RMHD simulations of low-mass star formation

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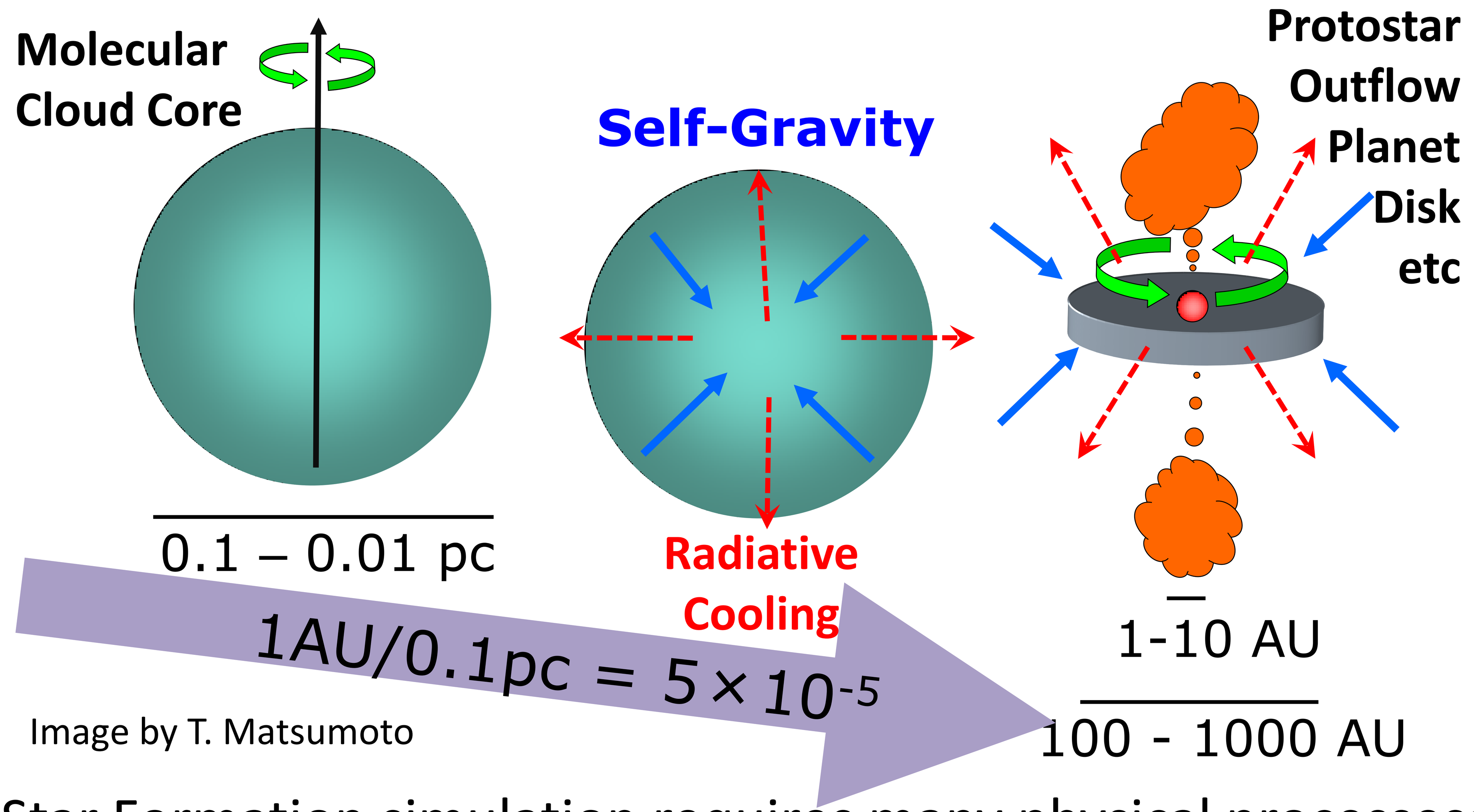
ファーストコアは星形成過程で形成される過渡的な天体である。この天体がLarson 1969によって提唱されてから40年以上経つが、その寿命が1000年程度と短くまたガスに深く埋もれているため観測が極めて困難であり、未だ観測的な証拠は得られていない。しかしながらファーストコアは星形成における二大問題である角運動量問題と磁束問題に関わる重要な舞台であり、またアウトフローの駆動や連星形成など豊かな現象の現場でもあるため、過渡的ではあってもその重要性は疑いない。ALMAなど次世代の観測装置によりファーストコアが直接検出され、星形成の理論に強い示唆が得られることが期待されている。
本講演では輻射磁気流体シミュレーションによる低質量星形成計算の結果について報告する。特に輻射磁気流体計算によりこれまでの計算よりも現実的な温度分布が得られるようになったため、この結果を用いて予測したファーストコアの観測的性質について議論する。

