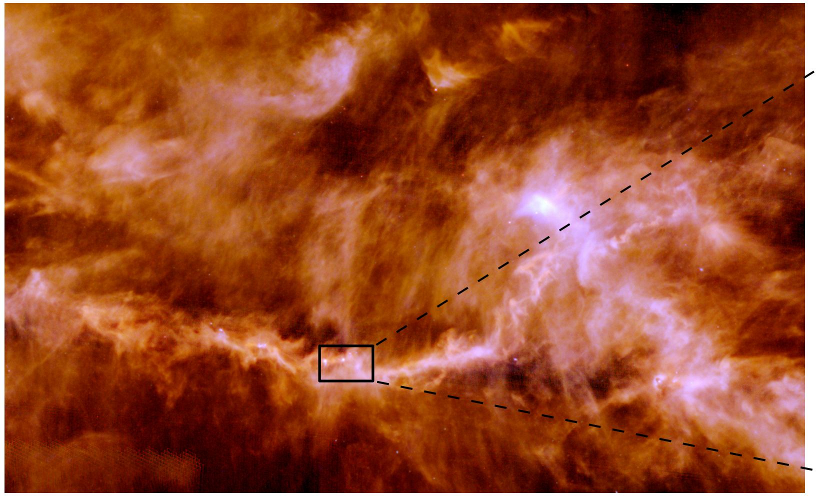
Solar-like star formation

Stars born in the molecular clouds which are huge reservoirs of dust and gas. These clouds are organized by filaments. Inside filaments, a succession of compressions and fragmentations leads to the creation of gas nuclei called pre-stellar cores. These dense cores collapse and one or several stellar embryos form in the center of an envelope composed of the matter of the parent pre-stellar core. This is the protostellar phase. The embryo will then grow by progressively accreting a large part of the matter which surrounds it. It is during this accretion phase that the star will obtain its adult stellar mass. A disk may form around the stellar embryo. Then, the stellar object evolves into a T-Tauri star surrounded by a large disk where planets begin to form. When the internal temperature is high enough to trigger nuclear fusion reactions, the stellar object obtain the official status of a star like our Sun.

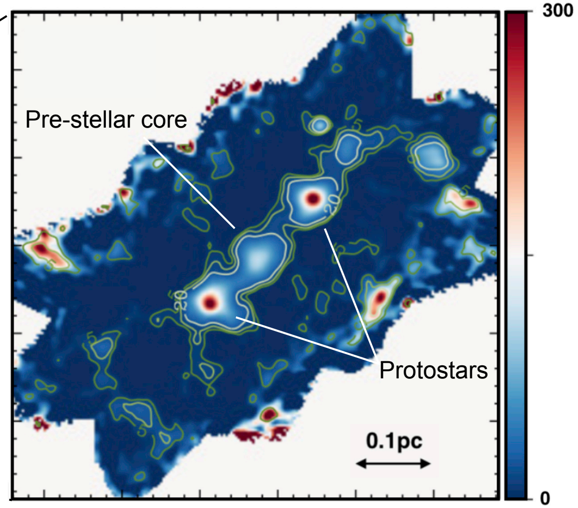
This star formation schema has been empirically established by astronomers from observations of stars in formation at different stages of evolution. The physical mechanisms linking the different stages are still poorly understood.

1 Molecular cloud organized by filaments



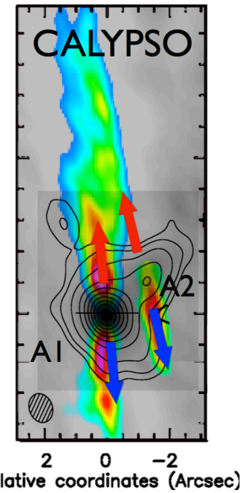
The B211/B213 filament in the Taurus Molecular Cloud.
ESA/Herschel/Gould Belt survey/Palmeirim+2013

