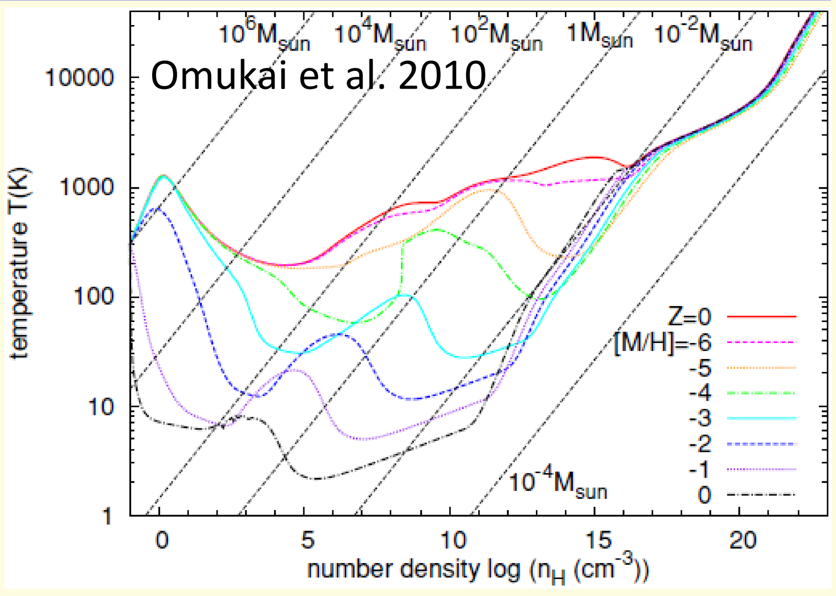
RMHD Simulations of Protostellar Collapse: Low-Metallicity Environment

Kengo TOMIDA (Princeton University / JSPS Postdoctoral Fellow for Research Abroad)

Introduction

As radiation is crucial in thermodynamics in star formation, metallicities affect star formation processes through the opacities. Omukai et al. 2010(→)studied star formation in various metallicity environments with many physical processes assuming 1D spherical symmetry. Myers et al. 2012 performed 3D RHD simulations of large-scale star formation with different metallicities. In this work, we investigate the effects of metallicities in first core and protostellar core scales using 3D RHD and RMHD simulations.



Methods and Models

Simulation Code: ngr³mhd (Tomida et al. 2013) Actually ngr²mhd in this work.

- 3D nested-grid
- 2nd-order ideal MHD with HLLD + Dedner's mixed cleaning
- Self-gravity: Multigrid (Matsumoto & Hanawa 2003)
- Radiation: Gray + FLD (Levermore & Pomraning 1981)
- Realistic EOS with X=0.7, Z=0.02 and H_2 ortho:para = 3:1 (Same EOS is used in both solar and low-metal models because the effects of heavy elements are not significant.)

Simulation Models: 2 (metallicities) x 3 (parameters)

- Solar Abundance
- Low Metallicity (0.1 Z_{sol})

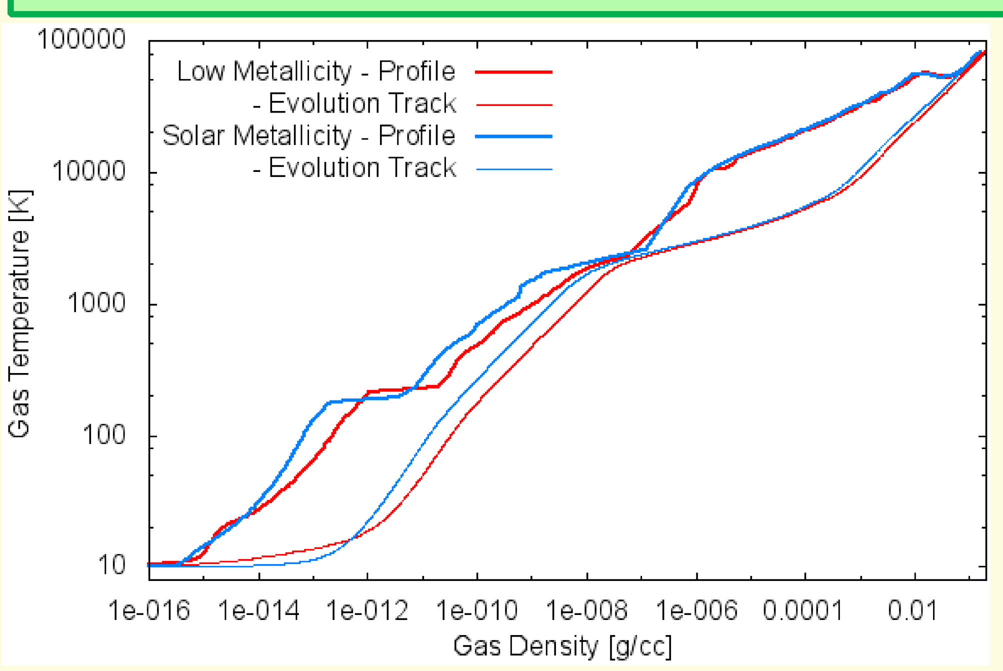
- Spherical
- Rotating w/o magnetic fields
- Rotating with magnetic fields