Introduction



Star Formation simulation requires many physical processes:
- Large dynamic range (**5** orders of magnitude or more!)
- Magnetic fields (MHD) ・Self-gravity
- Multidimensionality (←Rotation, Magnetic fields)
- ***Radiation Transfer***

⇒3D nested-grid self-gravitational RMHD simulation!

Method and Model

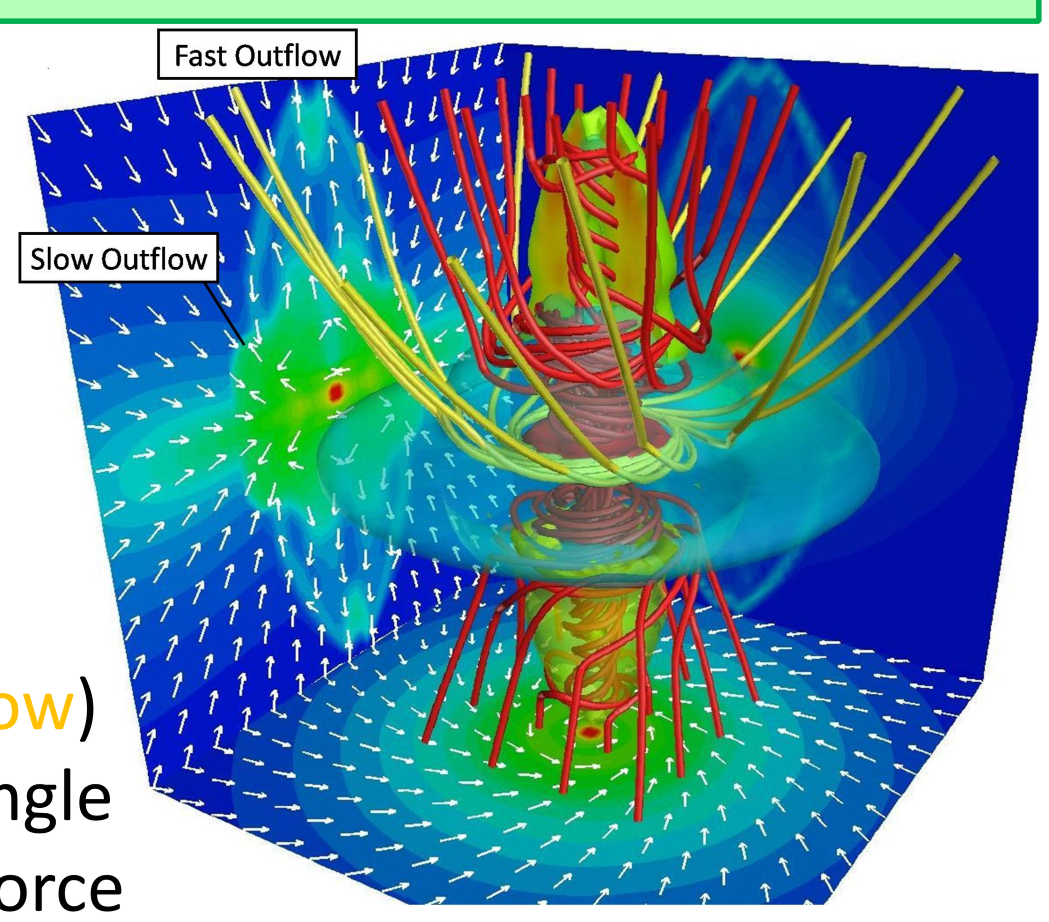
Features of our simulation code:
- 3D Nested-grids, synchronous timesteps
- MHD: 2nd-order Roe scheme with hyperbolic div **B** cleaning
- Self-gravity: Multigrid ・**Radiation Transfer: FLD** (gray)