2 Formation of pre-stellar cores



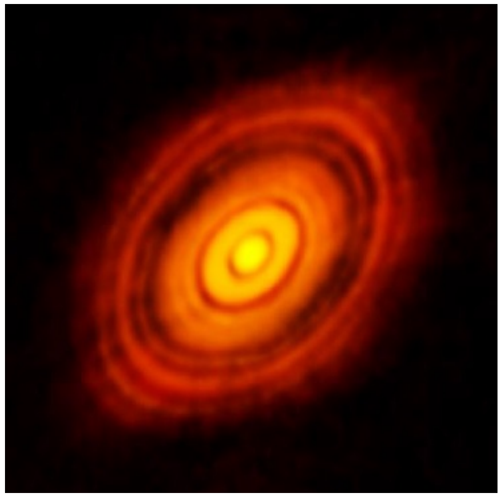
Dust continuum map of the B213 filament. IRAM 30m/NIKA/Bracco+2017

3 Protostar formation



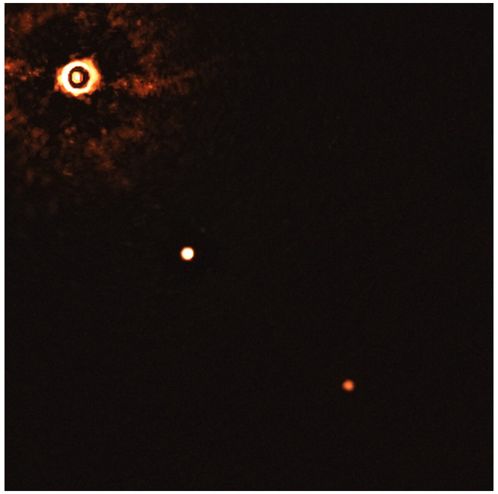
^{12}CO emission and continuum intensity contours for the IRAS4A protostar. IRAM PdBI/ CALYPSO survey/Maury

4 T-Tauri star surrounding by protoplanetary disk



Protoplanetary disk around the T-Tauri star HL-Tau. ALMA 2014

5 Star surrounding by planets



TYC 8998-760-1 solar-like star surrounding by two giant planets.
ESO/VLT/Bohn+2020

Rotational motions during star formation

From the classical scenario of star formation

A rotating core has a specific angular momentum:

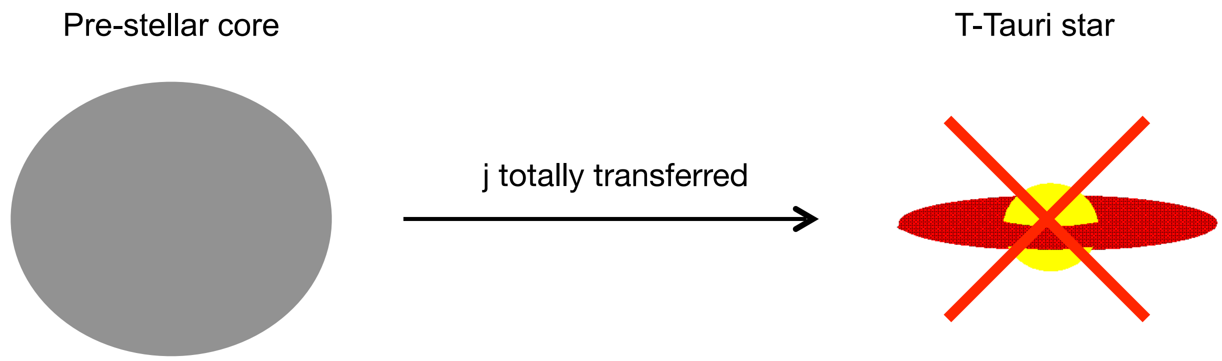
$$j = v_{rotation} \times r$$

In the classical scenario of star formation, which is described in the first slide, stellar embryo inherits its rotational motions from the parent pre-stellar core in which it form.

From historical measurements of velocity gradients *(Goodman+1993, Caselli+2002)*, the specific angular momentum in pre-stellar cores has been estimated to:

$$j_{pre\text{-}stellar\ cores} = 10^{-3} - 10^{-1}\ km\ s^{-1}\ pc$$

Problem



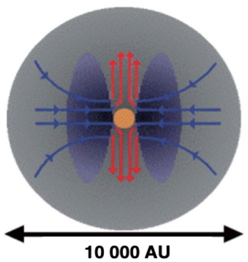
As a consequence of the angular momentum conservation, if the angular momentum of the pre-stellar core is totally transferred to the stellar embryo during the accretion phase, the embryo would rotate too quickly and would fragment before becoming a star like our Sun.

