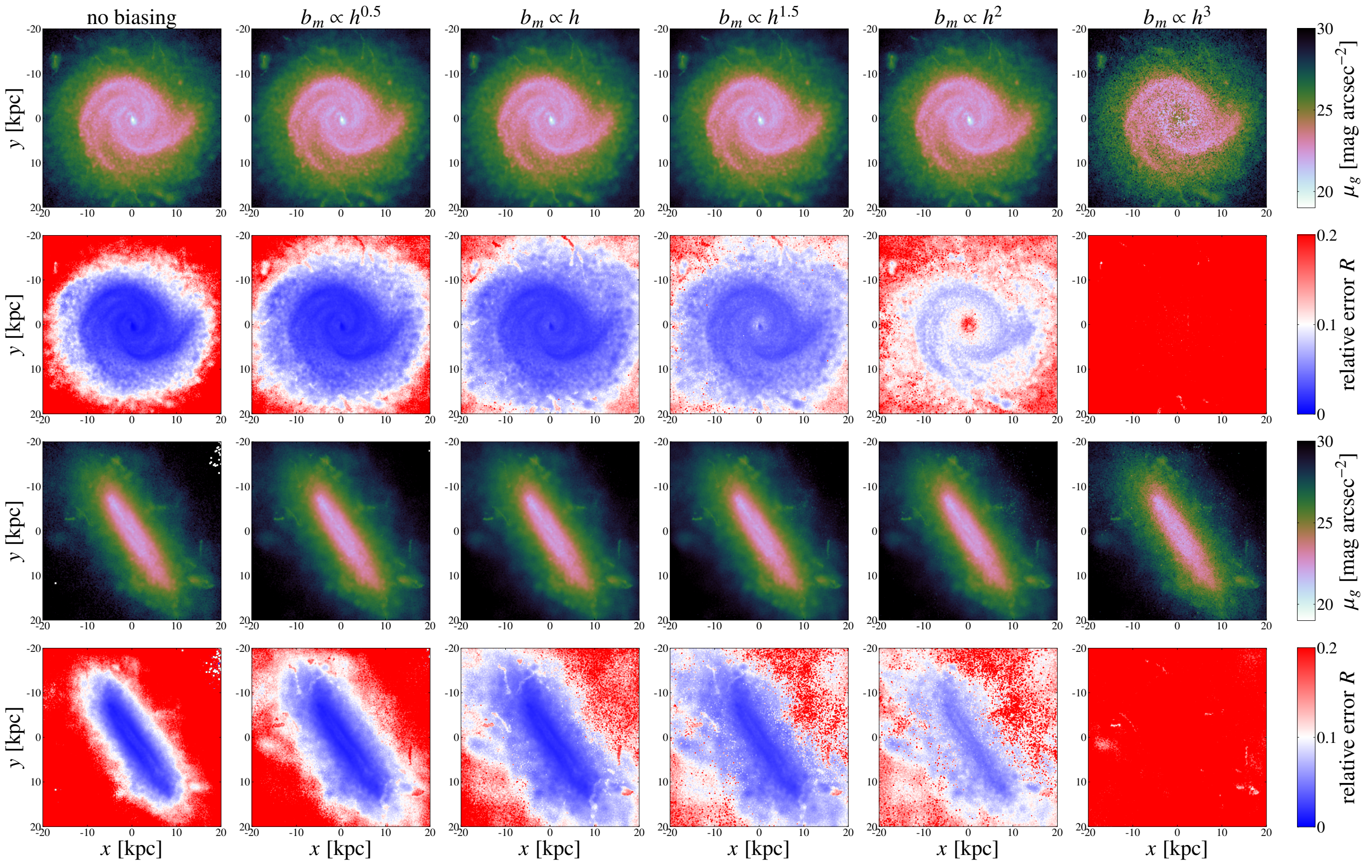

Figure 1. g-band images and relative error maps for SKIRT simulations of the galaxy TNG000008. Images are shown for face-on and edge-on orientations (rows) and six emission-bias schemes, ranging from no biasing to $b_m \propto h^3$ (columns).