Simulation Setup:
- Resolution: 64^3 for each grid-level
  32meshes / Jeans length (center of the cloud)
  $\Delta x \sim 0.01$ AU (finest), ~0.1 AU @ core surface
- Opacity: Semenov et al. 2003 + Ferguson et al. 2005
- Gas EOS: ideal, $\gamma = 1.4$ (assuming diatomic molecule)
- End of simulation: T=2000K (second collapse)

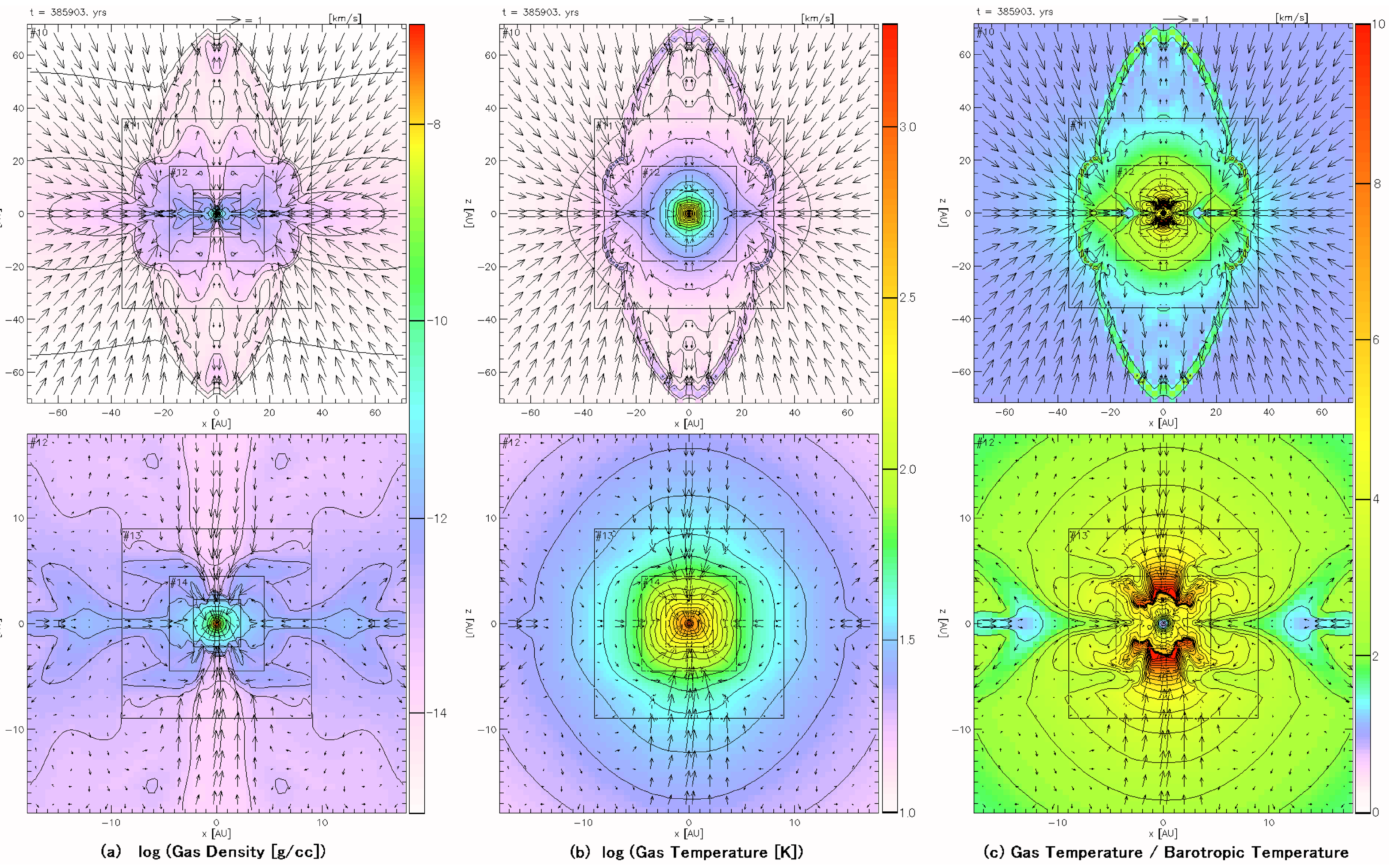
Initial condition: super-critical Bonnor-Ebert sphere
T = 10 K, $\rho_c = 10^{-19}$ g cm^{-3}, $M_c = 6.1\ M_{sol}$, $R_c = 0.18$ pc
Rigid body rotation: $\omega = t_{rot}/t_{ff} = 0.1$ (weak fields case)
Uniform magnetic fields: $B_z = 1.1\ \mu$G

