



# Star Cluster Formation Simulation with a Photoionization Feedback Model Designed for an Inhomogeneous Interstellar Medium

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Doctoral Dissertation  
博士學位論文（要約）

Star Cluster Formation Simulation with a  
Photoionization Feedback Model Designed  
for an Inhomogeneous Interstellar Medium  
(密度非一様性を考慮した大質量星の  
光電離フィードバックモデルを用いた  
星団形成シミュレーション)

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## Abstract

Molecular clouds, or interstellar molecular clouds, primarily composed of hydrogen, serve as the birthplaces of stars. Star formation typically occurs within the high-density cores of these molecular clouds, where gas and dust accumulate under the influence of gravity. The collapse of molecular cores leads to hydrogen nuclear fusion, resulting in the formation of stars.

Stars are believed to form predominantly in clusters, which often contain numerous massive stars (those with masses more than  $8M_{\odot}$ ). The formation mechanisms of these massive stars are considered to be less well understood. Due to their high temperatures and luminosities, the photons they emit ionize the surrounding hydrogen gas, which serves as the primary material for star formation. Other processes such as radiation pressure, stellar winds, and supernova explosions at the end of their life cycles can also significantly impact the surrounding star-forming environment. These effects are collectively known as the feedback mechanisms of massive stars. Studying these mechanisms is crucial not only for understanding star cluster formation but also for galaxy formation on a larger scale.

This study primarily focuses on the hydrogen photoionization feedback of massive stars that occurs during the early stages of massive star formation. This feedback is believed to have significant implications for subsequent star formation in the surrounding environment and the evolution of galaxies. Different morphologies of ionized structures affect the subsequent star formation process to different degrees, so we need to capture the more realistic morphology of ionized structures in our simulation studies.

Strömgren (1939) proposed a theoretical model for hydrogen photoionization regions, considering a scenario where the hydrogen gas surrounding a massive star is distributed sufficiently far and uniformly, with the presence of interstellar dust being neglected. In this model, the photoionized region is spherically symmetric. When the interior of this region is considered fully ionized and reaches a steady state, with ionization and recombination in equilibrium, the radius of the ionized region can be determined by the Strömgren sphere equation, known as the Strömgren radius.

However, due to the inherent inhomogeneity of actual star-forming regions, using this theoretical model in simulations inevitably leads to various errors. Another approach that directly handles radiative hydrodynamics is also employed in star evolution and other scales of simulation usually, it can address the photoionization process of massive stars accurately. This method can account for the inhomogeneous density distributions within star-forming regions. However, compared to the simpler model, it is computationally much more complex. Consequently, when dealing with large-scale star cluster formation, galaxy formation, or high-resolution simulations, the computational cost becomes exceedingly high, surpassing the capabilities of current supercomputers.

In this study, we introduced a model that independently evaluates the ionization structure in each direction of an icosahedron, incorporating the spatial inhomogeneity of star-forming regions in a simplified manner. This model is designed to account for the actual conditions of star-forming regions while managing large-scale, high-resolution astrophysical simulations with lower computational costs. We implemented and assessed this model within the  $N$ -body/smoothed particle hydrodynamics code ASURA+BRIDGE. Using a molecular cloud with an internal turbulent velocity field as the initial condition, we set

up multiple molecular cloud scales, ranging from small to large, with  $5,000M_{\odot}$ ,  $10,000M_{\odot}$ ,  $15,000M_{\odot}$ ,  $50,000M_{\odot}$  and  $500,000M_{\odot}$  the initial total gas mass, and compared clouds with different initial virial ratios ( $\alpha_{\text{vir}} = |E_K|/|E_P| = 0.5\&1$ ). To obtain statistically significant results, we also performed five sets of comparative calculations for several of the molecular clouds, each with five different initial random seeds. Additionally, we conducted comparative simulations using a spherical model based on the Strömgren sphere.

These simulations reproduced the anisotropic ionization structures corresponding to inhomogeneous density distributions in each direction for each massive star, as well as the corresponding anisotropic outflows during the evolution of the star formation process. In contrast, the spherical model only exhibited a purely spherical ionization structure, with a simple shell-like distribution of ionized hydrogen in the star formation simulation. Statistical results from multiple simulations indicated that the purely spherical model had a stronger suppressive effect on star formation compared to the icosahedral model. The total stellar mass formed in the icosahedral model is more than 1.5 times greater than that in the spherical model, which we attribute to the accelerated termination of star formation due to the unidirectional energy concentration in the spherical model. Other properties of the initial molecular cloud have not been shown to have a large impact on the performance of the two models in the current simulation experiments for the time being. Due to the ease of implementation and low computational consumption of this model, we will not only be able to use it for a more realistic analysis of ionization configurations in star cluster simulations, but we will also be able to apply it more readily to large-scale simulations such as Galactic-scale simulations that can handle single stars with lower computational effort and higher accuracy.

This thesis is organized as follows: In Chapter 1, We introduce the background and objectives of this study, including an overview of the physical processes involved in star formation, such as the formation of stars and the feedback mechanisms of massive stars, as well as star cluster formation simulations. We will also discuss commonly used simulation methods, with a focus on various approaches employed in prior research to handle the photoionization feedback of massive stars. The chapter concludes with the research objectives of this study. In Chapter 2, we will describe the research methodology, present the numerical methods, and introduce the codes used in this study. We will then introduce the new HII region feedback model developed for this research, along with the other feedback mechanisms employed in the simulations. The chapter will conclude with an explanation of the initial conditions set for all simulations conducted in this study. Chapter 3 and 4 will present the results of the study, including the properties of the ionization structures of massive stars and star formation after applying the new model to star cluster-scale simulations. The results will include a comparison between the theoretical spherical model and the new model, as well as the impact of different properties of molecular clouds with different initial conditions.

Chapter 5 will include a discussion on the effectiveness of the icosahedral HII region model, its performance in large-scale, high-resolution star cluster formation and evolution simulations, and an analysis of the statistical results obtained from multiple initial random seed conditions in our simulations, including the influence of randomness on the outcomes. Additionally, the feasibility of applying the new model to the formation and evolution of larger-scale systems, such as galaxies, will

be explored. The final chapter will provide a summary and conclusions of this study.