Cosmic rays in-situ injection in protostars
Insight from 3D numerical experiments

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Local CR acceleration

Figure 1 from Pineda et al. (2024) illustrates an increasing CR ionization rate (ζ_{H_2}) in the dense envelope surrounding YSOs, which may result from several particle acceleration mechanisms in protostars. One of the most possible mechanisms in the YSO environment is: **Diffusive shock acceleration** (*Figure 2*). Charged particles acquire energy as they traverse the protostar jet shock front (Padovani et al. 2016).

The transition from an ideal to a non-ideal MHD regime is largely governed by the ζ_{H_2} which determines the coupling strength between the magnetic field and the surrounding gas. Given that non-ideal environments are highly conducive to disk formation, we implement the two-moment CR physics module within the RAMSES framework to explore how cosmic rays shape these environments.

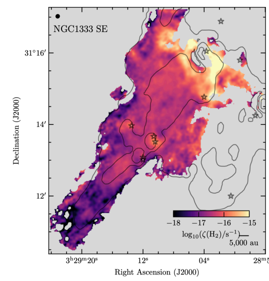

Figure 1: The star icons indicate the YSOs position.

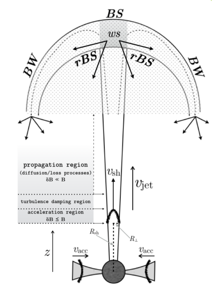

Figure 2: Sketch of the protostar jet configuration

CR Physcis

Two-moment CR Transport Equation (Rosdahl et al. 2025)

$$\frac{\partial e_c}{\partial t} + \vec{\nabla} \cdot \vec{F}_c = \vec{u} \cdot (\vec{\nabla} \cdot P_c) + \dot{e}_{c,inj} - \Gamma_{loss}$$

$$\frac{1}{\tilde{c}^2}\frac{\partial \vec{F}_c}{\partial t} + \vec{\nabla} \cdot P_c = -\sigma^{-1} \cdot [\vec{F}_c - \vec{u} \cdot (e_c + P_c)]$$

CR Energy Loss (Armillotta et al. 2024)

$$\Gamma_{loss} = \Lambda_c e_c n_H, \ \Lambda_c = 7.51 \times 10^{-16} \text{ @ 100 MeV}$$

CR ionization rate (Armillotta et al. 2021)

$$\zeta_{H_2} = \frac{\nu_p n_c(E_k) L_{ion}(E_k)}{\epsilon}, \quad L_{ion}(E_k) = L_0 \left(\frac{E_k}{E_0}\right)^{-0.82}$$

n_H: hydrogen number density
ν_p: CR proton velocity
n_c: CR number density
e_c: CR energy density
F_c: CR flux
P_c: CR pressure
$e_{c,inj}$: CR injection term
Γ_{loss}: CR energy loss term
$\tilde{c}$: Reduced speed of light
σ: Diffusion coefficient
ζ_{H_2}: CR ionization rate

RAMSES Simulation

The table and figure show the two initial conditions configursations:
- **One solar mass** isolated dense core collapse
- **B335 protostar** (Maury et al. 2018) collapse

RAMSES (Teyssier 2002) Simulation with the following physics:
- Non-ideal MHD solver (only ambipolar diffusion)
- Two-moment CR physics
- Sink particle (~1% of sink luminosity turns to CR energy)
- External CR energy includes ($\zeta_{H_2} \sim 10^{-17}$) at the boundary

	B335	1 $M_\odot$
$M_\odot$ - Core Mass	2.5	1.0
α - Thermal / Grav.	0.35	0.4
β - Rotation / Grav.	0.001	0.04
μ - Mass to flux ratio	6.67	3.33
θ (°) - Inclination	30	10
Δx (AU) - Resolution	1	1
ℓ - AMR levels	6 - 15	6 - 14

