Revealing Fundamental Processes of Filament-Filament Collisions: Toward Understanding the Hub-Filament Paradigm

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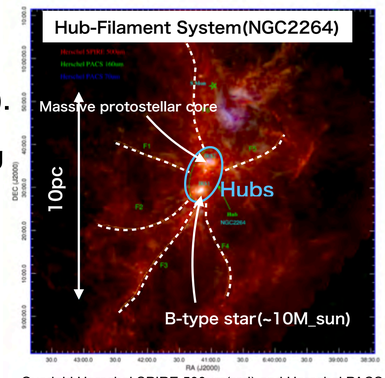
Background & Motivation

✦Star formation in filaments

- Filamentary molecular clouds = primary star-forming sites (e.g., André et al. 2014).
- Active star formation occurs at filament junctions —> “Hub-Filament Systems(HFSs)” (Myers 2009).

✦Hub-Filament Paradigm

- Almost all of the massive stars form at HFSs (Kumar et al. 2020).
- Considering the structure of HFSs is essential for understanding the processes of massive star formation.
- However the physical origin of hub structures remains unclear.
- One promising mechanism is the collision of filamentary clouds (Tokuda et al. 2019; Kumar et al. 2020).



Overlaid Herschel SPIRE 500μm(red) and Herschel PACS 160μm(green) and 70μm(blue) (Kumar et al. 2020)

✦Purpose of this study

- Revealing the evolutionary processes of filament–filament collisions.
- Identifying the conditions under which the shocked region becomes gravitationally unstable.

—> Advancing our understanding of how hub–filament systems form and evolve.

Moethods

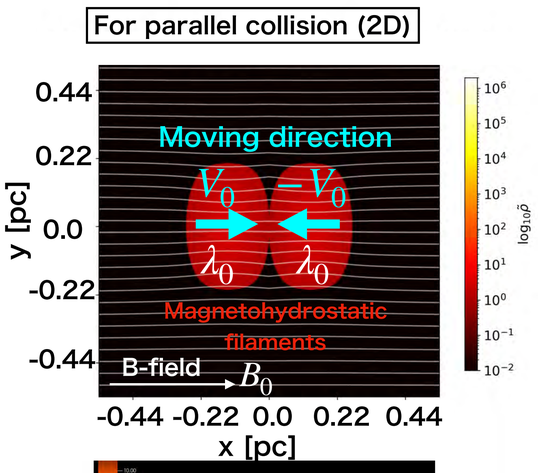
✦We performed ideal magnetohydrodynamic simulations with self-gravity for parallel and orthogonal filament–filament collisions.

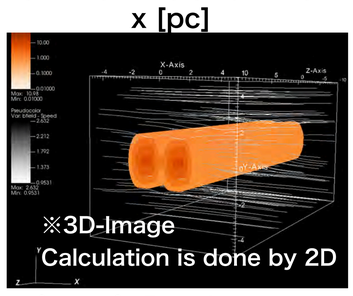
Simulation code : Athena++(Stone et al.2020, Tomida & Stone 2023)
Numerical Computation : XC50(CfCA/NAOJ)

✦Numerical Setup

- Collisions of the isothermal infinite filaments which has the same line mass.
- The magnetohydrostatic equilibrium filament threaded by lateral magnetic field (Tomisaka 2014; Kashiwagi&Tomisaka 2021)
- Moving direction is parallel to the B-field.
- The isothermal equation of state is maintained even after the collision

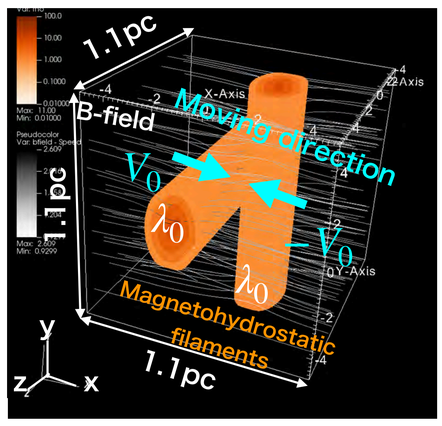
For parallel collision (2D)





Mesh: 8192^2 or 4096^2 Box size: ± 0.55 [pc]
Resolution: $\Delta x \simeq 1.3 \times 10^{-4}$ [pc] or 2.6×10^{-4} [pc]
Numerical limit: $\rho_{\rm lim} \simeq 1.6 \times 10^{9}$ or 4.1×10^{8} [cm^{-3}]

