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STARFORGE: Toward a comprehensive numerical model of star cluster formation and feedback

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ABSTRACT
We present STARFORGE (STAR FORmation in Gaseous Environments): a new numerical framework for 3D radiation MHD simulations of star formation that simultaneously follow the formation, accretion, evolution, and dynamics of individual stars in massive giant molecular clouds (GMCs) while accounting for stellar feedback, including jets, radiative heating and momentum, stellar winds, and supernovae. We use the GIZMO code with the MFM mesh-free Lagrangian MHD method, augmented with new algorithms for gravity, timestepping, sink particle formation and accretion, stellar dynamics, and feedback coupling. We survey a wide range of numerical parameters/prescriptions for sink formation and accretion and find very small variations in star formation history and the IMF (except for intentionally-unphysical variations). Modules for mass-injecting feedback (winds, SNe, and jets) inject new gas elements on-the-fly, eliminating the lack of resolution in diffuse feedback cavities otherwise inherent in Lagrangian methods. The treatment of radiation uses GIZMO's radiative transfer solver to track 5 frequency bands (IR, optical, NUV, FUV, ionizing), coupling direct stellar emission and dust emission with gas heating and radiation pressure terms. We demonstrate accurate solutions for SNe, winds, and radiation in problems with known similarity solutions, and show that our jet module is robust to resolution and numerical details, and agrees well with previous AMR simulations. STARFORGE can scale up to massive ($> 10^5 M_\odot$) GMCs on current supercomputers while predicting the stellar ($\gtrsim 0.1 M_\odot$) range of the IMF, permitting simulations of both high- and low-mass cluster formation in a wide range of conditions.

Key words: stars: formation – ISM: general – MHD – turbulence – methods: numerical – radiative transfer

1 INTRODUCTION

Many physical mechanisms are important in star formation (SF). It is initiated by the formation of radiatively-cooled, gravitationally-unstable cores of gas and dust from magnetized, supersonic, turbulent flows found in giant molecular clouds (GMCs) (Larson 1981; Mac Low & Klessen 2004; McKee & Ostriker 2007; Girichidis et al. 2020). These cores collapse to protostars, and once formed, protostars and stars influence the surrounding gas flow in via feedback: the injection of mass, momentum and energy into the ISM in the form of radiation, accretion-powered collimated bipolar outflows (hereafter simply "jets"), radiatively-driven stellar winds, and supernova (SN) explosions, which may ultimately limit the total stellar mass that can form. The accretion of individual stars is eventually truncated by feedback, gas exhaustion, or dynamical interactions with gas clumps or other stars, setting their final masses (Krause et al. 2020). Hence, the problem of SF is an intricate, tightly-coupled interaction of gravity, magnetohydrodynamics (MHD), atomic and molecular physics, radiation, stellar physics, and feedback.

A basic requirement of any star formation theory is to explain the hallmark phenomena of SF, including the stellar initial mass function (IMF), the (in-)efficiency of SF, and the properties of stellar clusters and associations (Krumholz 2014). These phenomena must emerge from the various processes at work in GMCs, so it is important to disentangle the physics' respective roles. This has yet to be accomplished, partly because the wide range of length-scales and multitude of physics involved make SF very challenging to model.

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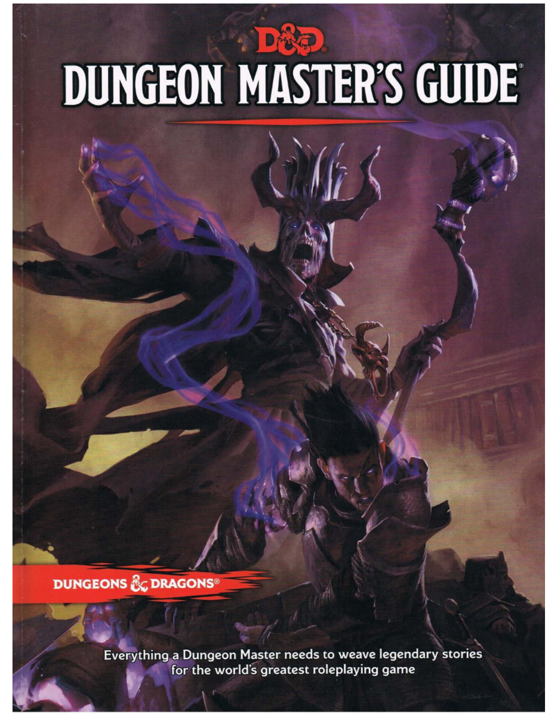