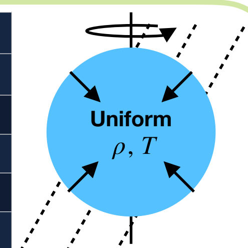

Figure 3: Uniform density and temperature dense core collapse model in our simulation

Simulation Results

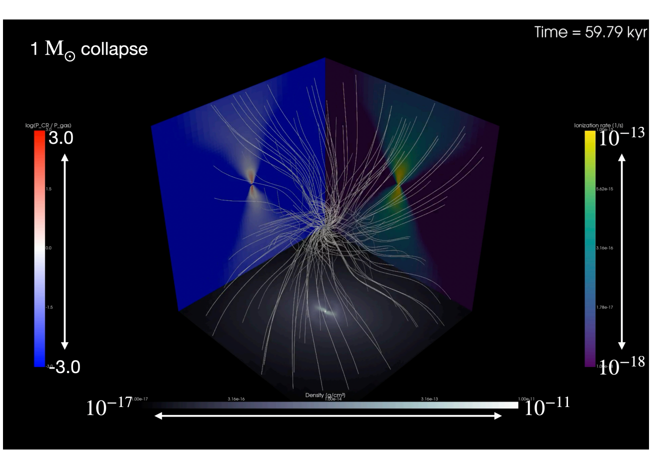

Figure 4

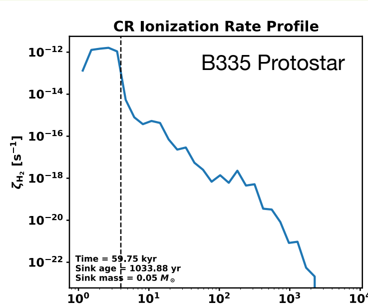

Figure 5

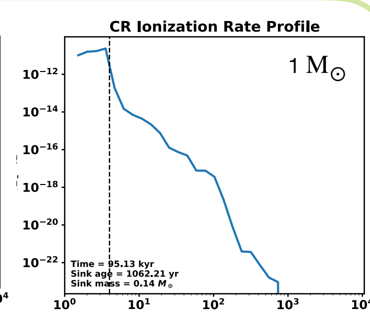

Figure 6

Figure 4: The left bottom walls of the box show the P_c/P_{gas}, the bottom wall shows the gas density, and the right wall shows the CR ionization rate. White lines indicate magnetic field lines.
Figures 5 and 6: The dashed line indicates the sink particle radius. The in-situ CR builds high $\zeta_{H_2} \sim 10^{-14}$ around YSOs in both initial conditions.

Conclusions

- Cosmic rays are an active factor in star/disk formation
- The high CR ionization rate can reach and is consistent with observations, whereas the typical background value is $10^{-17} s^{-1}$.
- The diffusion coefficient (σ) is highly uncertain in star-forming regions and requires careful constraint.
- Self-Consistency Resistive Non-ideal MHD solver is working in progress because CR ionized the surrounding gas changes the ion fraction -> Updating non-ideal MHD coefficient on-the-fly is mandatory.

Referecnes

Armillotta, L., Ostriker, E. C., & Jiang, Y.-F. 2021, ApJ, 922, 11
Brunn, V., Marcowith, A., Sauty, C., et al. 2023, MNRAS, 519, 5673
Brunn, V., Rab, C., Marcowith, A., et al. 2024, MNRAS, 530, 3669
Fitz Axen, M., Offner, S., Hopkins, P. F., Krumholz, M. R., & Grudić, M. Y. 2024, ApJ, 973, 16
Maury, A. J., Girart, J. M., Zhang, Q., et al. 2018, Monthly Notices of the Royal Astronomical Society, 477, 2760
Padovani, M., Marcowith, A., Hennebelle, P., & Ferrière, K. 2016, A&A, 590, A8
Pineda, J. E., Sipilä, O., Segura-Cox, D. M., et al. 2024, A&A, 686, A162
Rosdahl, J., Dubois, Y., Commercon, B., et al. 2025 (arXiv)
Teyssier, R. 2002, A&A, 385, 337