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THE THERMAL STRUCTURES OF PROTOSTELLAR ENVELOPES IN ISOLATED VS. CLUSTERED ENVIRONMENTS

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Introduction

The thermal structures and histories of the protostellar cores affect the chemical conditions of the cores, the protoplanetary disks, and in the end, the planets. The thermal structures of the protostellar envelopes are affected by the star-forming environments: e.g. clustered regions with high pressure, like the Orion Nebula Cluster, vs. lower-pressure regions, like the Taurus cloud, where stars form more sparsely in relative isolation. The formation of the planet in the solar system might also have been affected in such a way by its formation environment.

The pressure in a star-forming region is directly related to the mean surface density of that region ($P \sim G\Sigma^2$). The typical surface densities of various star formation regions:

Star Formation Regions	Mean Surface Densities
Massive star formation regions:	~ 0.2-1 g/cm^2 (Plume et al. 1997; Higuchi et al. 2013)
IRDCs	~ 0.1-0.5 g/cm^2 (Butler & Tan 2012)
Orion Nebula Cluster	~ 0.3 g/cm^2 (McKee & Tan 2003)
NGC 1333	~ 0.2 g/cm^2 (Knee & Sandell 2000)
ρ Oph	~ 0.1 g/cm^2 (Nakamura et al. 2011)
Serpens	~ 0.07 g/cm^2 (Sugitani et al. 2010)
Taurus	~ 0.03 g/cm^2 (Onishi et al. 1996, Qian et al. 2012)

Higher surface density → Higher pressure → More compact core → Higher accretion rate → Higher luminosity → Hotter core

Models

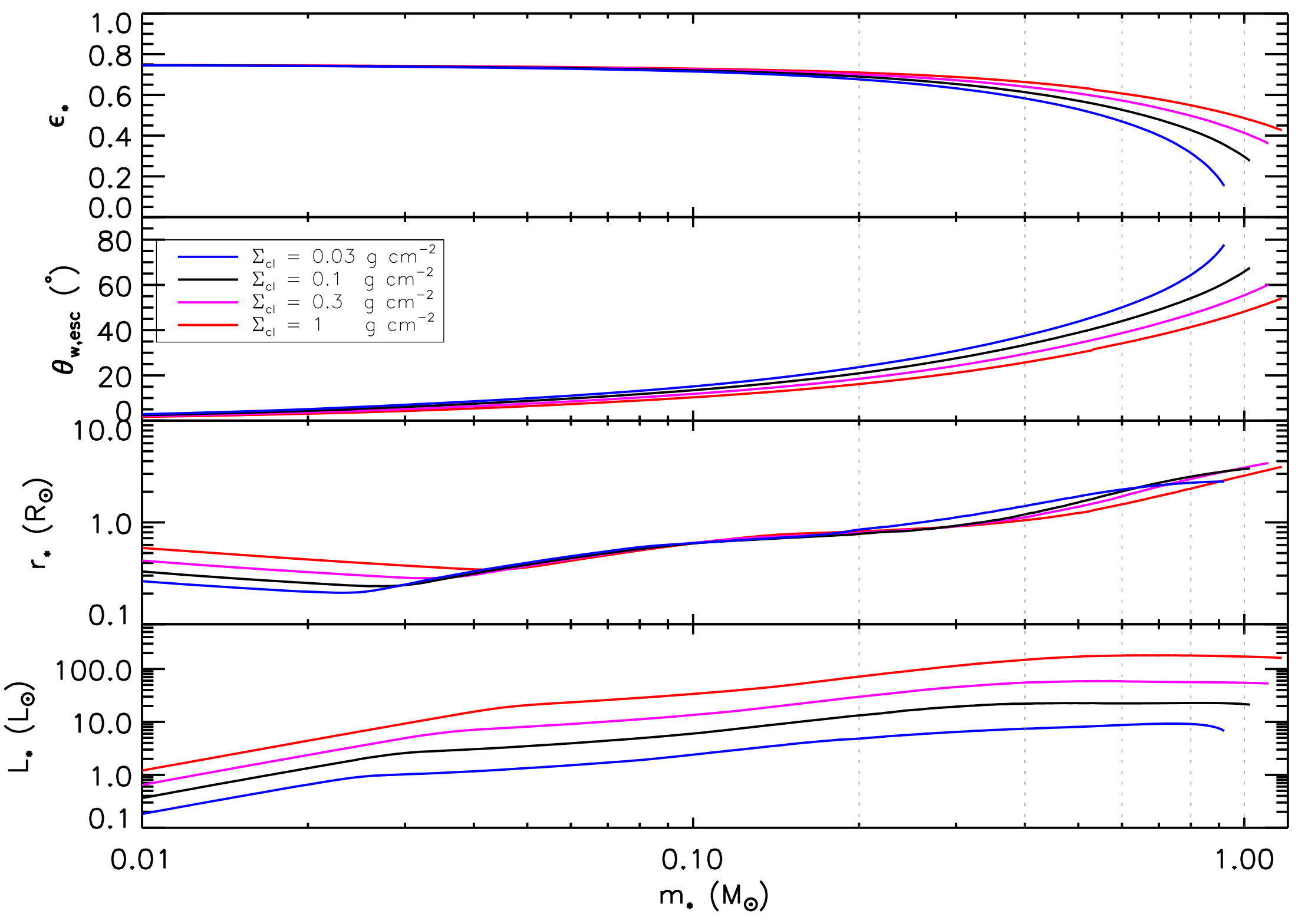
Core: If the initial pre-stellar cores are approximately virialized and in pressure equilibrium with their surrounding clump medium, the Turbulent Core model (McKee & Tan 2003) explicitly links the structure and the evolution of such a core to the environmental pressure (surface density). Building on this assumption, we have constructed an analytic model for the protostellar envelope, disk and outflow, self-consistently including an inside-out expansion wave, a rotating infall envelope, an accretion disk, and a bipolar magneto-hydrodynamic accretion-powered disk wind that sweeps up outflow cavities.

