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Binary Star Formation Part 2- Fragmentation

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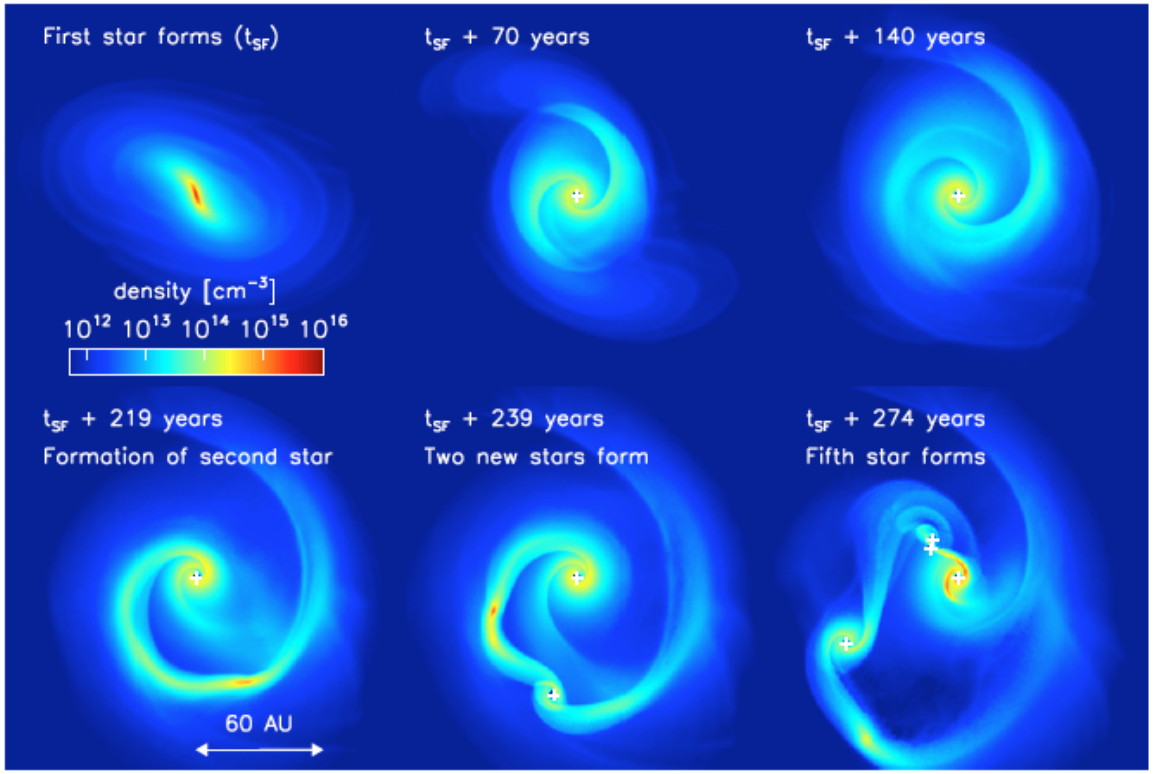
Outline

- Overview and Observations
- Fission
- Fragmentation
  - Isolated Core Fragmentation
  - Cloud Fragmentation
  - Magnetic Fields
- Conclusions: *Do the observations and models agree?*



Density evolution in a 180 AU region around a protostar, showing the build-up of the protostellar disk and its eventual fragmentation.

