STARForge

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

Paper: arXiv:2201.00882 (MNRAS accepted)

Our Galactic Ecosystem:
Opportunities and Diagnostics in the Infrared and Beyond
February 28 2022

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STAR FORMATION: I HAVE QUESTIONS 🤔

**GMCs**

CO (1-0) in M51: Schinnerer+13

**Stars**

R136 (ESA/Hubble)

PHYSICS HAPPENS
STAR FORMATION: I HAVE QUESTIONS 😐

GMCs •Life cycle of GMCs and star clusters?

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- IMF - why? Universal or variations?

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- Star formation efficiency?
- Multiplicity?
- How do stars get their mass?

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• Life cycle of GMCs and star clusters?
• IMF - why? Universal or variations?
• Star formation efficiency?
• Multiplicity?
• How do stars get their mass?
• How does feedback work?
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- How do stars get their mass?
- How does feedback work?
Simulating star formation
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High-resolution boxes/clumps:
• Total gas mass <10³ M☉
• Sometimes IR radiation and/or protostellar jets

Bate 2003

Federrath 2015

Cunningham 2018
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Global GMC simulations that do not resolve the IMF:
- Can survey much larger masses (entire GMCs)
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- But can’t resolve individual stars

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Kim 2018
Li 2019
Grudić 2018
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Simulating star formation

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3. Can scale up to massive (>10^4 M☉) GMCs
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4. Run from start to finish of SF (~10 Myr)
Simulating star formation

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STARFORGE

- GIZMO MFM MHD
- N-body dynamics
- Individual star formation
- Cooling/Chemistry
- Jets
- Stellar Winds
- Radiation
- Supernovae

STARFORGE methods paper (arXiv:2010.11254)

Mike Grudić & Collaboration
The Simulation

Full STARFORGE physics - Grudić et al. 2022 arXiv:2201.00882

https://www.youtube.com/watch?v=LeX5e51UkszI
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Star Cluster Evolution

$M_{\text{tot}}(M_{\odot})$

$t/t_{ff,0}$

50% of mass

Time (Myr)

0  1  2  3  4  5  6  7  8  9

0  1  10  100  1000  10000  100000

0.1
Star Cluster Evolution

\[ M^\text{tot}_* (M_\odot) \]

50% of mass

Time (Myr)

0 1 2 3 4 5 6 7 8 9

0.1 1 10 100 1000 10000 100000

\[ t/t_{ff,0} \]

0yr

10pc
Star Cluster Evolution

The graph shows the evolution of a star cluster over time, with the x-axis representing time in Myr (10^6 years) and the y-axis representing the total mass and number of stars. Key milestones include:

- At 4 Myr, 50% of the stars have formed.
- At 5 Myr, 50% of the mass has been formed.

The graph includes lines for:

- $M^{\text{tot}} (M_{\odot})$ (purple line)
- $N_\star$ (green line)

The x-axis is labeled $t/t_{\text{ff},0}$.
Star Cluster Evolution

![Graph showing the evolution of star clusters over time.](image)

- $M^\text{tot} (M_\odot)$
- $N_*$
- $R^\text{eff} (\text{pc})$

Key points:
- 50% of stars
- 50% of mass

Time (Myr): 0 to 9

$t/t_{ff,0}$ Scale: 0 to 2
Star Cluster Evolution

- $M_\text{tot}^\text{star} (M_\odot)$
- $N_\ast$
- $R_\ast^\text{eff} (\text{pc})$
- $\sigma_\ast (\text{km s}^{-1})$

Time (Myr): 0 to 9

$t/t_{\text{ff,0}}$: 0 to 2

50% of stars
50% of mass
Star Cluster Evolution

![Graph showing the evolution of various properties of star clusters over time.](image)

- $M^\text{tot}_* (M_\odot)$
- $N_*$
- $R^\text{eff}_* (\text{pc})$
- $\sigma_* (\text{km s}^{-1})$
- $|\vec{v}_r| (\text{km s}^{-1})$

Time (Myr) vs. $t/t_{\text{ff},0}$
Star Cluster Evolution

![Graph showing the evolution of various star cluster properties over time.](image)

- $M^\text{tot}_*$ ($M_\odot$)
- $N_*$
- $R^\text{eff}_*$ (pc)
- $\sigma_*$ (km s$^{-1}$)
- $|\vec{u}_r|$ (km s$^{-1}$)
- $\rho^\text{eff}_*$ ($M_\odot$ pc$^{-3}$)

50% of stars, 50% of mass
Star Cluster Evolution

The diagram shows the evolution of various properties of a star cluster over time, normalized to $t_{ff,0}$. The properties include:

