Five years after HL Tau: The First Hydrostatic Core!

Dary Ruíz-Rodríguez[1], Lucas A. Cieza[2] , John Tobin[1]

1. National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475, USA

2. Núcleo de Astronomía, Facultad de Ingeniería, Universidad Diego Portales, Av. Ejercito 441, Santiago, Chile

It is theoretically predicted that in between a starless core and a protostar, i.e. before the beginning of the Class 0 phase, a collapsing molecular core initially forms a central hydrostatic object known as the First Hydrostatic Core (FHSC). Several theoretical studies have investigated the physical properties of these FHSCs, however, this very short evolutionary stage has been highly elusive and challenging to prove observationally. As a matter of fact, many candidate FHSCs have been identified, but none have been definitively confirmed as such. Therefore, detecting observationally these objects is of central importance in studies of the earliest phases of low-mass star formation. Since more than 50 years ago (Larson 1969), astronomers have been pursuing an observational verification of the FHSCs, which would provide a laboratory for probing and understanding the earliest stellar stages and the formation of their associated protoplanetary disks, currently poorly constrained. Here, we present the robust detection of a FHSC, the first of its kind, by using the Atacama Large Millimeter/submillimeter Array (ALMA). Based on a kinematic modeling of the spherical rotating collapse phase, we estimate the characteristic physical properties of the object (central mass and accretion rate), which match those predicted for FHSCs.

THEORETICAL FRAMEWORK:

Due to internal turbulence and/or external perturbations, (a) a parental molecular core initiates an isothermal contraction, increasing its central density. (b) When the central density exceeds $\rho > 10^{-13}$ g cm^{-3}, the inner region becomes opaque to radiation, rendering an adiabatic core forms at the center. The central source continues to accrete material from the envelope, while the temperature rises resulting in an increase in the thermal pressure. (c) Eventually, the pressure balances the gravitational force, which leads to a central structure of a few astronomical units in size and 0.01-0.1 M$_\odot$ in mass, reaching quasi-hydrostatic equilibrium. This structure is known **as the first hydrostatic core (FHSC)** or first core (Larson 1969) . This process can result in the formation of a pseudo-disk, i.e., a non-rotationally supported disk, surrounding the FSHC, and is associated with the beginning of the launch of a slow and highly collimated outflow. (d) As the FSHC continues accreting material, and once the temperature reaches ~ 2000 K, molecular hydrogen dissociates in an endothermic reaction, triggering a second collapse in a small region (about 0.1 au) inside the first core. This second collapse leads to the formation of a second hydrostatic core, also known as a protostar.

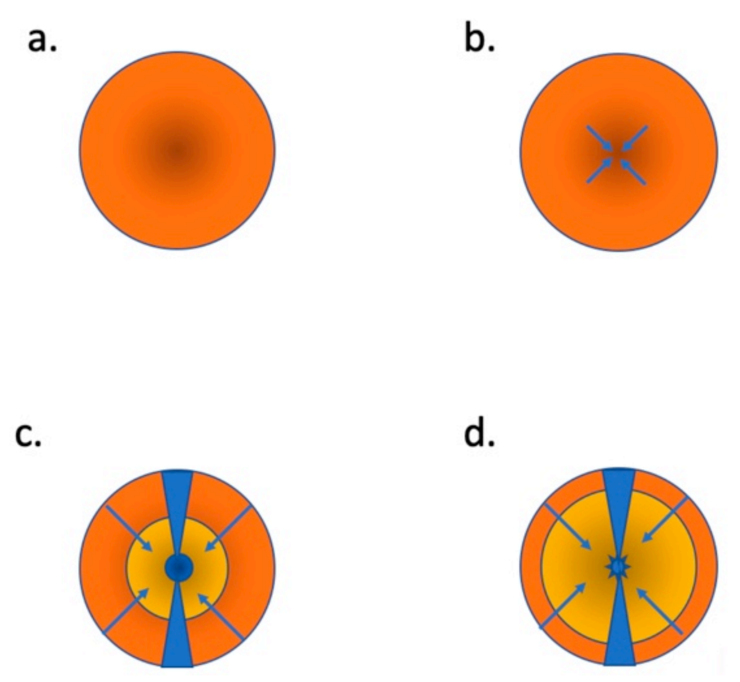

Figure 1. Key stages of low-mass star formation.