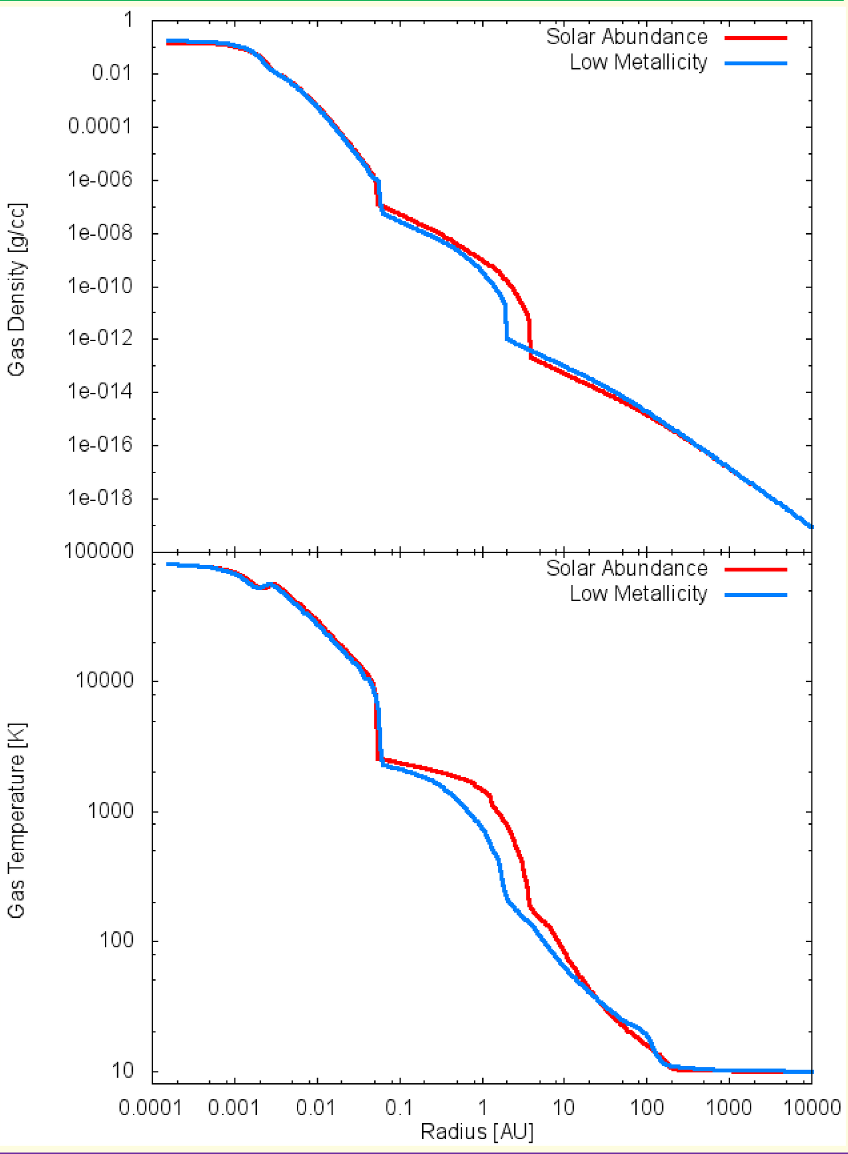
Dust Opacities: Semenov et al. 2003
(Simply reduced by a factor of 10 in low-metallicity models)
Gas Opacities: Ferguson et al. 2005 + Seaton et al. 1994 (OP)
(X=0.7 and Z=0.002 are adopted in low-metallicity models.)

