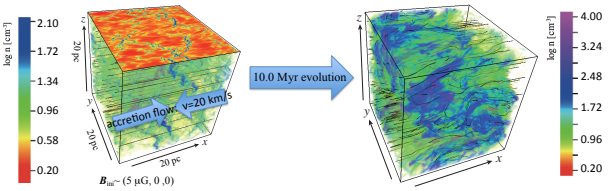
# Formation of Molecular Clouds and Initial Conditions of Star Formation

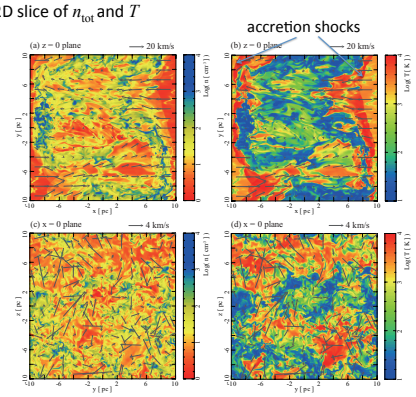
Tsuyoshi Inoue (Aoyama-Gakuin Univ.) and Shu-ichiro Inutsuka (Nagoya Univ.)

Inoue & Inutsuka 2012, ApJ, 759, 35
--- 2013 in prep.

- Observations suggest: Molecular clouds are formed and grown by accretion of HI gas with $\langle n \rangle \sim 10$ cm$^{-3}$ (Blitz+06; Kawamura+09; Fukui+09).
- 3D MHD simulation of molecular cloud formation by HI gas accretion with effects of chemical reactions, radiation transfer, cooling/heating, thermal conduction & self-gravity.
  - HI gas formed by thermal instability.
  - Molecular cloud formed by HI accretion.

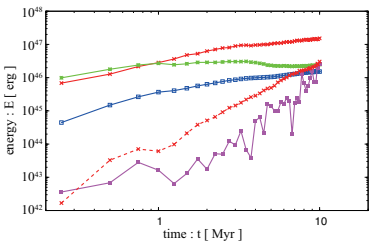



- 2D slice of $n_{tot}$ and $T$



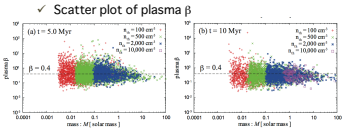

- ✓ Accretion of clumpy gas flows drives supersonic turbulence behind shocks.
- ✓ Cold molecular clumps ($T$~10K) are embedded in diffuse thermally unstable gas ($T$>1,000K) even deep inside region thanks to turbulent mixing.

- Evolution of energies (except accretion flows)

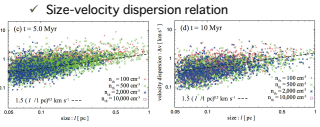



- ✓ Most of C$^+$ becomes CO at t ~ 7 Myr (birth of molecular cloud).
- → Dynamics of molecular cloud is governed by turbulence of diffuse gas component, but observations using molecular line emissions cannot detect it.

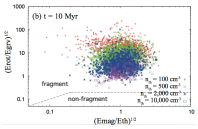
- Statistical features of molecular clumps (def. of "clump": connected region having $n > n_{thre}$)
  - ✓ Scatter plot of plasma β



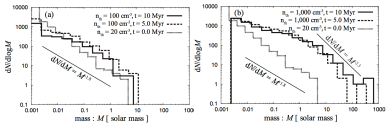

  - → Typical plasma β is temporally constant.
  - ✓ Size-velocity dispersion relation




  - → $\Delta v \sim 1.5$ km/s $(l / 1\ \mathrm{pc})^{0.5}$ for any clump density.
  - ✓ Rotation




  - → Clumps seem to evolve into star forming cores that satisfy the fragmentation condition to form binary proposed by Machida+04, 08.
  - ✓ Mass function




  - ✓ Low-density clumps with $n_{th} \sim 100$ cm$^{-3}$ and initial HI clouds show $dN \propto M^{-1.8}\, dM$, agrees with theoretical mass spectrum of clumps formed by the thermal instability (Hennebelle & Audit 07) and observation (Kramer+96; Schneider+02)
  - ✓ High-density clumps with $n_{th} \sim 1000$ cm$^{-3}$ show $dN \propto M^{-2.3}\, dM$, agrees with observations (Ikeda+07).

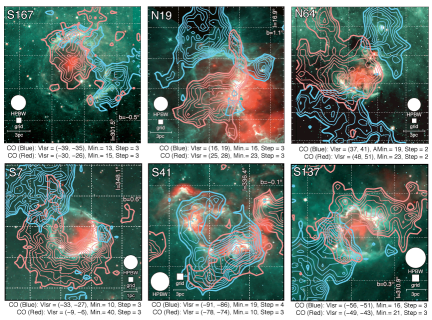
- Conclusion: realistic initial conditions of star/protoplanetary disc formation can be obtained by simulations!