Infall motion dominates in FHSC:

FHSC candidates usually are Identified through asymmetric line profiles (Inverse P Cygni line profile), because NO direct detection has been confirmed yet. Figure 2 shows a central infalling core and an outer hydrostatic envelope, mediated by an expanding rarefaction front located at radius R_{Shu}. The central absorption dip in the line profile is caused by the outer static envelope.

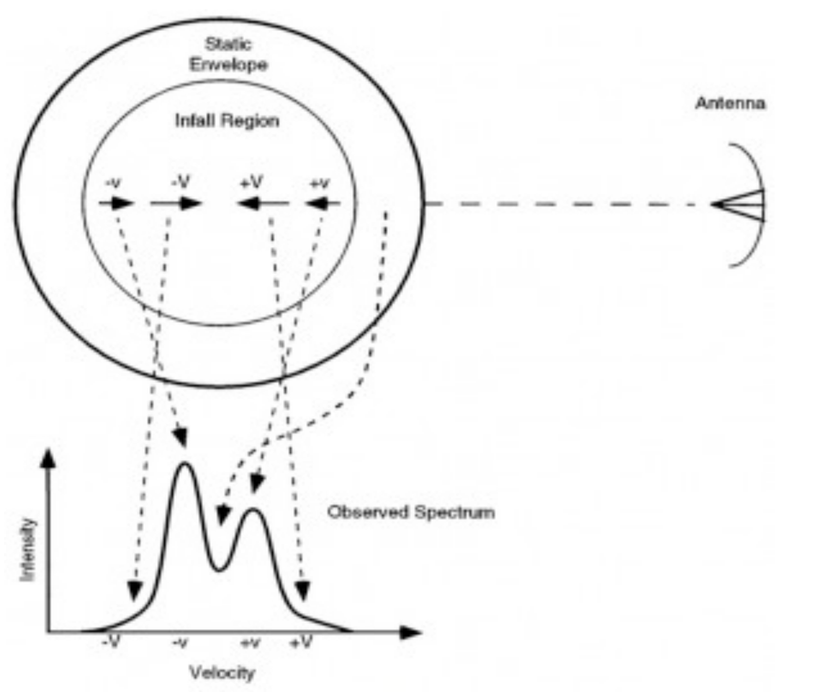

Figure 2. Inside-out collapse picture of line asymmetry (Evans 1999, Shu et al. 1977).

ALMA OBSERVATIONS AND MODELING:

ALMA observations[1] toward our FHSC target, see Figure 3, were carried out in Band 6 (211-275 GHz). Interestingly, we detected ^{12}CO and ^{13}CO emission, however, a lack of continuum detection indicates no dust close to the central object.