Disk: The size of the disk is based on the assumption that the rotational energy is 2% of the gravitational energy in the initial core. We improved the treatment of the disk by allowing radially varying accretion rate due to a supply of mass and angular momentum from the infall envelope and their loss to the disk wind. We also account for the transfer of accretion power to mechanical power of the wind.

Disk Wind: We developed an approximate disk wind solution partly based on the Blandford & Payne model (BP wind). In this solution, the wind is constrained by an inner boundary (a BP streamline) and an outer boundary which is described by an inflow streamline. The disk wind is assumed dusty if the streamline starts from the dusty part of the disk.

Evolution: We estimated the evolution of the star-forming efficiency based on the analytic model of the outflow, and improved the protostellar evolution using a multi-zone model (Hosokawa et al. 2009, 2010). With these efforts, we derive the evolutionary sequence of star formation depending on specific initial conditions of the pre-stellar core, such as its mass, surface density of its environment.

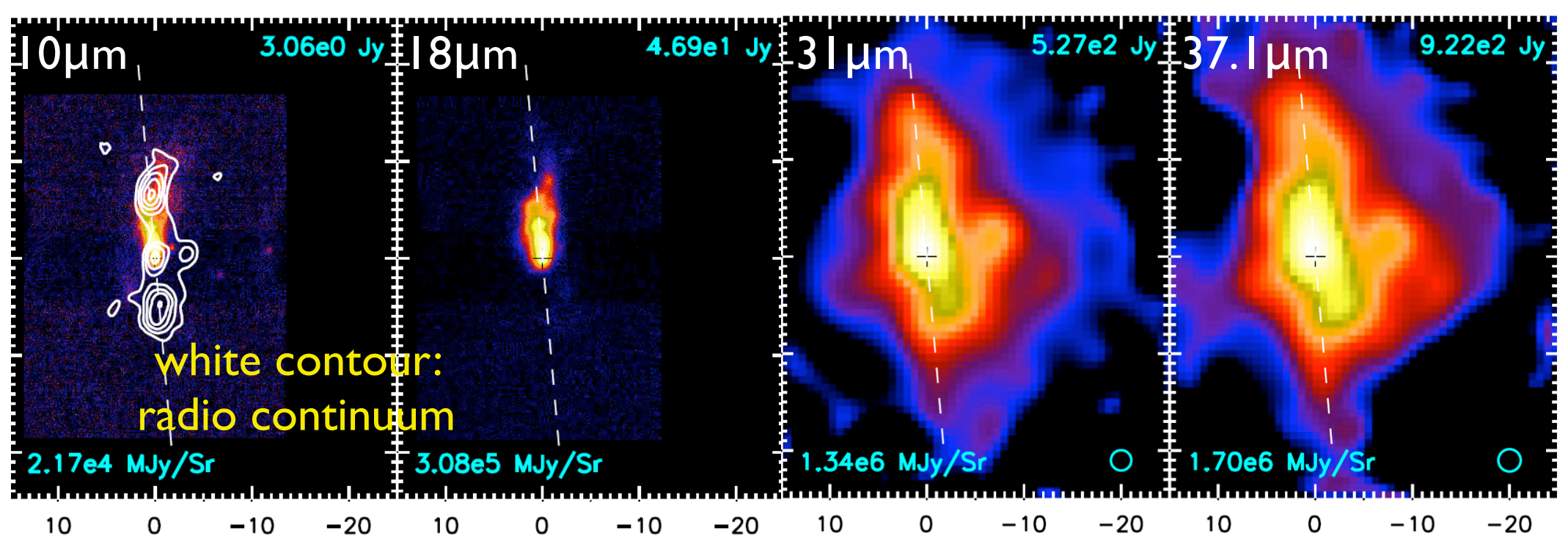
Simulations: The simulation was performed with the latest version of the Monte Carlo radiation transfer code by Whitney et al. (2013). Corrections made by adiabatic cooling/heating and advection are included, which are especially important for the outflow. We include gas opacities for the regions with T>1600K in the disk and in the wind starting from these regions.

