MASSES: An SMA Large-Scale Program Surveying Protostars to Reveal How Stars Gain their Mass

Ian W. Stephens
Postdoctoral Fellow
Harvard-Smithsonian Center for Astrophysics
SMA science in the Next Decade
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Image credit: Lynn Hilborn
Physical Processes Regulating Accretion

Conservation of angular momentum

Outflows

Fragmentation

Diagram adapted from M. Persson
**MASSES – Mass Assembly of Stellar Systems and their Evolution with the SMA**

- Continuum and molecular line survey of all 75 Perseus Class 0/I protostars
- Driving science question: how does a star gain its mass?
- Uses extended and subcompact SMA configurations to achieve:
  - 1″ (230 AU) resolution, 20″ (4600 AU) max scale
- ~600 (60 nights) hours over 3 – 4 years

*Slide credit: M. Dunham*
Observing Parameters

**Subcompact**
ASIC and SWARM+ASIC
230 GHz @ 4” resolution
345 GHz @ 2.5” resolution
Max angular scale: 20”

**Extended**
SWARM+ASIC and SWARM only
230 GHz @ 1” resolution

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**230 GHz**
Continuum
CO (2-1) 0.26 km/s
\(^{13}\text{CO} (2-1)\) 0.26 km/s
C\(^{18}\)O (2-1) 0.13 km/s
N\(_2\)D\(^+\) (3-2) 0.13 km/s

**345 GHz**
Continuum
CO (3-2) 0.085 km/s
HCO\(^+\) (4-3) 0.085 km/s
H\(^{13}\)CO\(^+\) (4-3) 0.085 km/s

For all 75 Perseus Class 0/I Protostars!
**CO(2-1) Outflows**

|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|

*Stephens et al. (in preparation)*
Multiple systems are preferentially randomly or anti-aligned

Lee et al. (2016), Offner (2016)
Accretion
Multiplicity/Fragmentation
Angular Momentum/Outflows
Accretion
Is protostellar accretion purely gradual, or is it episodic?

- Depending on temperature CO and C\textsuperscript{18}O can both sublime and freeze-out with the dust grains.

- Compare current luminosity with expected size based on chemical modeling.

Søren Frimann et al. (submitted)
Protostellar accretion traced with chemistry

**Blue line**: Expected size of C\(^{18}\)O for protostars’ current luminosity

**Dashed Green lines**: Expected size for 10 and 100 times current luminosity

Observed sizes are much larger!

Frimann et al. (submitted)
Can be explained by Episodic Accretion!!

Based on sizes of $^{18}\text{C}O$ sizes, accretion bursts every $\sim 10,000$ years.
Multiplicity/Fragmentation
Thermal Jeans Fragmentation

Thermal Jeans Mass (Spitzer formulation):

\[ M_J = \bar{\rho} \lambda_J^3 \]

where \( \lambda_J = \frac{\pi^{1/2} \sigma}{(G \bar{\rho})^{1/2}} \)

Jeans number

\[ N_J = \frac{M}{M_J} \]

Larger \( N_J \), fragmentation more likely
Thermal Jeans Fragmentation

MASSES
SMA

VLA

Lowest Jeans Number
Much Higher Jeans Numbers

Lee et al. (2015)
Given the Jeans number for each SMA envelope, how many protostars found with VLA?

Higher Jeans Number ➔ More Multiples!!!

Riwaj Pokrehl et al. (in prep)
Thermal Jeans Fragmentation

Higher multiplicity for Higher Jeans number seen at larger scales too!!

Envelope to Protostar
(few 1000 AU to 100 AU)

Core to Envelope
(~0.1 pc to few 1000 AU)

Clump to Core
(few pc to ~0.1 pc scales)

Pokrehl et al. (in prep)
Angular Momentum/Outflows
Misalignment of Outflow Axes

Wide Binaries separated by 1000 – 10000 AU

Lee et al. (2016)
Misalignment of Outflow Axes

Preferentially Perpendicular or Misaligned!

Lee et al. (2016)
3D MHD Simulations

Initial uniform field with mass to flux ratio of about ~2

Stars form via turbulent fragmentation of cores

**Signature of binary formation via turbulent fragmentation**

*Offner et al. (2016)*
Misalignment of Outflow Axes

Red: Projected angle between Planck B-field and Outflow
Lee et al. (2016)  Stephens et al. (in prep)
Outflow Opening Angle Versus Age
Does the opening angle of an outflow evolve with age?

Arce & Sargent (2006)

Age of MASSES protostars

Outflow Opening Angle Versus Age

Oscar de La Rosa et al. (in prep)
Survey of all 75 Class 0/I protostars in the Perseus molecular cloud

Largest molecular line survey in a single region at this resolution

Many people working on the project

Will provide major statistical constraints of outflows, multiplicity, protostellar evolution

Happy to share data: ian.stephens@cfa.harvard.edu