Results

Typical 3D structure→
(left&bottom=ρ, right=T)



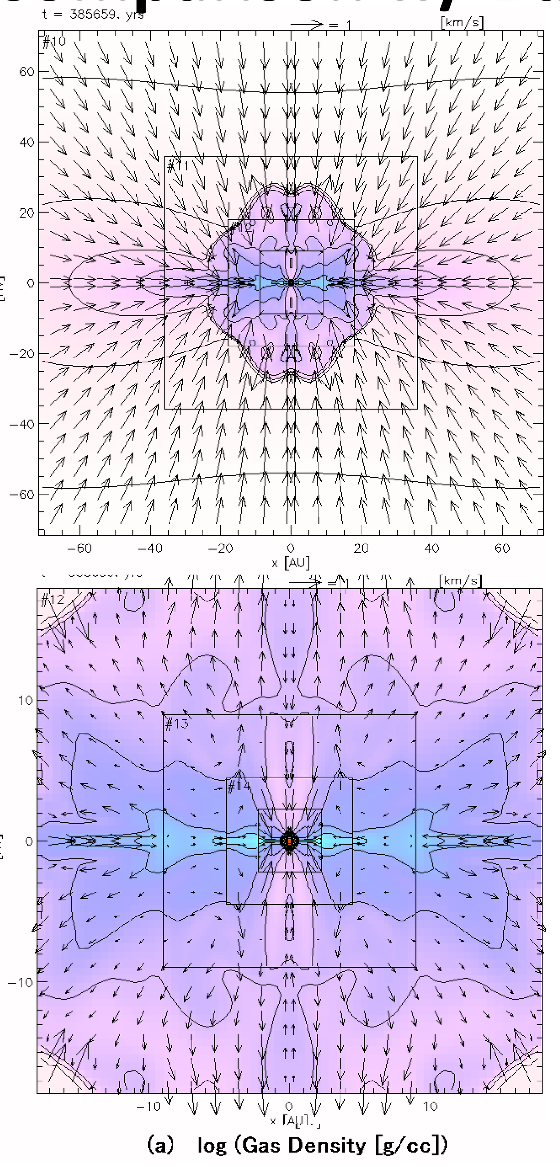
Two-component outflow
- **Inner component** (red)
  - Fast, travel farther
  - Well collimated
  - Magnetic pressure
- **Outer component** (yellow)
  - Slow, wide opening angle
  - Magneto-centrifugal force
  - Significant mass/angular momentum flux



↑Vertical slices of outflow scale (upper) core scale (lower)
- Complicated density distribution ←MHD process
- Nearly spherical temperature distribution in core scale
  ←radiation heating from the central hot region
- Shock heating at the edge of the outflow

⇒Considerably different picture from barotropic approx.