# Formation of Massive Molecular Cloud Cores by a Cloud-cloud Collision

Tsuyoshi Inoue (Aoyama-Gakuin Univ.) and Yasuo Fukui (Nagoya Univ.)

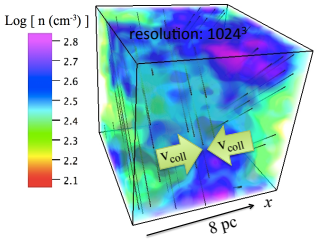
Inoue & Fukui 2013, ApJ submitted
arXiv:1305.4655

- Observations by NANTEN2 telescope (Fukui+13; Furukawa+09; Ohama+10; Torii+11):
  - Colliding two distinct molecular clouds are associated with Spitzer bubbles.



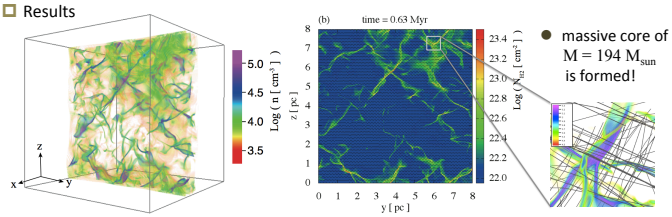

Contour: NANTEN2 $^{12}$CO J=1-0 (Fukui+13 in prep.)
Color: Spitzer 8, 24μm (Benjamin+03, Carey+09)

- Median parameters of the cloud-cloud collision.
  - ✓ $M_{cloud} \sim 10^4$-$10^5\ M_{sun}$
  - ✓ $L_{cloud} \sim 5$ pc
  - ✓ $v_{coll,\ relative} \sim 26$ km/s
  - → Intensive molecular cloud collision induces massive star formation?
- Isothermal 3D MHD simulation of cloud-cloud collision with self-gravity ($c_s = 0.2$ km/s).
  - Initial conditions (fiducial model):

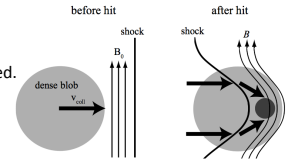



  - ✓ Initial density with fluctuations:
    $n_{ini} = 300$ cm$^{-3}$,
    $P_{\log \rho}(k) \propto k^{-4}$, $\Delta\rho/\langle\rho\rangle = 0.43$
  - ✓ Collision velocity: $v_{coll} = 10$ km/s
    ($M_s = v_{coll}/c_s = 50$, $M_A = v_{coll}/c_A = 12$)
  - —— initial $\boldsymbol{B}$ field ($B_{ini} = 20\mu$G)

- Results




  - massive core of M = 194 $M_{sun}$ is formed!
- Why are filaments formed behind shock?
  - ✓ Deformed shock induces focusing flows.
    → filaments perpendicular to $\boldsymbol{B}$ field is formed.




- Why does core become massive?
  - ✓ Alfven velocity is substantially enhanced behind shock: $c_A \approx \sqrt{M_A}\, c_{A,ini}$
  - → Enhancement of effective Jeans mass: $M_{J,eff} = G^{-3/2} \langle c_{eff} \rangle_{core}^{3} \langle \rho \rangle_{core}^{-1/2} \propto B_{ini}^2\, v_{coll}\, \rho_{ini}^{-3/2}$
  - → Effective Jeans mass should increase with $v_{coll}$, $B_{ini}$ and decrease with $\rho_{ini}$.
  - ✓ Results of parameter survey support the idea.

| Model | fiducial | large $\rho_{ini}$ | small $B_{ini}$ | small $v_{coll}$ |
|---|---|---|---|---|
| $\langle n \rangle_{ini}$ [cm$^{-3}$] | 300 | 1000 | 300 | 300 |
| $B_{ini}$ [μG] | 20 | 20 | 10 | 20 |
| $v_{coll}$ [km/s] | 10 | 10 | 10 | 5.0 |
| $M_{core,\ tot}$ [$M_{sun}$] | 194 | 126 | 35 | 24 |
| $M_{mag.}$ [$M_{sun}$] | 122 | 63 | 14 | 36 |
| $M_{turb}$ [$M_{sun}$] | 71 | 63 | 21 | 53 |
| $\langle n \rangle_{core}$ [cm$^{-3}$] | 8.4e4 | 4.9e5 | 3.1e5 | 2.0e4 |
| $\langle B \rangle_{core}$ [μG] | 2.8e2 | 6.3e2 | 2.9e2 | 1.8e2 |
| $\Delta v_{core}$ [km s$^{-1}$] | 1.2 | 1.3 | 0.86 | 0.23 |
| $t_{form}$ [ Myr ] | 0.63 | 0.29 | 0.36 | 0.78 |

- Conclusion: intensive molecular cloud-cloud collision discovered by NANTEN2 observations can induce massive star formation!