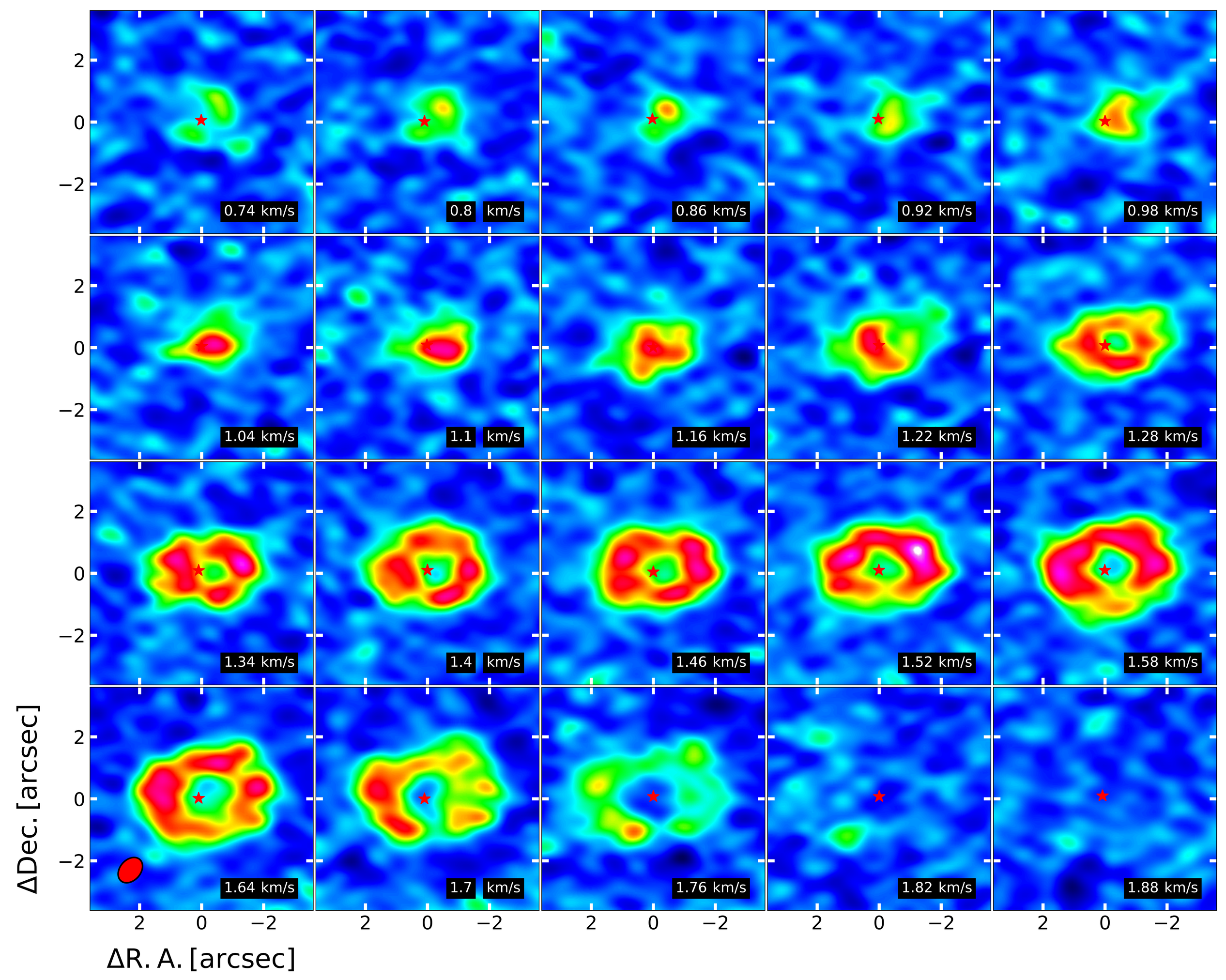

Figure 3. ^{12}CO channel maps. Blue-shifted emission. The red star marks the position of the central object.

To explain the spherical like-shape displayed in the 12 CO channel maps (see Figure 3), we adopt the canonical "inside-out" collapse model, i.e., a molecular cloud characterized by an inner region dominated by infalling motions and an outer region in a nearly static phase (Shu 1977). To probe the kinematics of the inner regions of the infalling cloud (Terebey et al. 1984), we use the density structure calculated jointly by Ulrich (1976) and Cassen & Moosman (1981, hereafter CMU) for a rotationally flattened, infalling envelope. To better compare the model to our interferometric data, we generate data cube and PV diagram models following Tobin et al. (2012), see Figures 4 and 5.