Initial Conditions (like the slow rotation model in Tomida+):

- 1 Ms BE-like sphere: $\rho_c=1.2 \times 10^{-18}$ g/cc, T=10K, R=8800AU
- Uniform rotation & magnetic fields aligned to z-axis : Bz=20μG (μ≈3.8), $\Omega=0.023/t_{ff} \approx 1.2 \times 10^{-14}$ s^{-1}
- 10% m=2 density perturbation in the rotating models
- 16 cells / λ_{Jeans}, 64^3 cells ・T_c=2000K (Rotating) or 8×10^4 K

Results I. Spherical Collapse





↑: Evolution Track and Profile in the ρ-T plane
→ Top: Density profile
Bottom: Temperature profile at the end of the simulations

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	FC Lifetime	FC Radius	FC Mass	PC Mass
Solar	720 yrs	3.8 AU	3.1 x 10^{-2} Ms	1.3 x 10^{-2} Ms
LowMetal	290 yrs	1.9 AU	1.7 x 10^{-2} Ms	1.2 x 10^{-2} Ms

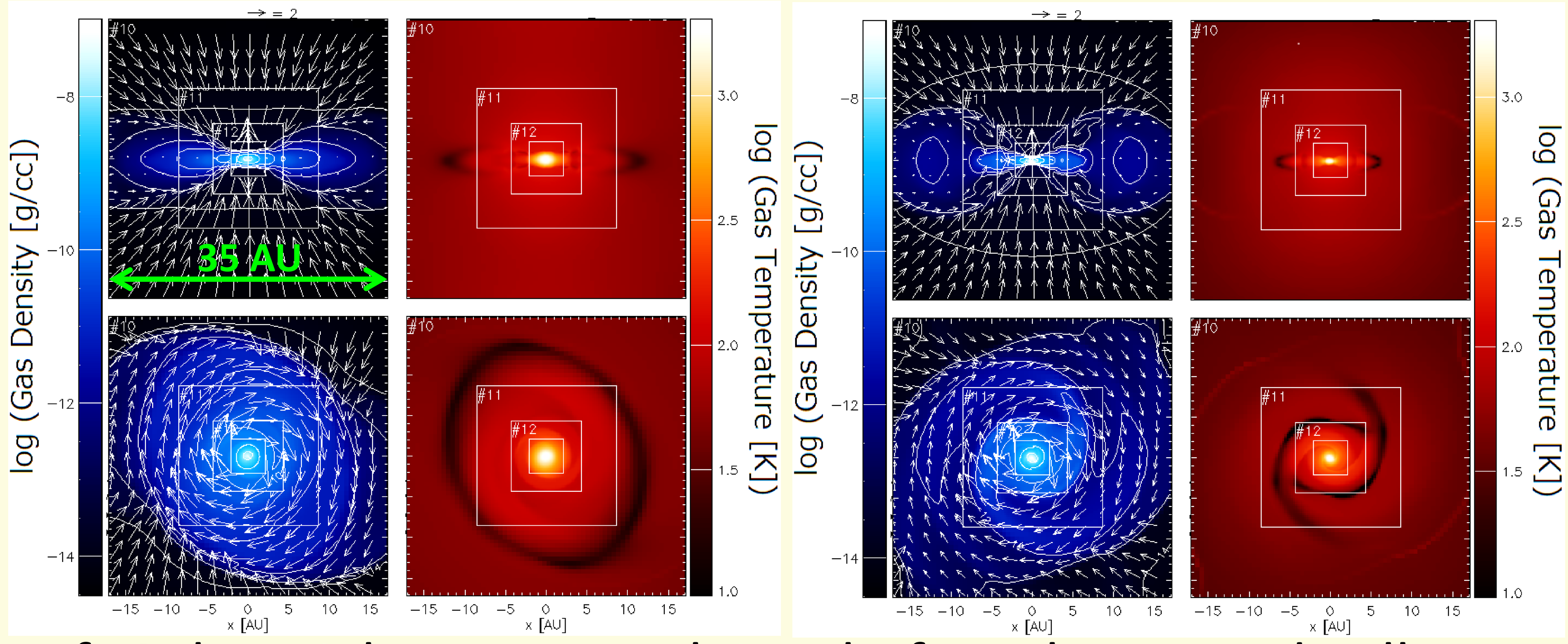
First Core properties are different, as expected:
Low-metal model takes lower temperature (higher density) evolution path due to more efficient radiation cooling.
(Note that lifetimes are almost proportional to the masses because the accretion rates onto the first cores are similar.)

Protostellar Core properties are essentially identical.

- PCs are very optically thick and adiabatic in both models.
- The gas energy after the second collapse is dominated by the energy released in the second collapse, which is originally from the binding energy of molecular hydrogen.