Reference: P.C. Clark, S.C.O. Glover, R.J. Smith, T.H. Greif, R.S. Klessen, V. Bromm: The Formation and Fragmentation of Disks around Primordial Protostars. Science Express, (2011)

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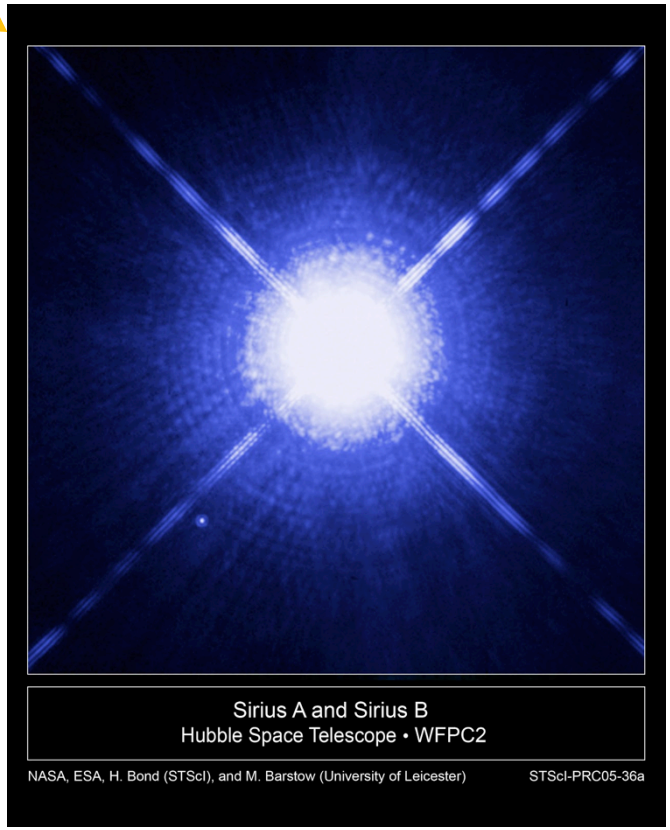
Observational Data

- What have we learned from observations?
  - **60%** of main sequence stars have one or more companion (multiplicity fraction = MF)

$$MF = \frac{B + T + Q}{S + B + T + Q}$$ where

S = # of single star systems
B = # of binary systems
T = # of triple system
Q = # of quadruple systems

- In many star forming regions such as the Turus-Aurigae, TW Hydrae and Rho Ophiuchi the MF is close to 100%!
  - Therefore stars must almost always be born in multiple systems and then multiplicity declines after ~300,000 years.
- The periods of main-sequence G-type binaries is
  - $0 < log[P(days)] < 9$
  - Maximum at about 180 years, or a mean separation of 30AU
- Binaries can be difficult to characterize because of
  - Wide range of separations
  - Large disparities in masses of primary and secondary



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Formation Mechanisms

- Although very common, not obvious how to form binary stars:
  - We have never observed the process happening
  - Wide range of scales (mass ratios, separations, etc…)
- Possible mechanisms that have been suggested:
  - **Capture** - Laplace (1796), Stoney (1867)
    - One star captures another initially unbound star into a bound orbit
    - *Alex talked about this earlier*
  - **Fission** - Kelvin and Tait (1883)
    - the breakup by dynamical instability of a rapidly rotating object in hydrostatic equilibrium
  - **Fragmentation** - Hoyle (1953)
    - The breakup of a rotating protostar during the hydrodynamical collapse phase.

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Fission

- Fission Hypothesis:
  - As a star contracts toward the main sequence after disk accretion has been completed
    - Star tends to spin up
    - If angular momentum is conserved → the ratio $\beta = E_{rot}/E_{grav}$ increases
  - When β obtains a critical value, the star becomes unstable to perturbations that are not axisymmetric
  - Fission hypothesizes that non-axisymmetric perturbations will breakup the star
  - Because only a small amount of angular momentum can be stored in a star, this mechanism would produce close binaries.