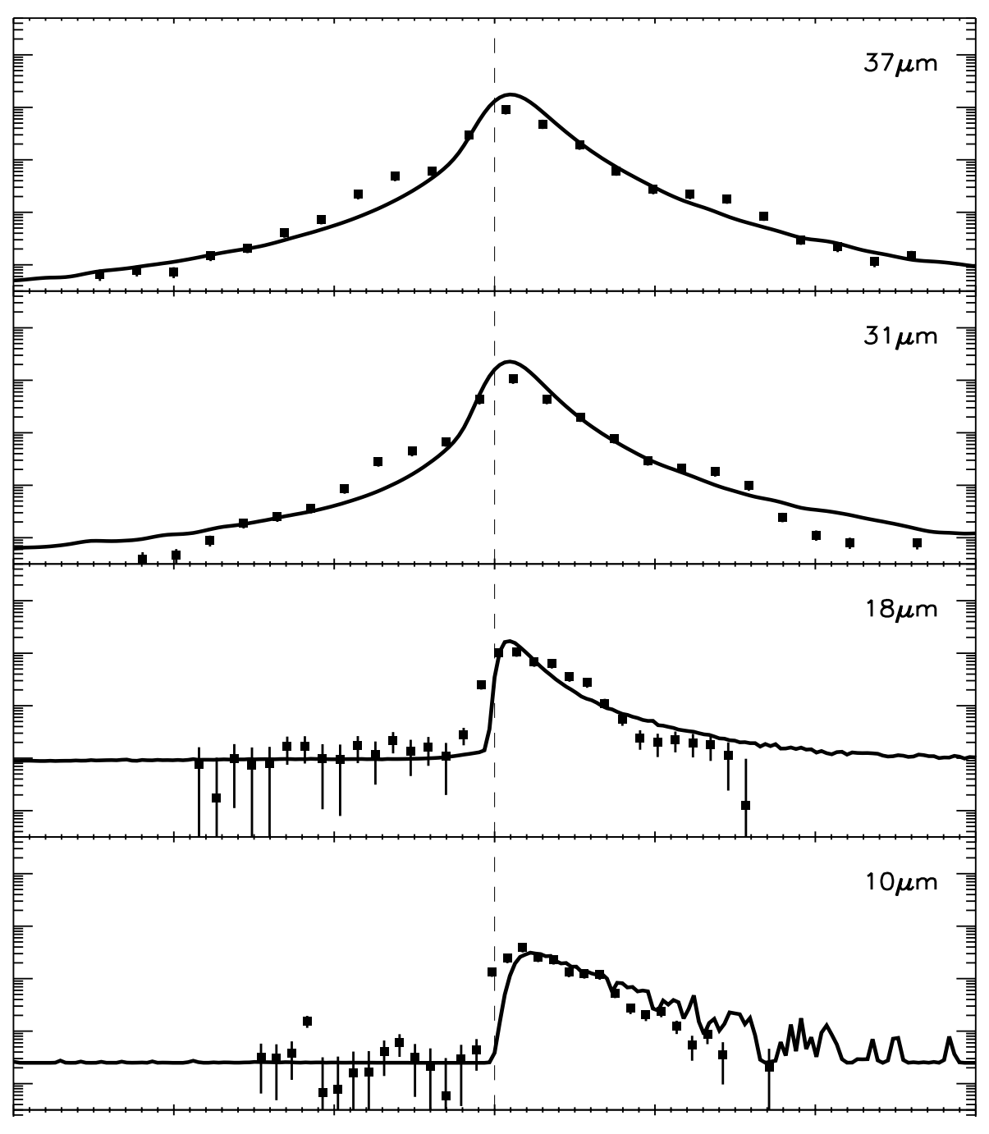


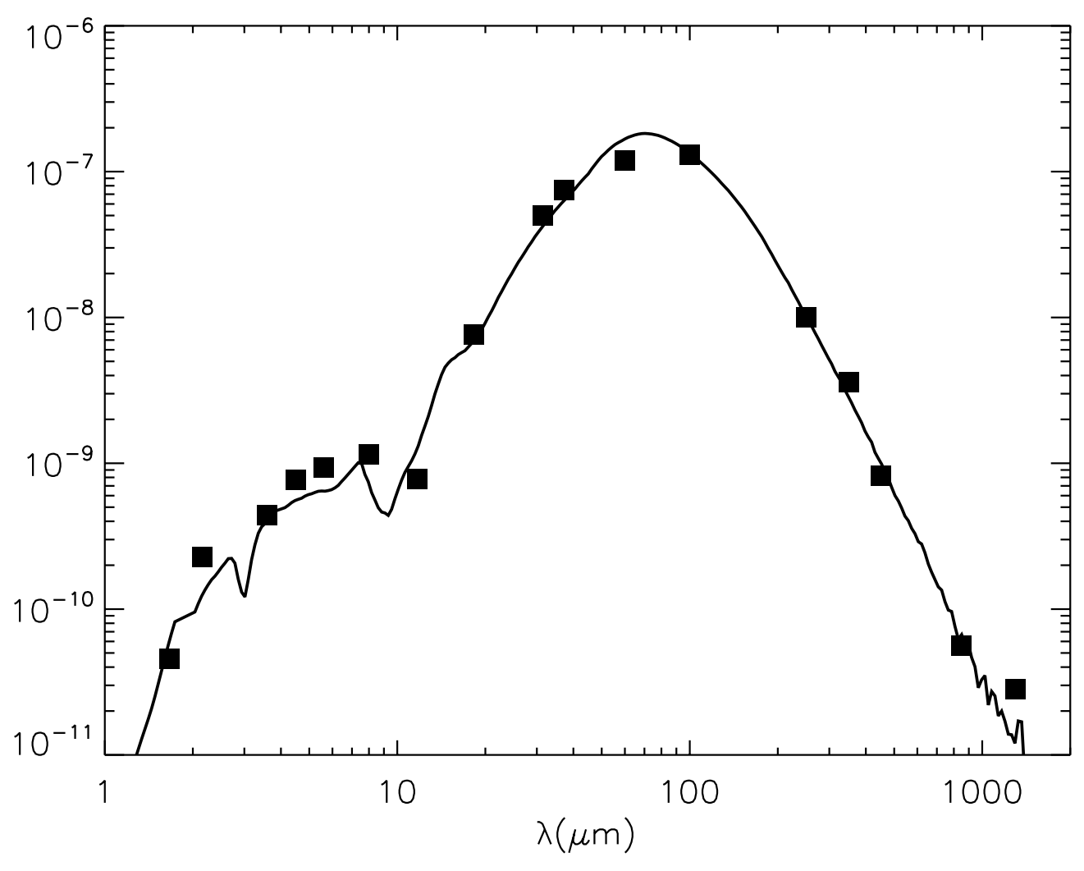
Left: The evolution of the instantaneous star-forming efficiencies, the opening angle of the outflow, the protostellar radii, and the luminosities (stellar + accretion) with the protostellar mass for initial 2 $M_\odot$ cores embedded in clumps with various surface densities (Σ_{cl}=1 g/cm^2, 0.3 g/cm^2, 0.1 g/cm^2, and 0.03 g/cm^2) mimicking different star-forming environments from very crowded area around massive protostars and those more isolated Taurus type environments.

