OBSERVATIONS OF BINARY PROTOSTARS

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Collaborators

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Outline

1. Introduction
2. Tracers and observing methods
3. MM dust continuum emission
4. Molecular outflows
5. Conclusions
Why do we study binary protostars?

- Most PMS stars are binaries and they are coeval → Most stars must form as binaries!
- Multiple systems undergo dynamical evolution → Studies of evolved systems cannot tell us all about formation
- Not much direct observational information on binary formation
- ``Standard`` assumption in theory and interpreting observations: formation of single stars
- State-of-the-art SF models produce binaries and make testable predictions \((J, M, a, q, \beta)\)
  
\(\text{(Bate, Bodenheimer, Bonnell, Boss, Burkert, Durison, Tohline, ...)}\)
Which physical regime and evolutionary stage do we trace?

- Cloud 20K
- Core 10K
- Disk 50K
- Star 6000K
- Planet 300K

Class 0/I protostars
Star Formation and Multiplicity
Star Formation and Multiplicity

- 78% of star-forming cores in globules are multiple (sample of 23 studied)
- Range of scales: 500 AU - 20,000 AU (0.1 pc)
- → Fragmentation/multiplicity and star formation are inherently coupled, even in simple Bok globules!
What do we want to know?

→ The formation mechanism
  - Initial (turbulent) fragmentation vs. prompt fragmentation during collapse
  - Delayed breakup → currently not directly accessible to observations

→ Efficiency of binary / triple formation, separations, mass ratios, relative orientation

→ Dependence of outcome on initial conditions
  (Density profiles, Angular momentum, Turbulence, …)
Key parameters:

1. Envelope structure and mass
2. Protostar masses and mass ratios
3. Separations
4. Distribution of angular momentum
5. Rate and distribution of mass accretion
6. Energy balance (e.g., $\beta = E_{\text{grav}}/E_{\text{rot}}$)
Which tracers?

- Near-infrared
  Scattered light
- NIR jets
  Line emission
  + scattered light
Which tracers?

- Mid-infrared
  - Hot protostellar cores, inner accretion disks
Which tracers?

- Millimeter dust continuum
  - Inner protostellar cores, accretion disks
  - Masses

Problem:
Need high angular resolution
⇒ Interferometers
Which tracers?

- **Molecular lines**
  (e.g., N$_2$H$^+$)
- Dense gas in envelopes
- Kinematics

- Problems:
  - Depletion
  - Chemistry
  - Outflow-envelope interaction
Which tracers?

- CO line wings
  - Outflows
  - Driving sources

- Problems:
  - Outflow-envelope interaction
  - Spatial filtering
Millimeter dust continuum observations

- Traces dust in protostellar cores and accretion disks
- Circumstellar masses, mass ratios, projected separation of embedded sources
- Major work on binary protostars done at BIMA (Looney, Mundy et al.)
  - OVRO (Launhardt et al.)
  - continued at ATCA and IRAM PdBI (Chen, Launhardt, …)
- Other facilities? CARMA, SMA, VLA, ALMA, …
Survey results: isolated Class 0 protostars

OVRO, ATCA, PdBI

- IRAS04166 – 1.3mm
- CB244 – 1.3mm
- IRAS03282 – 1.3mm
- L723–VLA1 – 3mm
- BHR12 – 3mm
- L1448 – 1.3mm

⇒ 15 objects, growing
⇒ Statistical analysis includes other published results

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Real object 1: BHR12 (CG30)

- $d = 200$ pc
- $\lambda = 0.45 - 3$ mm
- HPBW = 2'' - 22''

- Separation $\approx 4000$ AU
- Mass ratio $\approx 0.5$

- Sources have different mm spectral slopes
- More massive component more evolved?
- Difficult to infer mass ratio from fluxes without model
Real object 2: L723-VLA2

- $d = 300$ pc
- $\lambda = 3$ mm
- HPBW = 1.7´´

- Separation = 950 AU
- Mass ratio $\sim 0.8$
- Missaligned accretion disks

Launhardt et al. 2003

Launhardt et al. 2003
Real Object 3: IRAS 03282+3035

- $d = 300$ pc
- $\lambda = 3$ and $1.3$ mm
- HPBW = 2'' and 0.7''

- Separation = 420 AU
- Mass ratio $\sim 0.2$

- Unequal masses
Real object 4: NGC1333 IRAS4A-C

- $d = 350$ pc
- $\lambda = 3$ mm
- HPBW = 5...0.6´´

- Separation 10000 AU
  - 3700 AU
  - 600 AU
- Mass ratios $\sim 0.2-0.3$
- Hierarchical system

Looney et al. 2000
What do we learn from mm dust continuum?

Separations:

Mass ratios:

- Halbwachs et al. 2003, A&A 397, 159
- Mayor et al. 2001, IAU 200, 45

- P > 100 days
- P < 50 days

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Observations of molecular outflows
Outflows 1: L723-VLA2

- Equal-mass wide protobinary system (d~950AU, q~0.8)
  - True quadrupolar outflow
  - Missaligned axes
  - Equal outflow strengths

Lee et al. 2002
Outflows 2: CB230

- Unequal mass wide protobinary system ($d \approx 3800$ AU, $q \approx 0.1$)

- Large scale: one bipolar outflow
- Interferometer: additional fainter outflow (blue lobe) from secondary component
- Missaligned axes
Outflows 3: IRAS 03282+3025

- Unequal-mass wide protobinary system (d~420AU, q~0.2)
- Only one outflow from primary component detected
Outflow axes are often not aligned!
(at least not for wide binaries >100AU)
→ so must be the angular momenta and disks

Outflow strengths can be very unequal
or the secondary outflow is not even detected.

Why do we observe so few quadrupolar outflows?
→ Most (wide) systems have unequal masses
→ Unequal accretion rates
→ Unequal outflow strengths
→ Secondary outflow in most cases too weak!
→ Close binaries are expected to have q~1. Two parallel jets/winds may produce one single large-scale outflow.
Observing strategies:

- Interferometric (sub)mm continuum observations most efficient
- Mid-infrared observations seem very promising complementation
- Outflows and kinematic parameters very challenging, but we need this information

(Preliminary) Results:

1. Binary protostars are frequent and observed at all accessible separations (too early to derive separation distribution)
2. \( d < 4000 \) AU \( \rightarrow \) common envelope (prompt fragmentation?)
   \( d > 4000 \) AU \( \rightarrow \) separate envelopes (initial fragmentation?)
3. Disks and outflows can be misaligned
4. Flat mass ratio distribution, unequal masses preferred
   \( \rightarrow \) like wide MS binaries
5. Unequal masses / accretion rates produce unequal outflows, this may explain the observed lack of quadrupolar outflows
What do we dream off?

- ALMA …
- Lots of observing time with ALMA and manpower to reduce the data
- A 100m FIR space telescope or array …