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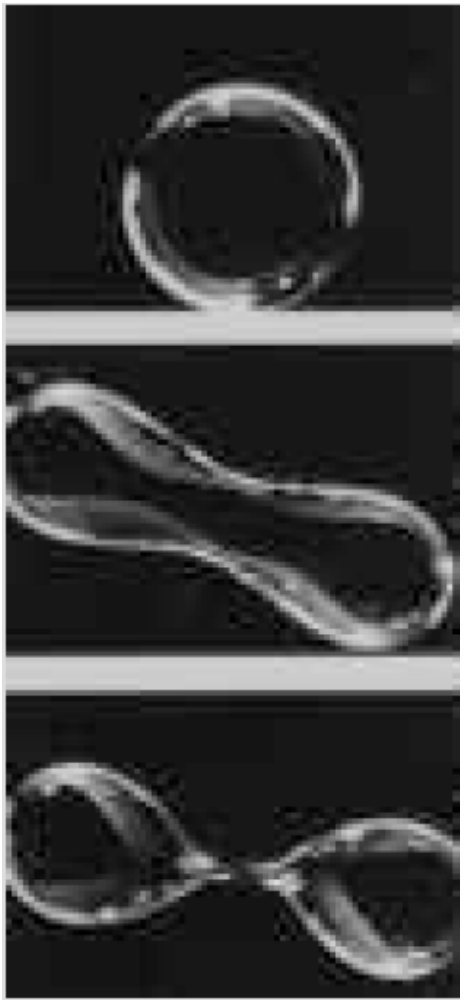
Fission Cont.

- Equilibrium shapes of rotating bodies of incompressible fluids are well known:
  - Spheres, Oblate spheroids & Ellipsoids
- Water droplets are an incompressible fluid
  - When spun up in zero gravity they fission into two
- Is this a way to form binary stars?
  - No, stars are compressible (much denser near the center than at the outside)
  - Do not have the surface tension like the droplet



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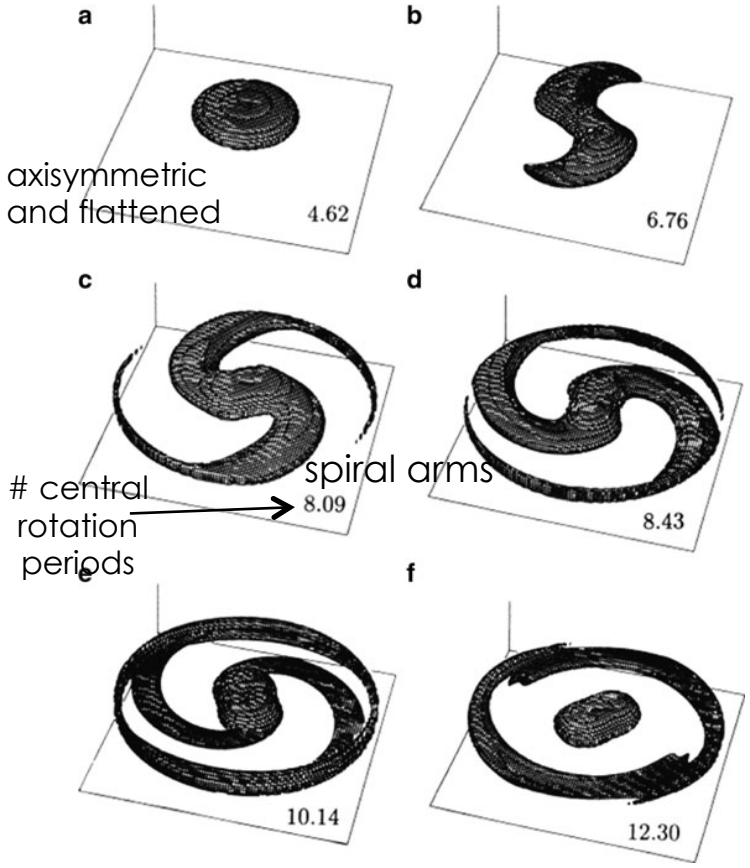
Fission – Example

- Figure on the right shows a calculation starting from a
  - Rapidly rotating polytrope of index 0.8
  - $\beta = 0.31$
- The figure shows that on a time scale of about 10 central rotation periods
  - System develops spiral arms
  - Spiral arms exert torques on the central object
  - Outcome is more slowly rotating central object plus a ring
- Don't get the right initial conditions for Fission, but it does give you a constraint on the maximum rotation rate of a star



Numerical simulation of the evolution of a rapidly rotating polytrope of index 0.8 with initial $\beta = 0.31$. Times are indicated on each frame in units of the initial central rotation period.