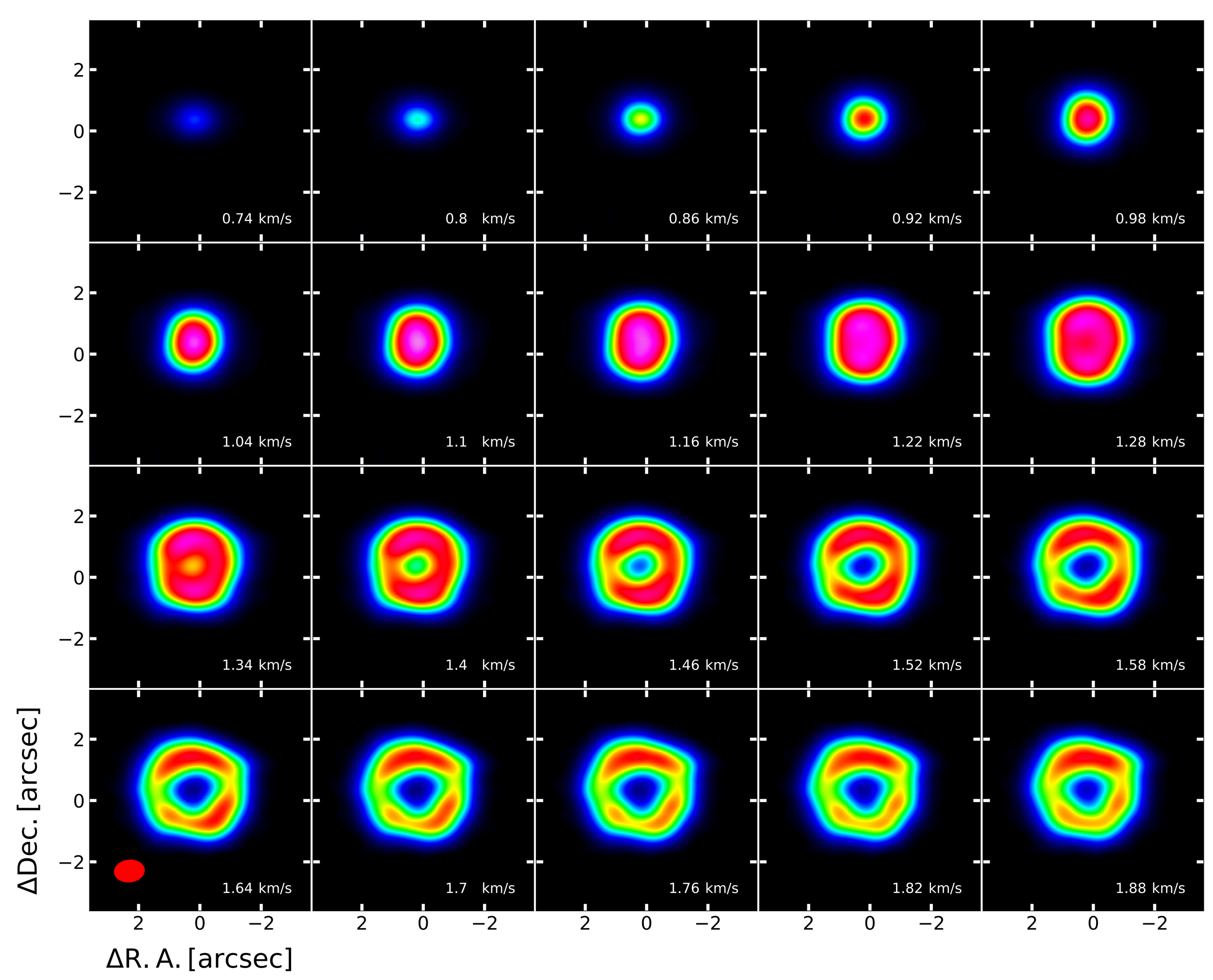

Figure 4. ^{12}CO synthetic channel maps obtained following Tobin et al. 2012 and CMU model. Blue shifted emission.

PHYSICAL PROPERTIES:

Following the above approach, the ^{12}CO line emission was modeled by using the Line Modelling Engine code (LIME). To minimize the number of free parameters, we fixed the inclination at I ~ 0º, R_c ~ 1 au, R_{outer} ~ 240 au, SV ~ 1.8 km/s. In the final fit, we varied : central mass, accretion rate, and R_{in}. (see Table 1).

Parameter	Best Fit	Range of Values
Accretion Rate [10^{-5} M_{sun}/y]	6.5	5 to 8
[$M_\odot$]	0.05	0.04 to 0.06
$R_{cav.}$ [au]	120	100 to 140

Table 1. Best-fit parameters for parametric model fit to ALMA CO(2–1) data, which match those predicted for FHSCs.