For orthogonal collision (3D)



Mesh: 512^3 Box size: ± 0.55 [pc]
Resolution: $\Delta x \simeq 2.1 \times 10^{-3}$ [pc]
Numerical limit: $\rho_{\rm lim} \simeq 6.5 \times 10^{6}$ [cm^{-3}]

Parameters

B-field strength: $B_0 \simeq 6\,\mu\mathrm{G} - 60\,\mu\mathrm{G}$

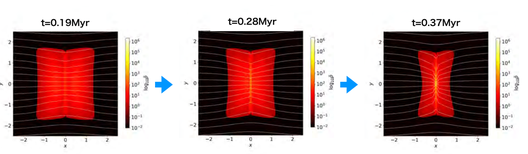
Line mass: $\lambda_0 \simeq 9.4 - 61.2\,M_\odot \mathrm{pc}^{-1}$ (Parallel)

$\lambda_0 \simeq 7.5 - 61.2\,M_\odot \mathrm{pc}^{-1}$ (Orthogonal)

Collision velocity: $V_{\rm int} = 2V_0 \simeq 0.19 - 1.90\,\mathrm{km\,s^{-1}}$
Assuming velocity dispersions within the molecular clouds.

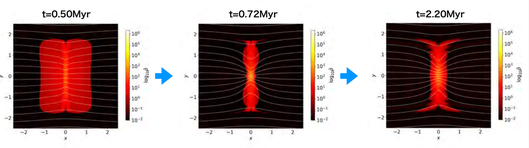
Results (parallel collisions)

★: collapse mode $B_0 = 19\mu\mathrm{G}, V_0 = \pm 0.5c_s, \lambda_0 = 22.9M_\odot\mathrm{pc}^{-1}$

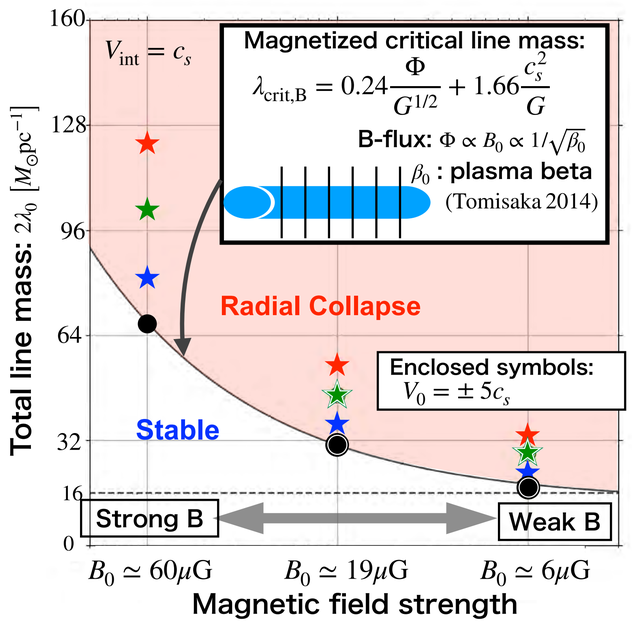


The shocked cloud undergoes radial gravitational collapse.

●: stable mode $B_0 = 19\mu\mathrm{G}, V_0 = \pm 0.5c_s, \lambda_0 = 15.3M_\odot\mathrm{pc}^{-1}$



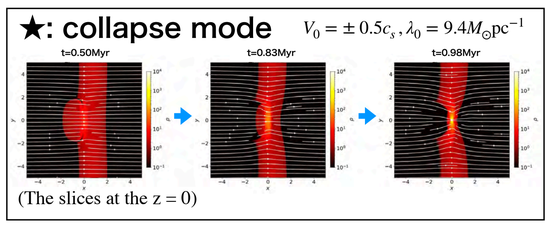
The shocked cloud does not collapse but exhibits a stable oscillation.



For parallel collisions, $\lambda_{\rm crit,B}$ can divide the evolution of filaments into two: radial collapse and the stable modes.