Source: H. Williams, J.E. Tohline, ApJ **334**, 449 (1988)

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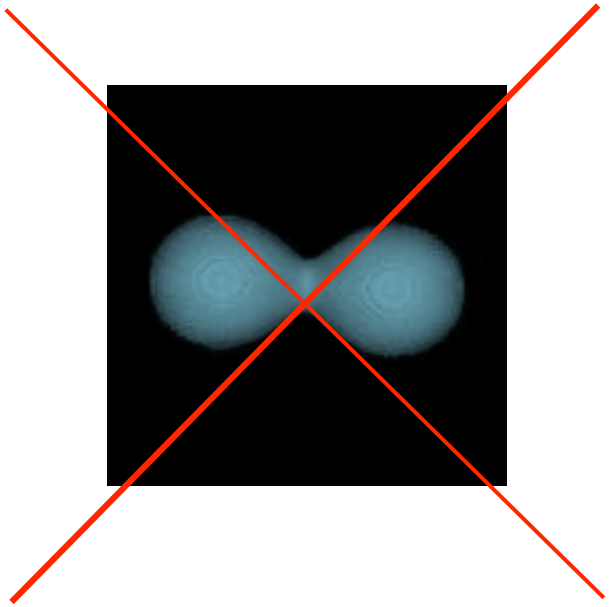
Fission Summary

- **Stars do not Fission**
- Don't get the initial conditions needed for Fission
- Fission gives you a constraint on the maximum rotation



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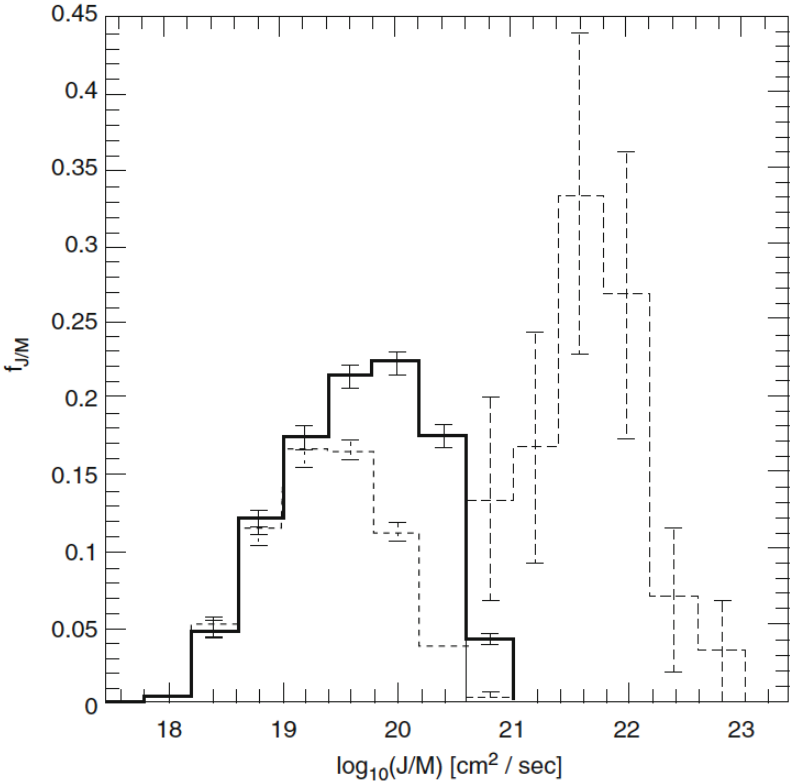
Angular Momentum