A general optimisation technique frequently used in Monte Carlo radiative transfer is biasing: one draws events from a modified pdf and compensates for this by multiplying the photon packet's weight by a correction factor (J. Steinacker et al. 2013). Assigning a bias factor b_m to each particle yields the biased pdf

$$q(m) = \frac{b_m L_m}{\sum_n b_n L_n}, \tag{2}$$

and the corresponding weight correction factor becomes

$$w(m) = \frac{p(m)}{q(m)} = \frac{\sum_n b_n L_n}{b_m \sum_n L_n}. \tag{3}$$

We have implemented this emission-biasing mechanism in SKIRT.[3] To enhance LSB sensitivity, the bias factors should preferentially increase photon emission from low-density regions. A natural choice is to scale b_m with a power of the particle's smoothing length h, which is typically set to the distance to the Nth nearest neighbour. Indeed, because smoothing lengths increase in low-density regions, they provide a natural proxy for identifying particles in the galaxy outskirts where LSB emission originates.

3. ILLUSTRATION

We applied this biasing scheme to synthetic images of the simulated galaxy TNG000008, a Milky-Way-like system from the $z = 0$ snapshot of the TNG50 simulation (A. Pillepich et al. 2019; D. Nelson et al. 2019). The galaxy contains 691k stellar particles, a total stellar mass of 3.73×10^{10} $M_\odot$, and SFR $= 3.98$ $M_\odot$ yr^{-1}. Using the dust-insertion recipe

[3] More generally, SKIRT employs composite biasing (M. Baes et al. 2016) to prevent excessively large correction factors. For clarity, we present here only the basic formulation.

outlined in M. Baes et al. (2024), the galaxy has a dust mass of 5.59×10^7 $M_\odot$. We assign each particle a smoothing length corresponding to the distance to its 32nd-nearest neighbour, as is conventionally adopted (e.g., P. Torrey et al. 2015; V. Rodriguez-Gomez et al. 2019; S. Schulz et al. 2020; M. Baes et al. 2024).

The first and third panels of the left column of Fig. 1 show face-on and edge-on g-band images generated using 10^8 photon packets with natural weighting (i.e., no emission biasing). Each image spans 40 kpc and contains 200×200 pixels. The second and fourth panels display the corresponding R maps, a reliability statistic calculated according to the methodology of X-5 Monte Carlo Team (2003) and P. Camps & M. Baes (2018, 2020). Pixel values with $R < 0.1$ are deemed reliable, and in this case R can be considered as the relative error on the observed surface brightness. On the other hand, pixels with $0.1 < R < 0.2$ are questionable, and those with $R > 0.2$ are unreliable. With natural weighting, only the central HSB regions reach the $R < 0.1$ threshold.

The remaining columns show results obtained with different emission-bias schemes. Because particles with the largest smoothing lengths reside in the outer parts of the galaxy, biasing increases photon emission in these regions while reducing it in the centre. This redistribution is subtle in the images but clearly evident in the relative error maps. For $b_m \propto h$ and $b_m \propto h^{1.5}$, the reliable region ($R < 0.1$) expands significantly, though the reliability in the inner regions decreases modestly. In contrast, $b_m \propto h^2$ shifts too many photon packets to the outskirts, making the central regions unreliable. For even higher powers, such as $b_m \propto h^3$, this effect becomes more extreme and the images are almost completely unreliable. We assessed all biasing schemes by counting pixels with $R < 0.1$ or $R < 0.2$. The choice $b_m \propto h$ performs best, and this conclusion is robust against changes in viewing angle and photon-packet number.

4. CONCLUSIONS

We conclude that emission biasing provides a simple and effective way to generate LSB-optimised synthetic images of simulated galaxies. The implementation in `SKIRT` assigns a user-defined bias factor b_m to each stellar particle. Choosing $b_m \propto h$ offers an optimal balance: it enhances signal-to-noise in the LSB regime while maintaining sufficient reliability in the bright central regions. This approach should facilitate synthetic comparisons with deep imaging surveys such as MATLAS (M. Bílek et al. 2020), LIGHTS (I. Trujillo et al. 2021), or VST-SMASH (C. Tortora et al. 2024), and forthcoming dedicated missions such as ARRAKIHS (R. Guzmán 2024).

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