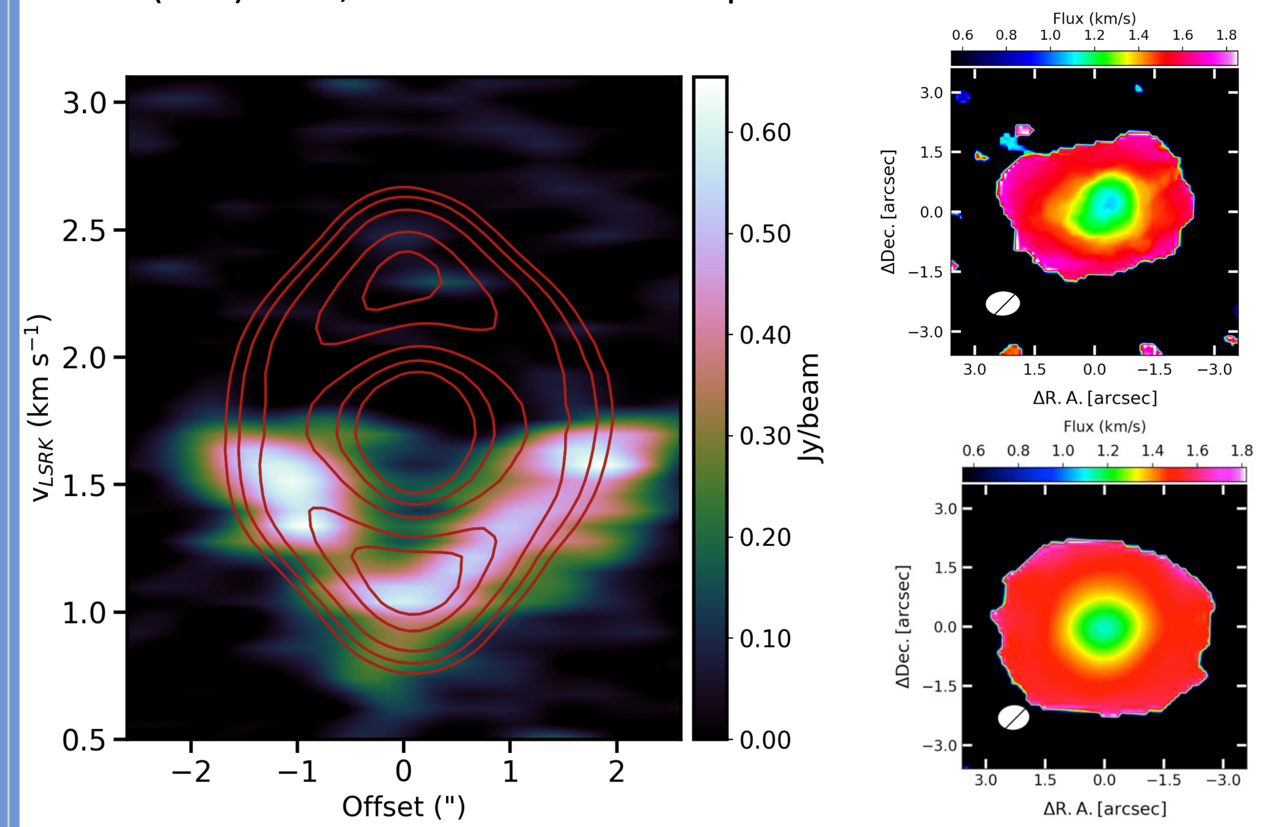

Figure 5. (a) PV diagram along the object "major axis" at an inclination of 40º. The PV diagram describes mainly infall motion as seen in the synthetic spherical-like shape -- red solid curves -- surrounding a mass of 0.05 (diamond-shape, see Tobin el al. 2012), and only in the blued-shifted emission. (b) Velocities maps for the observed FHSC (Top) and spherical like-shape model (Bottom) displaying no signs of rotation.

Summary:

- Based on a kinematic modeling of the spherical rotating collapse phase, we estimate the characteristic physical properties of the object (Table 1), which match those predicted for FHSCs, see Dunham et al. (2014).

Future Work:

- **Paper coming soon!!.**
- 1. We opted to not specify neither star-forming region nor object coordinates until further notice.

References:

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