- Consider a uniform spherical cloud:
  - R = 0.1 pc
  - M = $M_\odot$
  - Angular Velocity = $\Omega = 10^{-14} s^{-1}$
- Ratio of rotational energy to gravitational energy is small
  - $\beta = \frac{E_{grav}}{E_{rot}} \sim 0.4\%$
- Angular momentum of cloud
  - $l_{cloud} \approx 10^{53}$ g cm^2/s
- Angular momentum of Sun
  - $l_\odot \approx 10^{48}$ g cm^2/s
- Enormous amount of "excess" angular momentum can help fuel binary formation



Specific orbital angular momenta of binaries (J/M). The dashed histogram gives data from observations of the rotation of molecular cloud cores. The solid histogram gives a model of the initial binary population, in general agreement with observations.

Source: P. Kroupa: MNRAS 277, 1507 (1995)

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Forms of Fragmentation

1. Fragmentation during the collapse of a low-mass core, producing a binary or a small multiple system
2. Fragmentation of a higher-mass core, leading to formation of a small cluster
3. Fragmentation of a gravitationally unstable disk
4. Fragmentation induced by a cloud–cloud collision

➢ We will discuss cases 1 and 2 in further detail.

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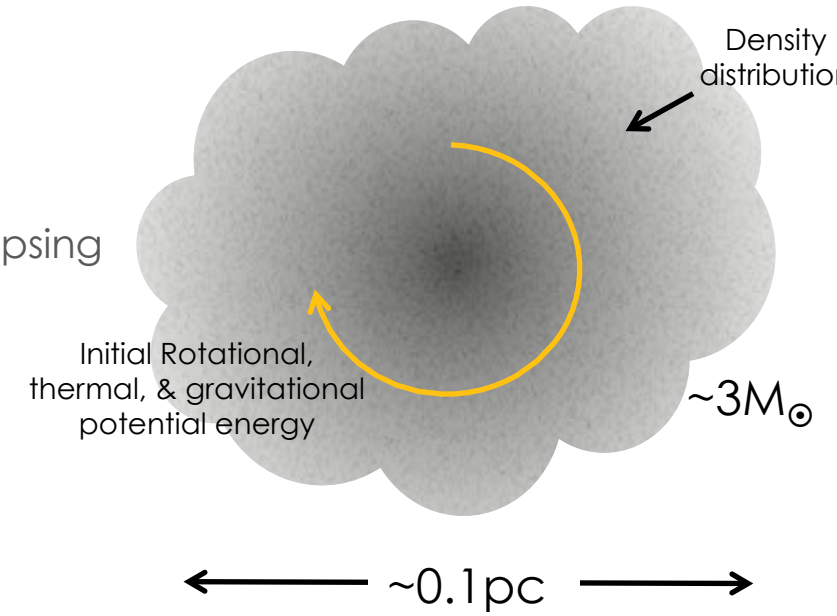
Case 1 (isolated core fragmentation)

- Calculations assume
  - A single, isolated, rotating, low-mass core
  - Often isothermally but sometimes include a collapse with cooling, radiation transport, magnetic fields, etc.
- Fragmentation is favorable during the initial isothermal phase when the protostar is collapsing
- Calculations start with initial conditions:

$$\alpha = \frac{E_{th}}{E_{grav}}$$ ← thermal energy / ← gravitational potential energy

$$\beta = \frac{E_{rot}}{E_{grav}}$$ ← rotational energy

  - density distribution
  - angular momentum distribution
  - shape of the cloud
  - initial density perturbation
- Outcome is dependent on the initial conditions



Initial conditions for modeling the collapse of a low-mass core, producing a binary or a small multiple system