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The dynamics and outcome of star formation with jets, radiation, winds, and supernovae in concert

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ABSTRACT
We analyze the first giant molecular cloud (GMC) simulation to follow the formation of individual stars and their feedback from jets, radiation, winds, and supernovae, using the STARFORGE framework in the GIZMO code. We evolve the GMC for ~ 9Myr, from initial turbulent collapse to dispersal by feedback. Protostellar jets dominate feedback momentum initially, but radiation and winds cause cloud disruption at ~ 8% star formation efficiency (SFE), and the first supernova at 8.3Myr comes too late to influence star formation significantly. The per-freefall SFE is dynamic, accelerating from 0 to ~ 18% before dropping quickly to <1%, but the estimate from YSO counts compresses it to a narrower range. The primary cluster forms hierarchically and condenses to a brief (~ 1 Myr) compact (~ 1pc) phase, but does not virialize before the cloud disperses, and the stars end as an unbound expanding association. The initial mass function resembles the Chabrier (2005) form with a high-mass slope $\alpha = -2$ and a maximum mass of $55 M_\odot$. Stellar accretion takes ~ 400kyr on average, but $\gtrsim$ 1Myr for $> 10 M_\odot$ stars, so massive stars finish growing latest. The fraction of stars in multiples increases as a function of primary mass, as observed. Overall, the simulation much more closely resembles reality, compared to previous versions that neglected different feedback physics entirely. But more detailed comparison with synthetic observations will be needed to constrain the theoretical uncertainties.

Key words: stars: formation – ISM: general – magnetohydrodynamics – turbulence – radiative transfer

1 INTRODUCTION

The basic story of how stars form has long been established: they form mainly in giant molecular clouds (GMCs) with masses $\sim 10^4 - 10^7 M_\odot$ (Goldreich & Kwan 1974; Zuckerman & Evans 1974; Williams & McKee 1997), due to the fragmentation and collapse of gravitationally-unstable cores (Jeans 1902; Larson 1969; Rosen et al. 2020). New stars generally form in relative proximity to other young stars, i.e. in clusters (Lada & Lada 2003; Krumholz et al. 2019). Yet many important details of star formation (SF) are not well understood, such as *why* stars have the particular masses that they do (i.e. the origin of the initial mass function, IMF), why and how they form in clusters, why they apparently form with such low efficiency, and why some are in multiple systems and others are not.

Theoretical and computational models can offer insights into these questions, but it has proven challenging to produce a detailed model of SF realistic enough to reproduce the basic hallmarks of star formation. Star-by-star simulations of star cluster formation have progressed for more than two decades (Klessen & Burkert 2000; Bate et al. 2003; Offner et al. 2009; Federrath et al. 2010; Haugbølle et al. 2018; Cunningham et al. 2018; Mathew & Federrath 2021), but only recently have started simulating star formation over the spatial (10 + pc), temporal (several Myr) and GMC mass ($\gtrsim 10^4 M_\odot$) scales that are directly comparable to well-studied nearby star-forming GMCs and young star clusters (e.g. Hillenbrand & Hartmann 1998; Hsu et al. 2012; Evans et al. 2014; Pokhrel et al. 2020), where important quantities such as star formation efficiency and the IMF are the most well-constrained, and massive ($\gtrsim 10 M_\odot$) stars can form.

In Guszejnov et al. (2020) (hereafter Paper 0) we ran a large suite of GMC simulations accounting for gravity and MHD turbulence with the GIZMO code's Meshless Finite-Mass (MFM) method (Hopkins & Raives 2016). We found these models inevitably predicted excessively-high star formation efficiency and an extreme excess of massive stars in Milky Way-like conditions, implying that additional mechanisms are important for star formation, and in particular some form of feedback must moderate stellar accretion. In Grudić et al. (2021a) (hereafter Paper I) we introduced the more-advanced STARFORGE[1] framework for the GIZMO code, combining modules for gravity, N-body dynamics, MHD, radiative transfer, cooling and

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