- $M^\text{tot}_*$ (M$_\odot$)
- $N_*$
- $R^\text{eff}_*$ (pc)
- $\sigma_*$ (km s$^{-1}$)
- $|\vec{v}_r|$ (km s$^{-1}$)
- $\rho^\text{eff}_*$ (M$_\odot$ pc$^{-3}$)
- $\rho^\text{NN}_*$ (M$_\odot$ pc$^{-3}$)

Key features include:

- 50% of stars
- 50% of mass
Feedback Evolution
Feedback Evolution

The graph shows the evolution of the luminosity of the accretion disk ($L_{acc}$) over time ($t$), normalized by the feedback time scale ($t_{ff,0}$). The x-axis represents time in Myr (million years), while the y-axis represents the luminosity in units of $L_\odot$. The data exhibits a increasing trend with fluctuations, indicating a dynamic process of feedback in the system.
Feedback Evolution

\[ \frac{L_{\text{acc}}}{L_\odot} \quad \frac{L_{\text{fus}}}{L_\odot} \]

\[ 0 \quad 1 \quad 2 \]

Time (Myr)
Feedback Evolution

![Graph showing the evolution of various luminosity components over time.](image)
Feedback Evolution

\[ L_{\text{acc}} (L_\odot) \]
\[ L_{\text{fus}} (L_\odot) \]
\[ L_{\text{tot}} (L_\odot) \]
\[ \dot{P}_{\text{wind}} (L_\odot / c) \]

Time (Myr)

0 1 2 3 4 5 6 7 8 9

0 10^3 10^4 10^5 10^6 10^7
Feedback Evolution

\[ L_{\text{acc}} (L_\odot) \]
\[ L_{\text{fus}} (L_\odot) \]
\[ L_{\text{tot}} (L_\odot) \]
\[ P_{\text{wind}} (L_\odot / c) \]
\[ P_{\text{jets}} (L_\odot / c) \]

Time (Myr): 0, 1, 2, 3, 4, 5, 6, 7, 8, 9

\[ t / t_{f,0} \]

Logarithmic scale on the y-axis from 10 to 10^7.
Feedback Evolution

$0 \leq t/t_{ff,0} \leq 2$

$L_{\text{acc}} (L_\odot)$
$L_{\text{fus}} (L_\odot)$
$L_{\text{tot}} (L_\odot)$
$\dot{P}_{\text{wind}} (L_\odot/c)$
$\dot{P}_{\text{jets}} (L_\odot/c)$

Time (Myr)

$0 \leq t \leq 9$
Feedback Evolution

![Graph showing the evolution of various quantities over time.](image)

- $L_{\text{acc}} (L_\odot)$
- $L_{\text{fus}} (L_\odot)$
- $L_{\text{tot}} (L_\odot)$
- $P_{\text{wind}} (L_\odot/c)$
- $P_{\text{jets}} (L_\odot/c)$
- $GM^2/R^2 (L_\odot/c)$

Time (Myr):
- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

$t/t_{\text{ff},0}$
Star Formation Efficiency - $\epsilon$
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SFE $\sim$ Bremmstrahlung / CO emission

Per-freefall SFE (%)

$t/t_{\text{ff},0}$

0 1 2

0 1 10 100

Time (Myr)

0 1 2 3 4 5 6 7 8 9

$\varepsilon_{\text{ff},\rho_0}$

$\varepsilon_{\text{ff,br}}$
Star Formation Efficiency - $\varepsilon_{\text{eff}}$

- $SFE \sim \text{Bremmstrahlung} / \text{CO emission}$
- $SFE \sim N_{\text{YSOS}} / \text{dust mass}$
The Long Road to the IMF
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![Graph showing the distribution of initial mass functions (IMFs) with two different models: Standard IMF (Chabrier 2005) and Isothermal MHD. The graph plots the number of star masses per mass bin against mass, showing the IMF's distribution from low to high mass.]
The Long Road to the IMF

- Standard IMF (Chabrier 2005)
- Isothermal MHD
- Cooling + MHD

$dN/dM_{ZAMS} \ (M_\odot^{-1})$ vs $M_{ZAMS} \ (M_\odot)$
The Long Road to the IMF

![Graph showing the distribution of mass in different IMF models.](image)
The Long Road to the IMF

![Graph showing the IMF distribution with various models including Standard IMF, Isothermal MHD, Cooling + MHD, Cooling + Jets + MHD, and Full Physics.](image-url)
The Long Road to the IMF

Jets set the IMF turnover/avg. stellar mass

\[ \frac{dN}{dM_{\text{ZAMS}}}(M_\odot^{-1}) \]

\[ M_{\text{ZAMS}}(M_\odot) \]