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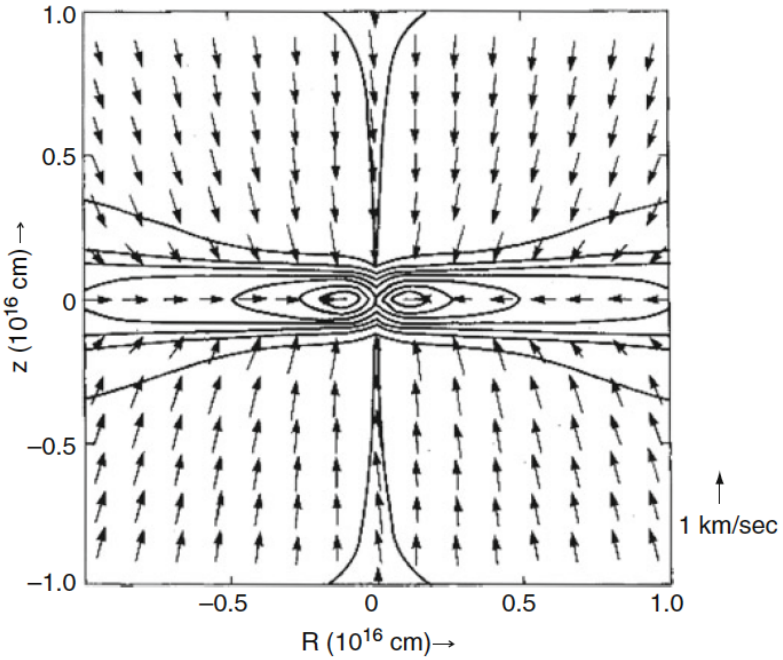
Case 1 (isolated core fragmentation): Example 1

- Early (1980's) simulations of fragmentation showed that
  1. Before fragmentation occurs the cloud must collapse to disk-like configuration
  2. During a free-fall collapse the time scale for the growth of perturbations in density is nearly the same as the time scale for collapse of the overall cloud
  3. For this case, β must be relatively large for this to work so it leads to long period binary systems
- More recent models show that rotational flatting is not necessarily a precursor to fragmentation



Numerical 3D simulation of the evolution of a collapsing molecular cloud core.

Source: P. Bodenheimer, J.E. Tohline, D.C. Black, ApJ **242,** 209 (1980)

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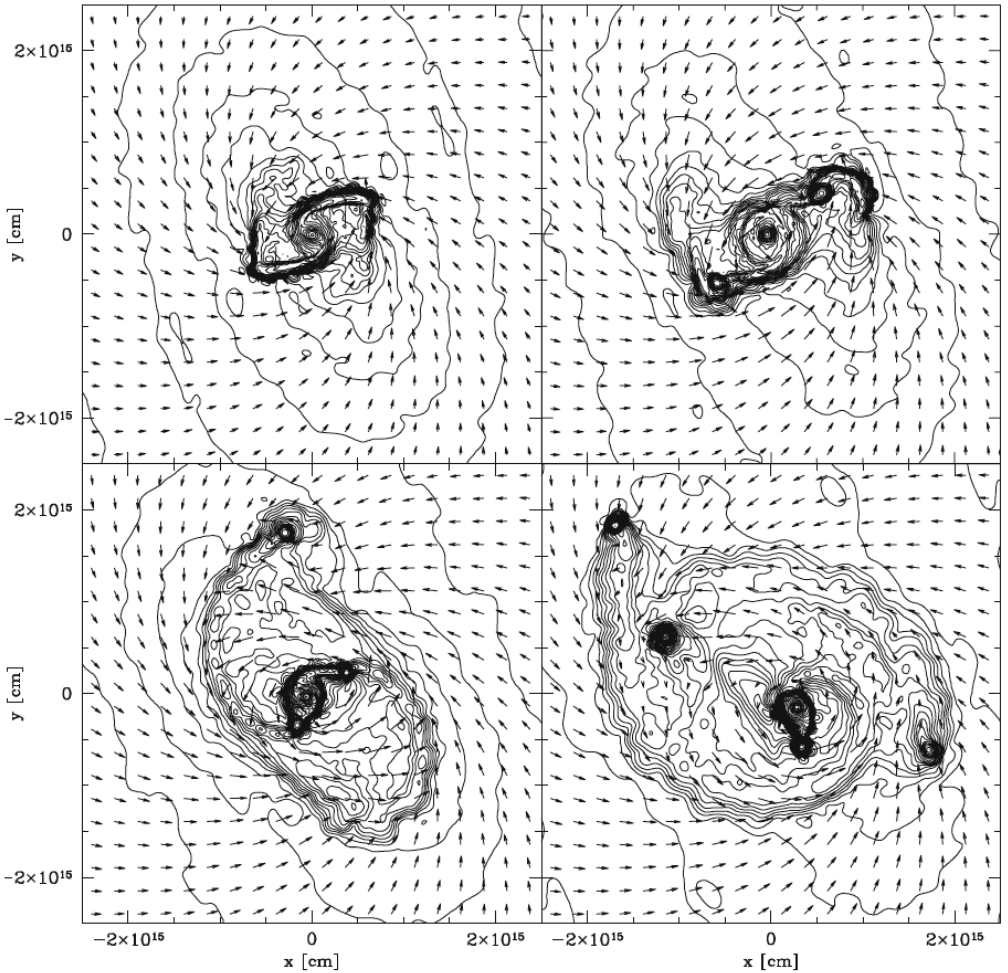
Case 1 (isolated core fragmentation): Example 2