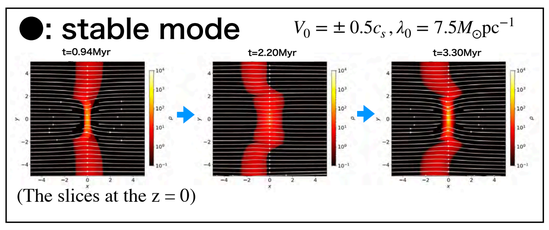
Results (orthgonal collisions)

★: collapse mode $V_0 = \pm 0.5c_s, \lambda_0 = 9.4M_\odot\mathrm{pc}^{-1}$



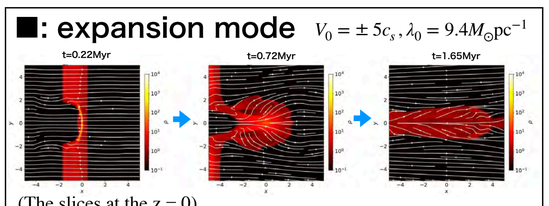
(The slices at the z = 0)

●: stable mode $V_0 = \pm 0.5c_s, \lambda_0 = 7.5M_\odot\mathrm{pc}^{-1}$



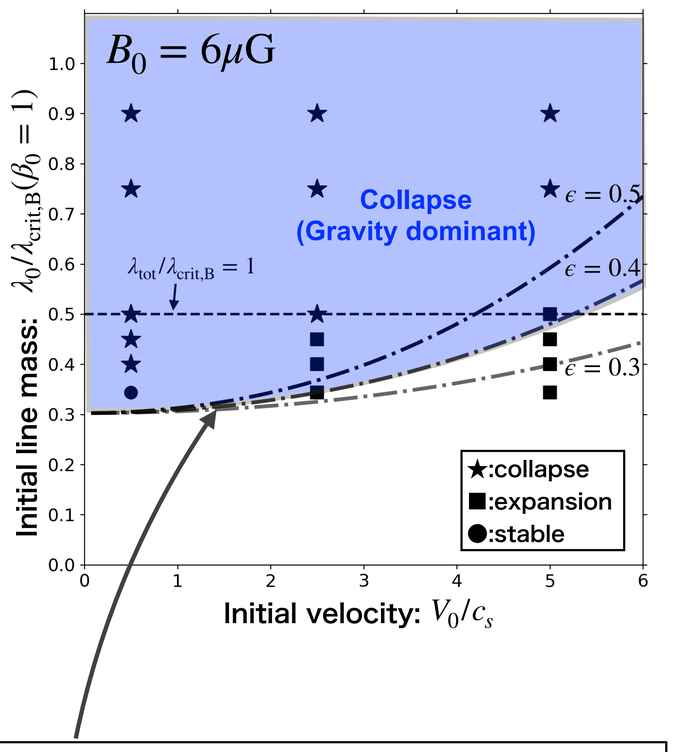
(The slices at the z = 0)

■: expansion mode $V_0 = \pm 5c_s, \lambda_0 = 9.4M_\odot\mathrm{pc}^{-1}$

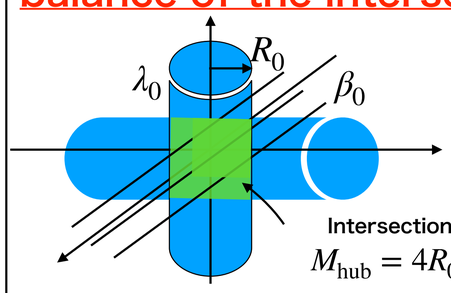


(The slices at the z = 0)

The shocked cloud neither collapses nor oscillates, but expands.



Making the analytic formula, we focused on the energy balance of the intersection.



For the gravitational energy, we used the MacLaurin spheroid model (approximated as a thin disk->

$e = (1 - \mathrm{semiminor\,axis}^2/\mathrm{semimajor\,axis}^2) \approx 1$)

$$GE \simeq -\frac{3}{5}\frac{GM^2}{R_0}\frac{\sin^{-1}e}{e} = -\frac{3\pi}{10}\frac{GM^2}{R_0}$$

Total energy equation:

$$E_{\rm all} = KE_{\rm after} + PE + ME + GE$$

$$= \underbrace{2\lambda_0 R_0 \epsilon^2 V_0^2}_{\text{Kinetic energy}} + \underbrace{6c_s^2\lambda_0 R_0}_{\text{Thermal energy}} + \underbrace{\frac{2}{\pi}\theta R_0^3 B_0^2}_{\text{Magnetic energy}} - \underbrace{\frac{3\pi}{10}\frac{GM_{\rm hub}^2}{R_0}}_{\text{Gravitational energy}}$$

