Bridging the Gap between Large-Scale Simulations and Observations of Star Forming Cores

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Great advances in both observations and computer simulations of star forming regions
Fundamental Questions

• How do protostars evolve through their earliest few $10^5$ years?

• What is the relation between the newly formed protostars and their parental environment?

• When and where do disks form?
Methodology

• Directly compare simulations of star forming regions with real observations by creating “synthetic observations”
• Do this for a large number of objects to create a statistical sample
• “Benchmark” simulations against observations
• Use simulations to put observations into a physical context
Simulation

- Large and small scales in one simulation
- Uses Adaptive Mesh Refinement (AMR)
- $\Delta x_{\text{min}} = 8$ AU
- Running time = 760 kyr
- $N_{\text{star}} = 303$
- $N_{\text{snapshot}} = 189$

Haugbølle et al. in prep
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Synthetic Observations

- Raw simulation
- Dust radiative transfer
  RADMC-3D
- Dust continuum image
- Only the central protostar is emitting \( L = 1 \ L_{\text{sun}} \)
Synthetic Observations

- Raw simulation
- Dust radiative transfer
  RADMC-3D
- Dust continuum image
Synthetic Observations

Dust radiative transfer
RADMC-3D

- Raw simulation
- SED
Synthetic Observations

Simulations

Continuum images

SEDs

Wavelength (µm)
Classification of Protostars

- $\max(T_{\text{bol}}) \approx 200$ K
- $n_{\text{Class } 0}/n_{\text{Class } I} \approx 1.5$

- The different classification methods ($T_{\text{bol}}$ & $L_{\text{smm}}/L_{\text{bol}}$) predict the same class 87% and 81% of the time for respectively synthetic and real observations
Classification of Protostars

- $L_{\text{smm}}/L_{\text{bol}}$ is a better evolutionary tracer than $T_{\text{bol}}$

- Caveat: All stars have the same luminosity, so for real observations scatter will be higher
Protostellar Cores

- Detect cores at two sample distances with CLFIND2D (Williams et al., 1994)

- Luminosity sources are the central protostar and the external interstellar radiation field with spectrum as in Black (1994)
Core to Protostar distance distribution

- 75% of synthetic cores contain a protostar. The same is true for 35% of Ophiuchus cores, and 58% of Perseus cores.

- Caveat: Continuum images are 30,000 AU × 30,000 AU around protostars, so we cannot expect to see all the starless cores in simulation.
Core Extinction Threshold

- Where are the cores located relative to the mass in the cloud?

Matches the extinction threshold for protostellar cores found by Johnstone et al. 2004
Disks

\[ \langle v_\phi \rangle \text{ average rotational speed} \]

\[ \langle v_r \rangle \text{ average radial speed} \]

\[ \langle v_{r,\phi} \rangle \text{ is calculated within a radius of 400 AU from the protostar} \]

\[ \alpha = 0 \text{ pure rotation} \]
\[ \alpha = \pi/2 \text{ pure infall} \]
\[ \alpha = 0.2 \times \pi/2 \text{ disk limit} \]
Disks

- Dynamical studies are important for our understanding of star formation
- Using 3D non-LTE line radiative transfer we can also make direct comparison of kinematics.
- Disks are common at all evolutionary stages – even the most deeply embedded objects
- Out of all the systems in the simulation ≈50% have a disk (i.e. $\alpha \leq 0.2 \times \pi/2$)
Summary

- Lowering of spatial resolution means we lose completeness in our sample for less embedded sources.

- $T_{bol}$ and $L_{smm}/L_{bol}$ agree on the classification 87% of the time.

- $L_{smm}/L_{bol}$ is tightly correlated with envelope mass, and is thus a good evolutionary indicator.

- The distribution of distances between protostellar cores and protostars match observations very well.

- The protostellar cores are predominantly located in regions of high column densities/extinction.

- Disks form at all ages and are common in both Class 0 and I sources.