- This shows a numerical 3D grid-based simulation
- The density distribution in the equatorial plane is shown at four different times
- The initial cloud had
  - a power-law density ($\rho \propto r^{-1}$)
  - mode m = 2 density perturbation of 10% amplitude:

$$\rho(r,\phi) = \rho_0(r)[1 + 0.1cos(2\phi)]$$

  - initial cloud radius of 0.016pc
  - α = 0.25, β = 0.23
  - Maximum density in all frames is about 10^{-10} g/cm^3
- The final time is 38,000 years



Credit: A. Burkert, M. R. Bate, P. Bodenheimer: MNRAS 289, 497 (1997).

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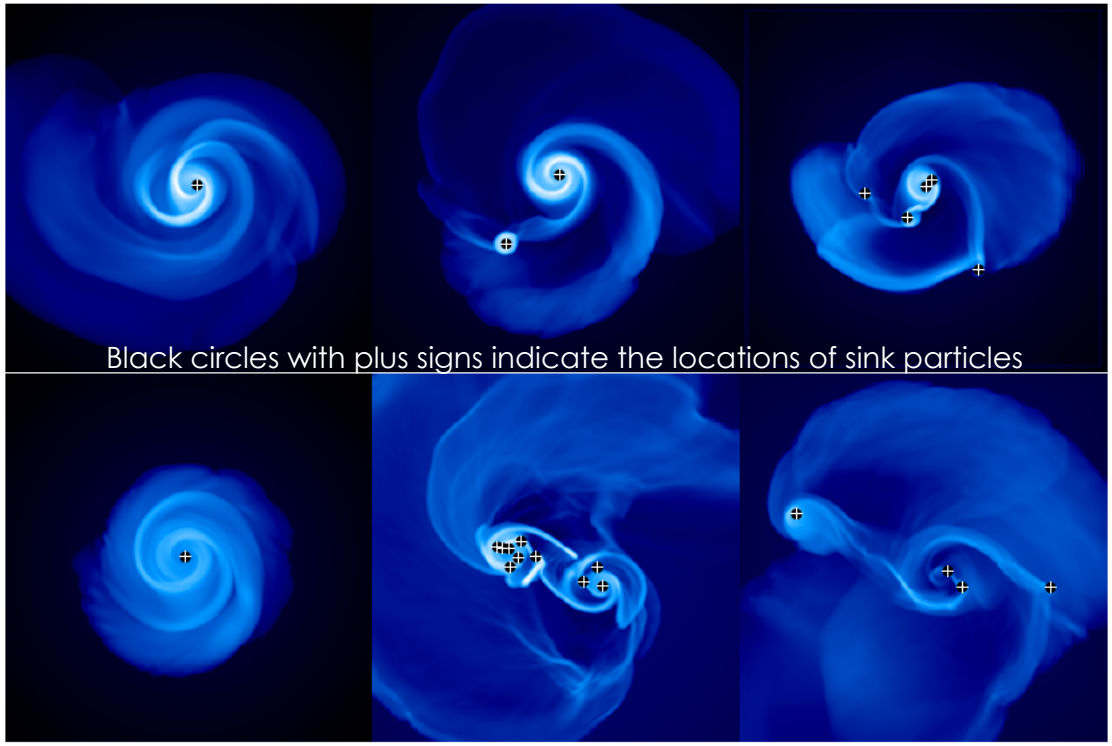
Case 1 (isolated core fragmentation): Example 3