We propose to find a solution to this problem

With which objets ?

Young protostars ($M_{envelope} >> M_{embryo}$) because:

→ it is the beginning of the accretion phase
→ they keep imprint of the initial conditions



Why?

→ To better understand the link between rotational motions at different scales
→ To put new constraints on angular momentum content within young stellar objects

How?

By studying in detail the velocity field and building radial distribution of angular momentum at all scales of protostellar envelopes, from the stellar embryo (1 au) to the outer edges of the envelope (5 000 au).

CALYPSO: an IRAM large program

- Project name: Continuum and Lines in Young Protostellar Objects
- PI: Ph. André
- Website: http://irfu.cea.fr/Projets/Calypso
- Observations from IRAM Plateau de Bure Interferometer and 30-meter telescope of kinematic tracers
- Study sample: 12 young protostars (140 < d < 400 pc)

Plateau de Bure Interferometer (PdBI)

IRAM

- 6 antennas of D=15m with a maximum separation of 760m
- High angular resolution: 0.35''

→ Observations only trace the inner part of the protostellar envelopes because the large scale emission is filtered out by the interferometer.

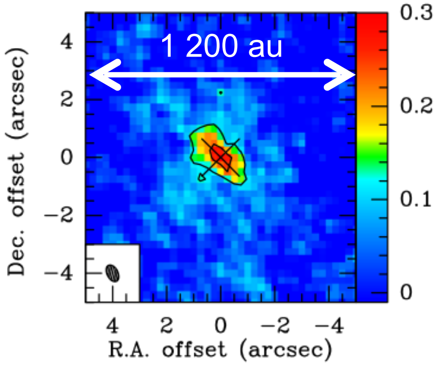
30-meter telescope (30m)

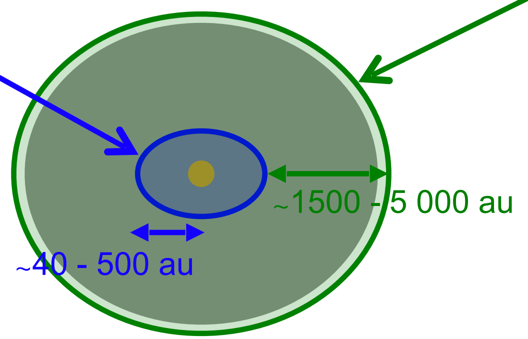
IRAM

- 1 antenna of D=30m
- Angular resolution: 12''

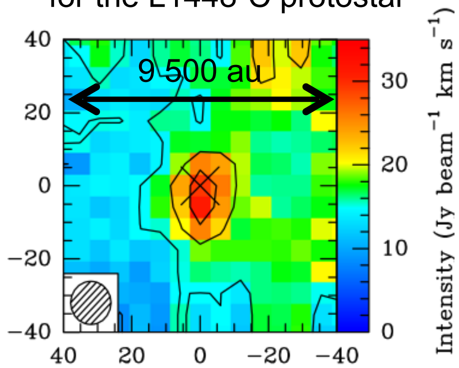
→ Observations recover all the emission from the protostellar envelopes but the angular resolution does not allow us to resolve the inner part.

Example: $C^{18}O$(2-1) emission for the L1448-C protostar





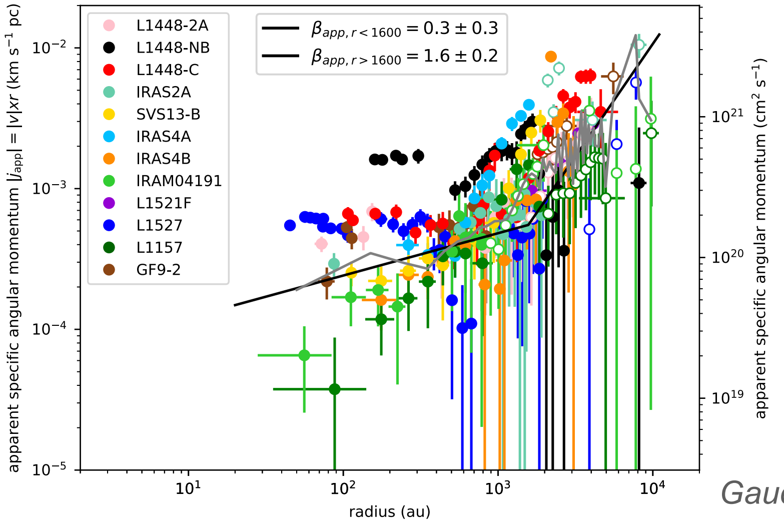
Example: $C^{18}O$(2-1) emission for the L1448-C protostar



→ We built a high dynamic range dataset by combining PdBI and 30m observations in order to probe protostellar envelope kinematics from ~40 to ~5 000 au.