Comparison w/ Barotropic case at the same central density



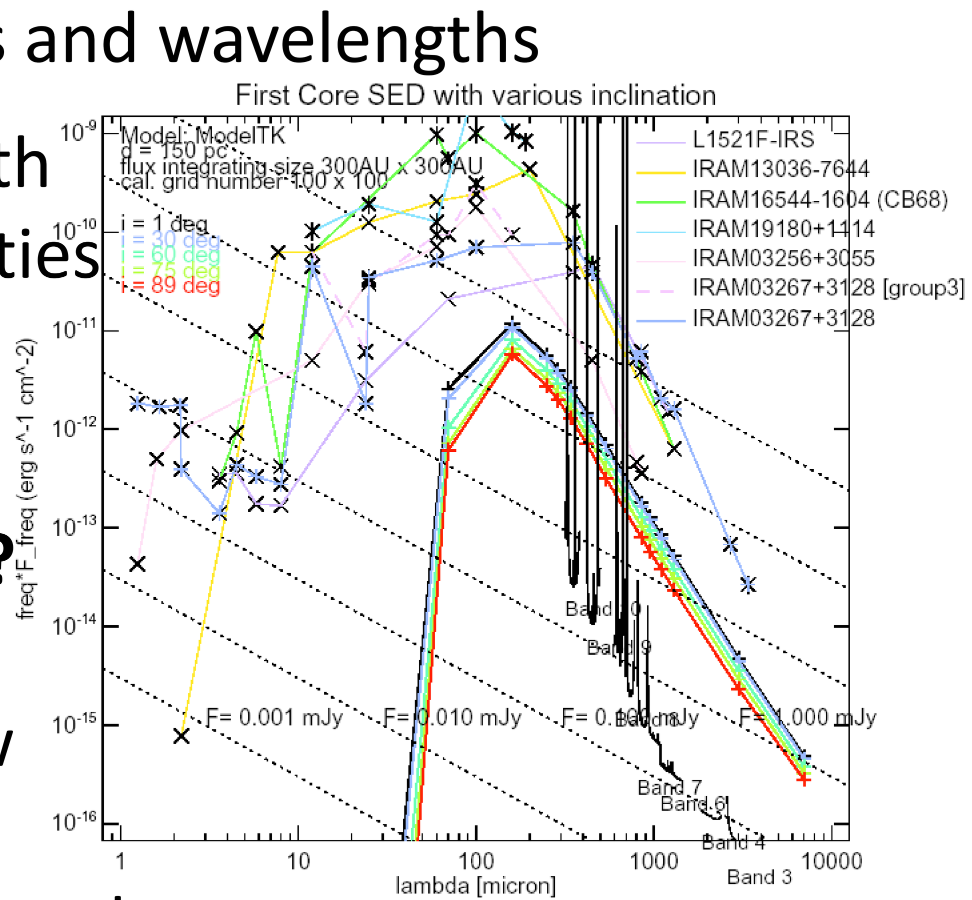
EOS:
$$T_{bar} = 10 \times \left[\frac{\max(\rho, \rho_{crit})}{\rho_{crit}}\right]^{\gamma-1} K$$
($\gamma=1.4$, $\rho_{crit}=2.0\times10^{-13}$ g cm^{-3})

Barotropic MHD simulation results:
- Smaller outflow = Faster core evolution
- Smaller core ← Lower gas entropy
- Mechanical properties of the outflow are not so different
  (2 components, driving region, velocity)

Realistic thermal evolution affects…
- Significant difference in temperature
- First Core's kinematic properties

Observational Visualization

Post-processing radiation transfer → "Observation"
SED with various inclinations and wavelengths



→Rotating First Core SED with ALMA Early Science sensitivities compared with VeLLOs' SED

⇒Far fainter than VeLLOs

Can we find FCs with ALMA?

→Probably **YES** if they exist, but its possibility is quite low (1/100 or less!) since the lifetime of the first core is very short.

Therefore we require a sufficient number of targets and highly efficient methods to identify good candidates.