Open Questions

1. What is the origin of the Stellar Initial Mass Function?

2. What is the Role of Star Formation Feedback?

3. How do Molecular Clouds Form?
All Together Now

Theory

Observation

It's a pachyderm!

Simulation

It's a Sheet!

It's a Fan!

1.1 mm

24 um

CO

HI

Hα

It's a Shock

N₂H⁺ It’s a Filament!

It’s a Cloud!

It’s a Cloud!
What is the origin of the IMF?
IMF SAMPLING

Chabrier 2005

- Milky Way Field
- Dwarf Galaxies
- Milky Way Bulge
- Galactic Center
- IC348 Cluster
- M31 Clusters
Resolved IMF: Universal

IMF Appears Universal in Young Clusters

Chabrier 2005 IMF -- not a fit

Offner et al. PPVI
Figure credit: E. Moraux

Poisson errors - do not include systematic errors
Studies of the field, local young clusters and associations, and old globular clusters suggest that the vast majority were drawn from a "universal" IMF. 

- No systematic variations found in High-Mass end in M31 (Weisz et al. 2015)
CMF and the IMF

• Dense cores are suspected precursors of stars (star systems)
• Core mass function (CMF) is shifted by $\sim 1/3$ compared to the stellar IMF

Mon R2 (850pc) observed with LMT, Gutermuth et al. in prep.

Cores identified in Aquila
Andre et al. 2010

How much does Turbulence matter?

The IMF...

is
Padoan & Nordlund
Hennebelle & Chabrier
Hopkins
Myers, McKee, Klein

is sort of
Cartwright & Whitworth
P. Myers
Adams & Futuzzo
Offner & McKee
Krumholz

is not
Clark, Bonnell, Klessen,
Smith
Stamatellos & Whitworth
B. Elmegreen

Manifest Destiny

Central Limit Theorem

...determined by the Core Mass Function (CMF)
Multiplicity

Cores form multiple stellar systems.

What if protostellar multiplicity varies with core mass?

Fragmentation is not self-similar. Here we show the emerging IMF that could arise if the cores in the CMF fragment based on the number of initial Jeans masses they contain.
What is the Origin of the Stellar IMF?

- Cores: High-sensitivity ($M<0.08$ Msun), high-resolution ($\Delta x \leq 0.01$ pc out to 500 pc) continuum ($\geq 850$ um) observations

- Cores: High-resolution, spectroscopic dense gas surveys ($\Delta v \leq 0.05$ km/s): e.g., NH$_3$, N$_2$H+

- Protostars: $<0.1$” resolution to study multiplicity

- Synthetic Observations: evidence of CMF universality or systematic variation
Open Questions

1. What is the origin of the Stellar Initial Mass Function?

2. What is the Role of Star Formation Feedback? Heating, Ionization, Pressure, Outflows, Winds...

3. How do Molecular Clouds Form?
Protostellar Outflows

- Interact with the cloud (global)
- Interact with parent core (local)

NGC 1333
~150 YSOs
Image: Gutermuth & Porras

Walawender, Bally, Reipurth et al. 06
Spitzer/IRAC
Jorgensen et al. 08

HH 46/47

Velusamy et al. 07
Spitzer

0.1pc

Hα  [SII]

Hα  Walawender, Bally, Reipurth et al. 06

Spitzer/IRAC
Jorgensen et al. 08
ALMA

- Wide angle wind + episodic jet
- Outflow momentum can disperse parent core

HH 46/47, $^{12}$CO, $^{13}$CO, C$^{18}$O, CS

Zhang, Arce, Mardones et al. in prep.
Protostellar Outflows & Cores

“Isolated” Star Forming Core

M_{core} = 4 M_{sun}

L=0.26pc

Offner & Arce 2014
Outflow Mass Evolution

- Stage 0 Defn: $M^* < M_{\text{env}}$
- Sim. Stage 0 ~ 0.1 Myr
- Obs. Class 0 ~ 0.1 Myr (Enoch et al. 08)

$f_{\text{wind}} = 0.2$
$\theta = 0.01$

Offner & Arce 2014
B5 Star-Forming Region in 13CO(1-0)

A Bubbling Nearby Molecular Cloud
Stellar Winds

Perseus Molecular Cloud
Arce et al. 2011

Winds may inject significant energy

See also:
Swift & Welsch 2008,
Narayanan et al. 2008,
Nakamura et al. 2012
Lei et al. 2015
Wind Simulation

$V_{\text{rms}}^{12\text{CO}(J=1-0)}(\text{km s}^{-1})$

$1 \text{pc}$

$t = 4.947 \text{ Myr}$
Observe

Radiative Transfer

Statistic: SCF

Gaches, Offner, Rosowlosky, Bisbas 2015
Proof of Concept: Winds

Wind features appear in Principle Component Analysis

Covariance: $S_1(v, v') = \sum_{x,y} O_1(x, y, v)O_1(x, y, v')$,

Boyden, Offner et al. in prep
What is the Role of Stellar Feedback?

• Outflows: High-sensitivity, high-resolution ($\Delta x \leq 2''$) continuum ($\geq 850$ um) and spectroscopic ($\Delta v \leq 0.2$ km/s) observations

• Turbulence: High-resolution ($\Delta v \leq 0.05$ km/s, $\Delta x \leq 0.01$ pc) $^{12}$CO and $^{13}$CO maps

• Synthetic Observations: robust statistics, parameter studies
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Origin Scenarios

Colliding Flows / GMC collisions

$\text{t} = 0.76 \ \text{Myr}$

Heitsch et al. 2008
(see also Audit & Hennebelle 2005, Vazquez-Semadeni et al. 2007, Tasker & Tan 2009)
Origin Scenarios

Kim, Ostriker, & Stone 2002

Gravitational Instability / Magneto-Jeans Instability

Dobbs, Pringle & Burkert 2011
Origin Scenarios

Parker Instability

Mouschovias et al. 2009
(see also Franco et al. 2002
Kim & Ostriker 2006)
How Do Molecular Clouds Form?

• Simulations: Full physics (gravity, radiation, MHD) modeling from galaxies down to sub-pc scales; emission predictions for each scenario

• Context: HI/CO/HCN emission maps of other galaxies

• Transition to Molecular Gas: Detailed photo-dissociation region (PDR) maps of local clouds in H/C/C+
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