Results of the velocity field analysis

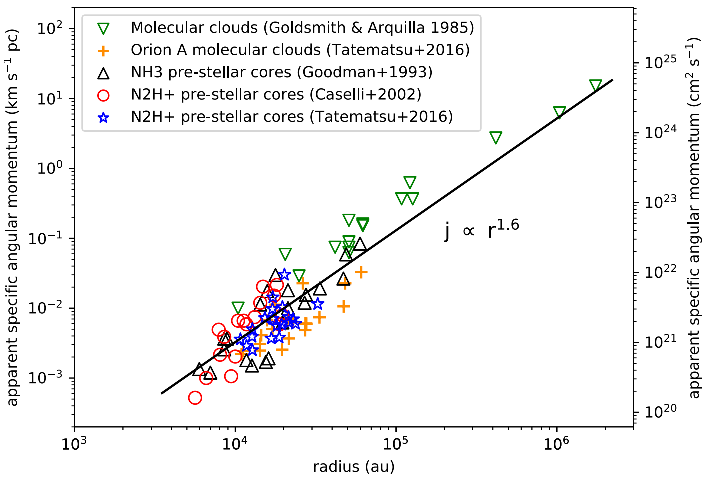
Radial distributions of angular momentum within protostars



Gaudel+2020

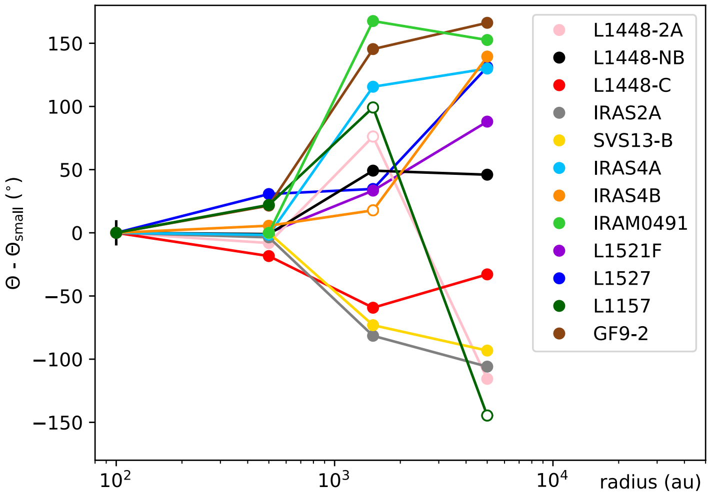
These distributions, built for the first time in a large sample of protostars, reveal **two distinct regimes**: a relatively constant profile in the inner part of the envelopes and an increase in angular momentum in the outer part.

Angular momentum observed in pre-stellar cores



The increase in angular momentum observed in the outer part of the protostellar envelopes is consistent with the angular momentum observed in the pre-stellar cores. Historically, **the gradients measured in the pre-stellar cores were interpreted as rotational motions but a recent study** *(Tatematsu+2016)* **interpreted them as (gravitationally-driven) turbulence**.

Dispersion of velocity gradients within protostellar envelopes



Evolution of the orientation θ of the mean velocity gradient measured to build the angular momentum distributions with respect to the orientation of the velocity gradient observed at small scales. Gaudel+2020

In the outer part of the envelopes, the orientation of the velocity gradients becomes random and disorganized, suggesting that **the origin of the velocity field is not the same as in the inner envelope where rotational motions are identified**. Thus, the motions in the outer part are not due to pure envelope rotation but seem to be dominated by other mechanisms.

Conclusions:

These new results question the origin of star rotation: the rotational motions of the stellar embryos would not be inherited from the pre-stellar phase, as postulated in the classical scenario of star formation, but would be a consequence of the collapse and/or turbulence during star formation.