Application to High-mass Star Formation: Case Study of G35.2N

At the high-mass end, we applied our model to G35.2-0.74N, a massive protostar at 2.2kpc. Radio continuum emission has been found along the N-S direction indicating a bipolar outflow. The northern side has been clearly seen in mid-IR continuum. In our recent SOFIA-FORCAST observation at 31 and 37μm, both sides of the outflow can be seen. By exploring the parameter space based on the fiducial model, we find our model can reproduce both the SED and the axis intensity profiles. Our results suggest that G35.2N is a massive protostar forming from a high mass surface density core, via relatively ordered collapse and accretion, which is driving relatively symmetric bipolar outflows, supporting that the massive stars form similarly to their low-mass counterparts. (see Zhang et al. 2013b)







Fitted Values:

M_{core} ~ 240$M_\odot$

m_* ~ 20-34 $M_\odot$

Σ_{cl} ~ 0.4-1g/cm^2

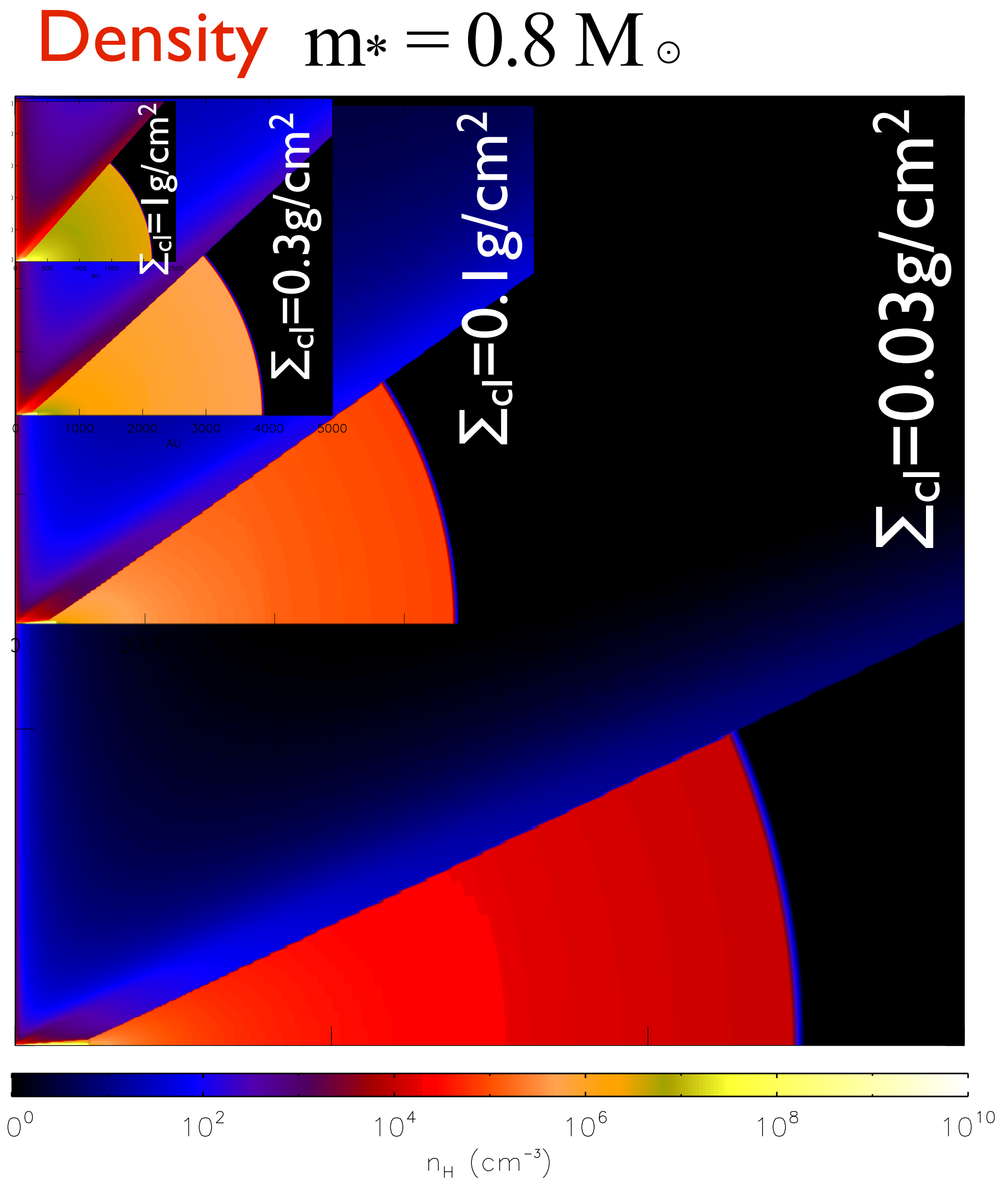
L_{bol} ~ (0.66-2.2)×$10^5 L_\odot$

Upper: Images from T-ReCS and SOFIA-FORCAST. **Left**: The model SED (curve) and the observations (data points). **Right**: Intensity profiles along the axis of the outflow comparing with the observations.

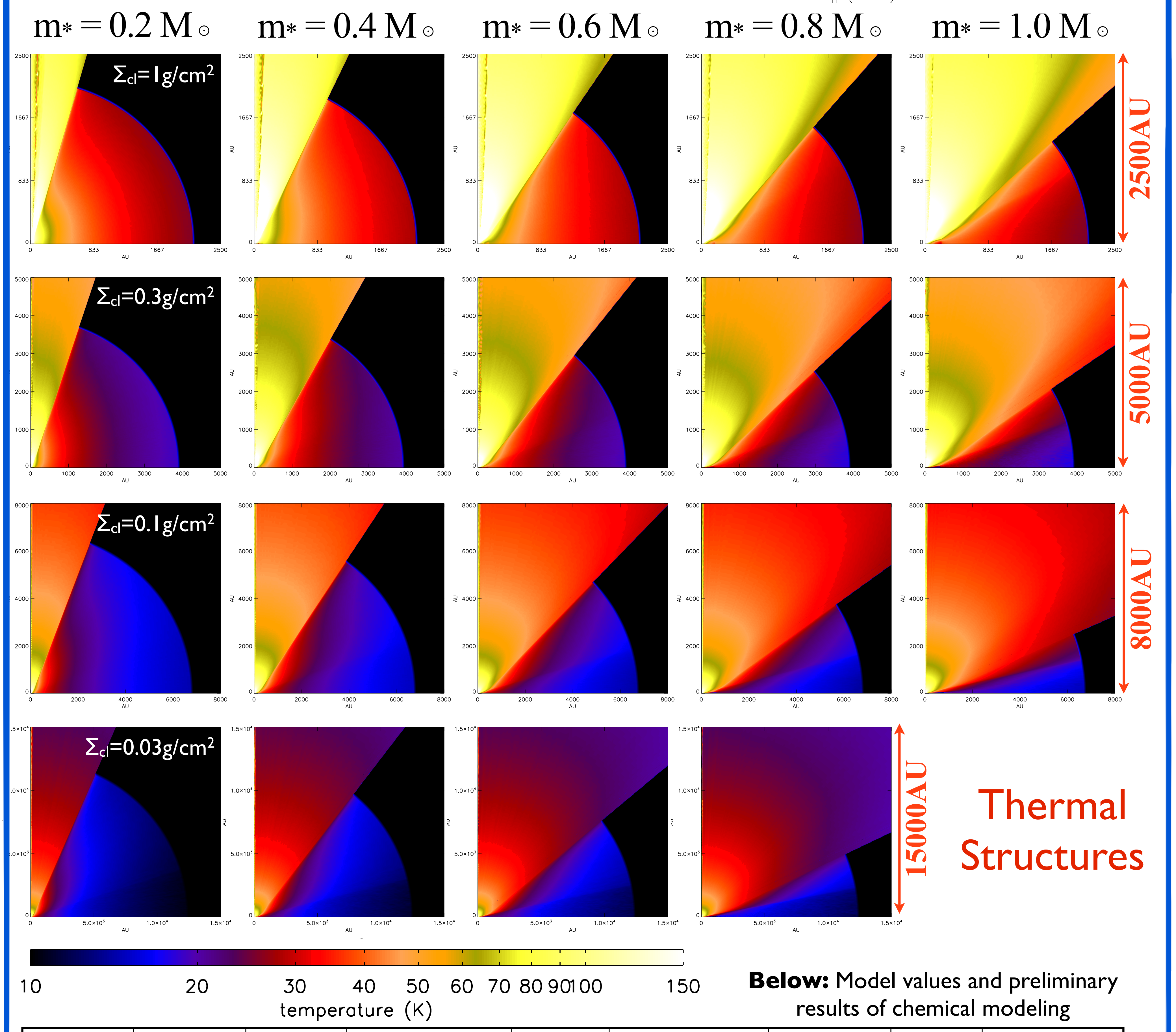
Application to Low-mass Star Formation:

Thermal Structures of Protostellar Cores in Different Environments

We applied our radiative transfer model to low-mass star-forming cores (2 $M_\odot$) in environments with four different surface densities, ranging from 1 g/cm^2 (in massive star-forming regions) to 0.03 g/cm^2 (similar to Taurus environment). This makes a difference in surface pressure of about 3 orders of magnitudes. With a higher surface pressure, the core is much more compact, denser, and hotter due to the higher accretion rate. The typical temperature is ~35K in a core in an Orion-like environment and ~15K in a core in a Taurus-like environment. Such a difference in the temperature may affect the chemical conditions in the envelope such as the deuterium fraction, the ice mantle composition, which further will affect the growth of large grains into planetesimals.



Right: The density structures of the 2 $M_\odot$ cores in environments with different surface densities, compared in the same size scale. **Below:** The temperature structures of these cores with difference surface densities (rows) and in different evolutionary stages (columns). Note the size scales are different.



Below: Model values and preliminary results of chemical modeling

M_{core} ($M_\odot$)	Σ_{cl} (g/cm^2)	R_{core} (pc)	R_{core} (Observational for reference)	n_H (cm^{-3})	n_H (Observational for reference)	T_{env} (K)	$R_{D,eq}$ ***	$R_{o\text{-}p\ H2,eq}$ ****
2	0.3	0.02	0.01~0.02*	10^6	10^6~10^7 *	~35	0.001	0.1
2	0.03	0.06	~0.05**	5×10^4	10^5 **	~15	0.2	6×10^{-4}

*: Typical values for cores in ρ Oph, Orion, Serpens (e.g., Ward-Thompson et al. 2007)

**: Typical values for cores in Taurus (same reference as above)

***: Equilibrium deuterium fraction ($R_D = N_2D^+/N_2H^+$), results from gas-phase-only chemical model (Kong, Caselli, Tan, et al. in prep.)

****: Equilibrium ortho-para H_2 ratio

Summary and Conclusions

- We have built a radiation transfer model for star-forming cores, including expansion wave collapse, rotating infall envelopes, accretion disks, bipolar disk winds, covering the evolutionary sequences, and self-consistently linking these structures and their evolution to the initial conditions of the pre-stellar cores, such as their masses and environmental surface densities.
- For high-mass star formation, our model successfully explained observations of one massive protostars, supporting the idea that the massive star formation is a scaled-up version of low-mass star formation.
- For low-mass star formation, our modeling suggests that the temperature in the envelope can be significantly affected by the surface density (i.e., the surface pressure) of the star-forming environment. This is caused by the varying size, density, accretion rate, outflow intensity, and luminosity of the protostar and disk. This temperature difference may affect the ice mantle composition of the dust grains and other chemical conditions, potentially affecting the growth of the dust grains into the planetesimals.

References

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