Origins: From the Protosun to the First Steps of Life
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MASSES: An SMA Large Project Surveying Protostars to Reveal How Stars Gain their Mass

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Abstract. Low-mass stars form from the gravitational collapse of dense molecular cloud cores. While a general consensus picture of this collapse process has emerged, many details on how mass is transferred from cores to stars remain poorly understood. MASSES (Mass Assembly of Stellar Systems and their Evolution with the SMA), an SMA large project, has just finished surveying all 74 Class 0 and Class I protostars in the nearby Perseus molecular cloud to reveal the interplay between fragmentation, angular momentum, and outflows in regulating accretion and setting the final masses of stars. Scientific highlights are presented in this proceedings, covering the topics of episodic accretion, hierarchical thermal Jeans fragmentation, angular momentum transfer, envelope grain sizes, and disk evolution.

Keywords. stars: formation, surveys, ISM: jets and outflows, ISM: clouds, ISM: kinematics and dynamics, ISM: molecules, accretion, astrochemistry

1. Introduction

Stars form via the collapse of molecular cloud cores ($\sim$0.05 pc in size). The collapse and accretion onto the star itself encompasses a complex interplay of physical processes. To constrain these physical processes at $\sim 200 - 5000$ au scales, we embarked on a Submillimeter Array (SMA) large project called the Mass Assembly of Stellar Systems and their Evolution with the SMA (MASSES). The MASSES survey (e.g, Stephens *et al.* 2018) observed all 74 known Class 0 and I protostars within the Perseus molecular cloud to create a complete and unbiased protostellar sample within a single star-forming cloud. The survey included both continuum and spectral line observations at both 230 GHz and 345 GHz. In the SMA's subcompact configuration, we observed at both of these frequencies simultaneously, and in the extended configuration, we observed at 230 GHz only. The lines and continuum frequencies observed are listed in Table 1. Notably, CO(2–1) and CO(3–2) trace the outflows (e.g., Figure 1), while the continuum and $C^{18}O$(2–1) trace the envelopes. The approximate age of each protostar can be assessed via the bolometric temperatures, allowing us to assess the evolution of protostars based on these tracers. More details of the MASSES survey are discussed in Stephens *et al.* (2018).

Table 1. Tracers Probed by MASSES

Tracer	Transition	Frequency (GHz)
1.3 mm cont		231.29
CO	$J = 2 - 1$	230.53796
^{13}CO	$J = 2 - 1$	220.39868
$C^{18}O$	$J = 2 - 1$	219.56036
N_2D^+	$J = 3 - 2$	231.32183
850 μm cont		356.410
CO	$J = 3 - 2$	345.79599
HCO^+	$J = 4 - 3$	356.73424
$H^{13}CO^+$	$J = 4 - 3$	346.99835

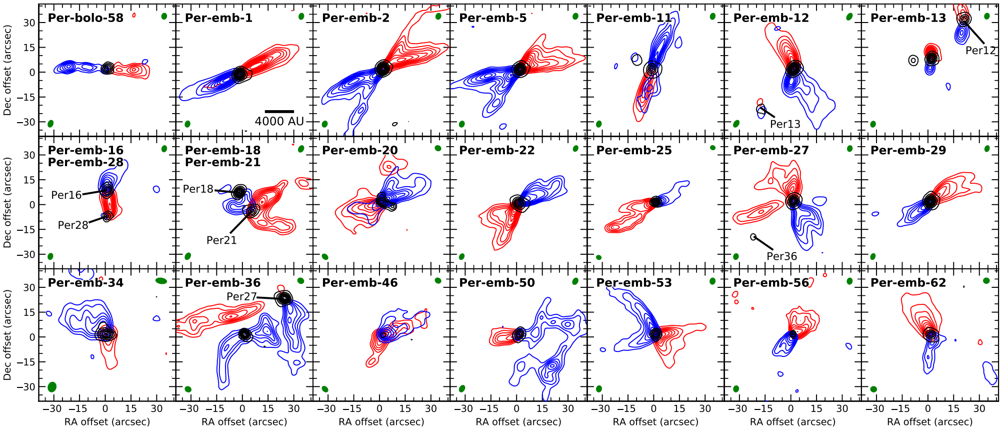

Figure 1. Selected CO(2–1) outflows from Stephens *et al.* (2018), as mapped by the MASSES survey in the SMA's subcompact configuration. Red and blue contours show the red-shifted and blue-shifted outflow lobes, respectively.

The MASSES survey is made more powerful using the ancillary data from the Karl G. Jansky Very Large Array (VLA) from the VLA Nascent Disk and Multiplicity (VANDAM) survey (Tobin *et al.* 2016). This survey imaged the continuum in the Ka-band with resolution up to ∼15 au.

Individuals can go to https://dataverse.harvard.edu/dataverse/MASSES to download the subcompact visibility and image data. The full subcompact+extended data will be released in a forthcoming paper. In this proceedings, we discuss the initial scientific results of the MASSES survey.

2. Scientific Highlights

2.1. *Evidence for Episodic Accretion*

CO and $C^{18}O$ molecules freeze out on dust grains at temperatures between ∼20 and 30 K. Protostellar envelopes have a temperature gradient. Near the protostar, the temperature is expected to be significantly higher than the sublimation temperature, while far from the the protostar, the temperature is expected to be much lower. If one assumes that the bolometric luminosity of the protostar is relatively constant, simple chemical modeling can be used to predict the size of an envelope as measured by $C^{18}O$(2–1) based on the current bolometric luminosity of the source. Jørgensen *et al.* (2015) observed $C^{18}O$(2–1) for 16 protostars across 6 different molecular clouds, and found that the $C^{18}O$(2–1) sizes were typically much larger than that predicted by the current bolometric luminosity of

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the protostars. Frimann *et al.* (2017) used MASSES data to attempt the same experiment for 21 protostars in Perseus and found the same result.