⇒**Protostellar cores are insensitive to metallicities.**

Results II. Non-magnetized Rotating Models

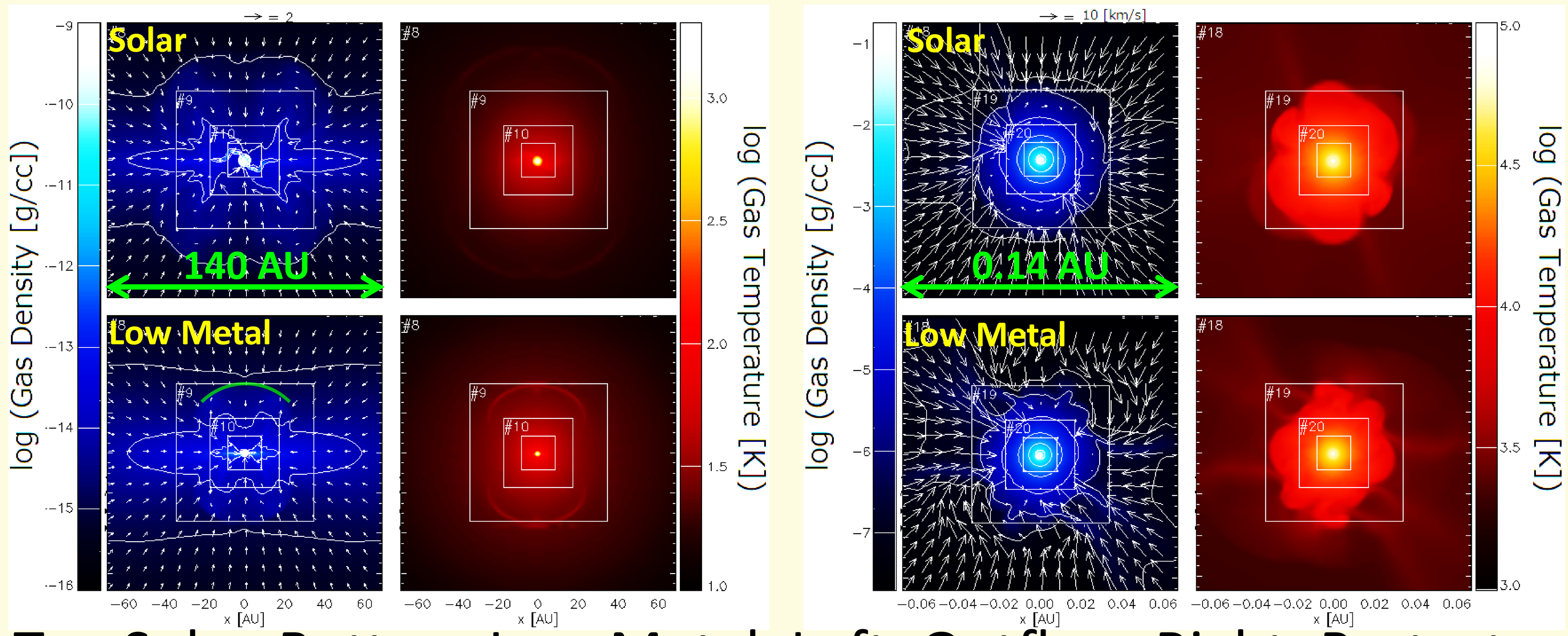


Left:Solar, Right:Low Metal, just before the second collapse
LM model is colder because of lower first core mass and efficient cooling, but it's not easy to tell which is dominant.

	FC Lifetime	FC Mass
Solar	2800 yrs	8.5 x 10^{-2} Ms
LowMetal	1510 yrs	5.7 x 10^{-2} Ms

Note: It is hard to compare the radii because it's consequence of highly non-linear angular momentum transport and very time-dependent.

Results III. Magnetized Rotating Models



Top:Solar, Bottom:Low Metal, Left: Outflow, Right: Protostar
Dynamical properties of the outflows are similar, but the outflow is smaller in LM model due to its short lifetime.
Protostellar cores are essentially the same, as in Results I.

	FC Lifetime	FC Mass	Outflow Size	Outflow Speed
Solar	700 yrs	3.6 x 10^{-2} Ms	50 AU	≲ 1km/s
LowMetal	300 yrs	2.6 x 10^{-2} Ms	30 AU	≲ 1km/s

Conclusions and Discussions

- Low-metallicity first cores are colder, smaller, short-lived.
- Protostellar core properties do not depend on metallicities ⇒ "Universal" initial condition for stellar evolution
- Outflows in MHD models are similar because thermodynamics is not important in the launching mechanism.
- Long-term evolution will be more significantly different as radiation cooling and heating will be more prominent.