- Standard IMF (Chabrier 2005)
- Isothermal MHD
- Cooling + MHD
- Cooling + Jets + MHD
- Full Physics

Incomplete
The Long Road to the IMF

Jets set the IMF turnover/avg. stellar mass

Radiation + winds from massive stars regulate high-mass tail

\[ \frac{dN}{dM_{\text{ZAMS}}} (M_\odot^{-1}) \]

\[ M_{\text{ZAMS}} (M_\odot) \]

- Standard IMF (Chabrier 2005)
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- Cooling + Jets + MHD
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The Long Road to the IMF

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See upcoming STARFORGE IMF paper by Dávid Guszejnov
Magnetic fields in STARFORGE Simulations

Clearly feedback is important - but what about magnetic fields?
Magnetic field vs. density

$B$ at high densities insensitive to low-density field strength - asymptotes to $v_A \sim c_s \sim 0.2 \text{ km s}^{-1}$ - see also Wurster+19, Guszejnov+20
Effect of magnetic fields on SFE

Many effects likely at work:
• Confinement of HII regions suppressing blowout? (e.g. Krumholz 2007)
• Anisotropic accretion \rightarrow less massive SF \rightarrow less feedback (e.g. Lee 2014)
• Suppression of fragmentation \rightarrow slower SF \rightarrow feedback less apt to “overshoot”
Star formation at high $B$ ($20\mu$G; $\mu = 0.42$)

0.23Myr

10pc
Star formation at high $B$ ($20\mu G; \mu = 0.42$)

$0.23\text{Myr}$
Effect of magnetic fields on the IMF
Effect of magnetic fields on the IMF

- Standard IMF (Chabrier 2005)
- $\mu = 4.2$ (fiducial weak field; $2\mu G$)
- $\mu = 1.3$ (moderate field; $7\mu G$)

![Graph showing the effect of magnetic fields on the IMF](image-url)
Effect of magnetic fields on the IMF
Where are the disks? 😳

Very high-resolution ($10^{-5}$Msun, ~1AU resolution) MHD STARFORGE simulations that should resolve disks show a “braking catastrophe”
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Summary
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- Key phenomena reproduced: IMF, SFE - different feedback channels must work together! Jets ❤️ Radiation ❤️ Winds ❤️ SN
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  - Strong field has slower, more quiescent SFR until SNe go off
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    • Strong field has fewer massive stars (i.e. steeper IMF)
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  - Strong field has slower, more quiescent SFR until SNe go off
  - Strong field has fewer massive stars (i.e. steeper IMF)
  - No disks in any high-resolution ideal MHD runs - non-ideal MHD needed?
GMC initial conditions: can we do better?
Lane, Grudić, et al. 2022MNRAS.510.4767L
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Henry Lane
Pennsbury High School, PA
Caltech
Feedback Coupling Methods

1. Local injection
   Inject mass/momentum/energy into pre-existing cells conservatively

2. Cell spawning
   Create new Lagrangian gas cells, still conserving COM/momentum to machine precision
Meshless Lagrangian MHD with GIZMO

Mach 9 Supersonic MHD Turbulence

0yr

1.2pc
Meshless Lagrangian MHD with GIZMO

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- Timestep not constrained by $\Delta t = \Delta x/v$ - MUCH faster with jets/winds/disks
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- Timestep not constrained by $\Delta t = \Delta x/v$ - MUCH faster with jets/winds/disks
- Less diffusive in supersonic flows than AMR (e.g. Roberston 2010, Pontzen 2020)
Protostellar Jets

- Jet launching powered by accretion onto the disk/protostar

- Very important for regulating stellar accretion, the IMF, SFE on <1pc scales (e.g. Rosen & Krumholz 2020, Guszejnov+2021MNRAS.502.3646G,)

- Use phenomenological model (Cunningham 2011)

- Use cell spawning technique
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Radiation

Radiative transfer in 5 bands:

- LyC (13.6+eV)
- Photoelectric (8-13.6eV)
- NUV (3.4-8eV)
- Optical/NIR (0.4-3.4eV)
- Far-mid IR (0-0.4eV)

Solved with GIZMO's M1 RMHD solver (Hopkins & Grudić 2018, Hopkins et al. 2020)
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- Inject winds from OB and WR stars
- Simple phenomenological prescription following Smith 2014
- Adaptive hybrid method: Use local injection if free expansion cannot be resolved, cell spawning if it can

9.8 yr

10 pc
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Supernovae

• >8M☉ stars undergo a $10^{51}$ erg supernovae at the end of their life

• Use cell spawning to directly resolve ejecta and free expansion

0.0098 yr

10 pc
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