Episodic accretion may possibly account for the discrepancy between the expected size and the observed size of $C^{18}O$. If there was a sudden burst of accretion in past that greatly increased the luminosity, the $C^{18}O$ size would grow rapidly. When the luminosity goes back to normal, carbon monoxide does not freeze out instantaneously onto dust grains. The freeze-out time scale is about 10,000 yr for densities $\sim 10^6\,\mathrm{cm}^{-3}$ at 10 K (Visser & Bergin 2012). Thus, the larger sizes observed may have been from past accretion bursts. Based on the fraction of sources showing larger than expected $C^{18}O$(2–1) sizes, Frimann *et al.* (2017) estimated that accretion bursts occur every 20,000 to 50,000 years.

2.2. *Inefficient Thermal Jeans Fragmentation*

A Jeans Mass, M_J, defines the amount of mass needed to overcome pressure support so that an object can collapse. The thermal Jeans mass, $M_{J,th}$ is the mass needed to overcome the thermal support. The thermal Jeans number is defined as $N_{J,th} = M/M_{J,th}$, where M is the mass of the object. Objects with higher $N_{J,th}$ are more likely to fragment into more sources. Complete (i.e., efficient) thermal Jeans fragmentation suggests that $N_{J,th}$ is equal to the number of fragments. Lee *et al.* (2015) compared MASSES observations of the three envelopes in L1448N to high resolution VANDAM observations and found that the envelopes with higher $N_{J,th}$ indeed fragment into more protostars.

Pokhrel *et al.* (2018) followed up on this survey using an expanded MASSES dataset and found with over 95% confidence, Perseus envelopes with higher $N_{J,th}$ had higher multiplicity. This trend of parent objects with higher $N_{J,th}$ fragment into more children was also true at other scales in Perseus: from clouds (scales of $\sim$10 pc) to clumps ($\sim$1 pc), from clumps to cores ($\sim$0.05 pc), and from cores to envelopes ($\sim$1000 AU). At each scale, complete Jeans fragmentation suggests more fragments than observed. Therefore, fragmentation in Perseus can be described by inefficient thermal Jeans fragmentation. Including non-thermal support based on velocity linewidths predicts no fragmentation on large scales, and has no effect on small scales.

2.3. *Lack of Angular Momentum Transfer from Large to Small Scale*

If a collapsing core transfers its angular momentum directly to smaller scales, one would expect that wide binaries (defined here as protostellar pairs with separations between 1,000 and 10,000 au) would have the same angular momentum axis (i.e., axes are parallel). Lee *et al.* (2016) used MASSES data to analyze wide binaries in the Perseus cloud. The angular momentum axis of each protostar is ascertained from the outflow direction. Lee *et al.* (2016) found that the angular momentum axes actually appear randomly or perpendicularly oriented with each other, even when considering projection effects. Simulations by Offner *et al.* (2016) suggested that this is a signature of turbulent core fragmentation.

A filament may have two kinds of flows: accretion flow onto the filament or flow through the filament. If one of these flows dominates, a vorticity could be induced on the filament. Thus, a protostar could inherit angular momentum from gas flow on or through filaments. Stephens *et al.* (2017) compared the outflow direction (again, as a proxy for the angular momentum axis) to the protostar's filament direction. When considering projection effects, the alignment between outflows and filaments were significantly not parallel or perpendicular. Instead they were consistent with being randomly aligned. However, another possibility is that outflows and filaments are sometimes parallel and sometimes perpendicular, with perpendicular outflows and filaments about 3 times more common than parallel.

2.4. *The Ability to Estimate Protostellar Disk Masses and Evolution from Unresolved Observations*

Jørgensen *et al.* (2009) proposed a model where one can estimate Class 0 and I disk masses using unresolved (∼1000 au resolution) interferometric observations along with large-scale single dish observations. The model is a simple radiative transfer model that assumes a density profile and dust opacity index. The accuracy of this method has mostly been untested, as there are very few observations of the disks about embedded Class 0 and I protostars. The VANDAM survey has high enough resolution to resolve disks, and disk masses from this survey were estimated in Segura-Cox *et al.* (2016, 2018) and Tychoniec *et al.* (2018). In Andersen *et al.* (2019), we used the MASSES survey to test whether we can accurately apply the Jørgensen *et al.* (2009) model to estimate disk masses with at ∼1000 au resolution. We found that the method works extremely well; the estimated disk MASSES were very similar and strongly correlated to those estimated with high resolution in the VANDAM survey. We find that disks masses are relatively constant with age, but envelope MASSES decrease with age.

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Discussion

Zinnecker: Why are the outflows randomly directed?

Stephens: Simulations by Stella Offner have shown turbulence in a core can change the spin axis of a protostar on short timescales. The outflow direction may also be random from their filament because filament direction could change with time, so the current filament direction may not reflect the natal environment.

Khaibrakhmanov: Can the magnetic field be responsible for inefficient fragmentation?

Stephens: Yes, it may be able to provide support, but the field strength is not well constrained at all scales. We also have working models showing that substructure may also reflect why we see inefficient thermal Jeans fragmentation.