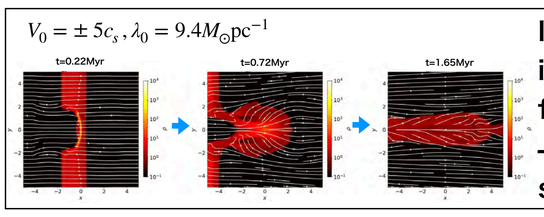
R_0 : filament width ($R_0 = 0.22$pc)
ϵ : coefficient of restitution
θ : geometric factor of a initial filament ($\theta \simeq 0.5$)

$E_{\rm all} = 0$ **(i.e.,** $KE_{\rm after} + PE + ME = GE$**)**

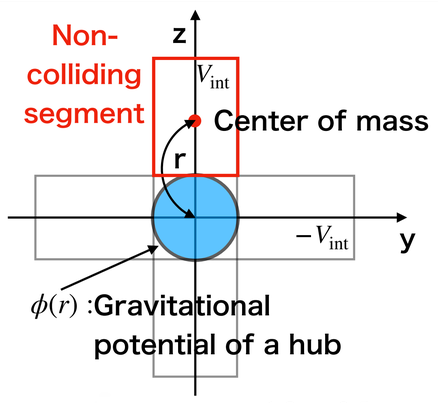
$E_{\rm all} < 0$: The shocked cloud undergoes gravitational collapse.

For orthogonal collisions, $E_{\rm all}$ is a good indicator of the instability of the shocked cloud.

Discussion (Collision conditions for Hub-filament system)



In orthogonal collisions, if the collision velocity is too high, the non-colliding segments detach from the system.
—> This is unfavorable for hub formation and subsequent gas accretion to the hub.

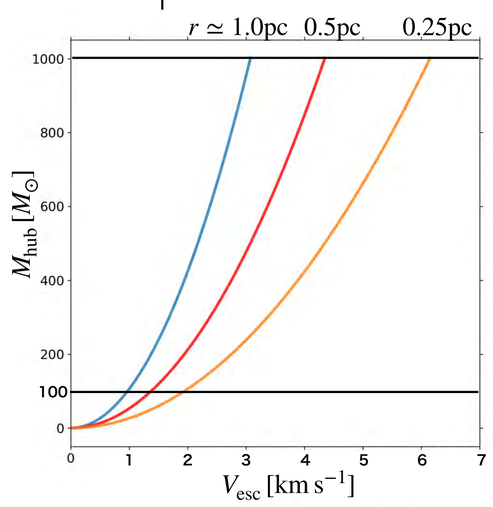


Escape velocity: $V_{\rm esc} = \sqrt{-2\phi(r)}$

$|V_{\rm int}| \gtrsim V_{\rm esc}$: Escaping non-colliding segments

$|V_{\rm int}| \lesssim V_{\rm esc}$: Bound non-colliding segments

(For simplicity, we assume that the hub is spherical and employ the gravitational potential of a sphere.)



$$V_{\rm esc} \simeq 1.3\sqrt{\left(\frac{M_{\rm hub}}{100M_\odot}\right)\left(\frac{r}{0.5\mathrm{pc}}\right)^{-1}}\ \mathrm{km\,s^{-1}}$$

$M_{\rm hub} = 1000M_\odot$—> $V_{\rm esc} \simeq 3 - 6\mathrm{km\,s^{-1}}$

$M_{\rm hub} = 100M_\odot$ —> $V_{\rm esc} \simeq 1 - 2\mathrm{km\,s^{-1}}$

These values represent the upper limit of the collision velocity required to form massive hub–filament structures.

References:
André et al. 2014, PPVI; Myers 2009, ApJ, 700, 1609; Kumar et al. 2020, A&A, 642, A87; Tokuda et al. 2019, ApJ, 886, 15; Stone et al. 2020, ApJS, 249, 4; Tomida&Stone 2023, ApJS, 266, 7; Tomisaka 2014, ApJ, 785, 24; Kashiwagi&Tomisaka 2021, ApJ, 911, 106; Kashiwagi et al. 2023, ApJ, 954, 129; Kashiwagi et al. 2024, ApJ, 974, 265.

QR for papers:

Parallel collisions
Kashiwagi et al. 2023

Orthogonal collisions
Kashiwagi et al. 2024