- Two examples of single, binary, and multiple systems:
- The single runs are
  - ξ = 2.9, Γ = 0.018 (top)
  - ξ = 1.6, Γ = 0.009 (bottom)
- The binaries are
  - ξ = 4.2, Γ = 0.014 (top)
  - ξ = 23.4, Γ = 0.008 (bottom)
- The multiples are
  - ξ = 3.0, Γ = 0.016 (top)
  - ξ = 2.4, Γ = 0.01 (bottom)



Black circles with plus signs indicate the locations of sink particles

Credit: Kratter et al. ApJ 708 1585 (2010)

Rotational parameter: $\xi = \frac{\dot{M}G}{c_s^3}$

Thermal parameter: $\Gamma = \frac{\dot{M}}{M_* \Omega} = \frac{\dot{M} J^3}{G^2 M_*}$

J = mean specific angular momentum

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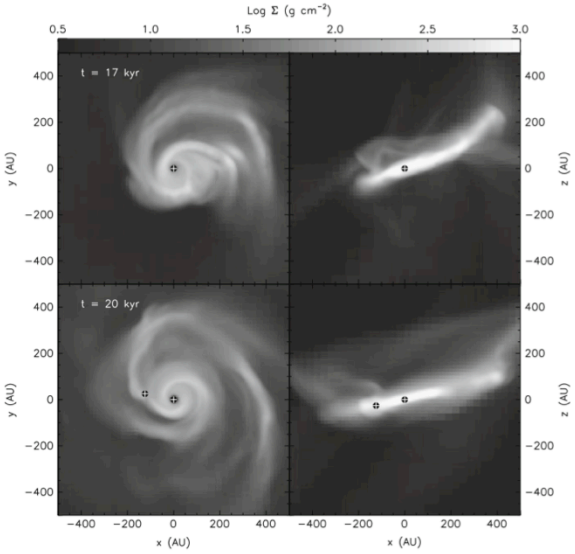
Case 1 (isolated core fragmentation): Conclusions

- Collapsing, rotating clouds are unstable to fragmentation
  - **Fragmentation works!**
- **Numerical spatial resolution is important**, particularly for small initial perturbations or investigation of higher-order modes of fragmentation
- Angular momentum of a fragment as compared with that of the initial rotating cloud is about a factor 15–20 → approximately same order of magnitude = **progress towards solving the angular momentum problem**
- Fragment interactions can play a role
- Disk fragmentation, as well as spontaneous fragmentation, can occur during the collapse of an individual core.
- Attempt to use realistic **initial conditions**, but still include
  - Radial density profiles
  - Higher initial densities then are observed in molecular clouds (clouds typically 10^2 cm^{-3} whereas simulations start at ~10^5 cm^{-3})



Massive binary (~6$M_\odot$ primary) is shown above. Result of the collapse of a core of 100$M_\odot$ which initially resulted in the formation of a single fragment with a massive disk; the disk later fragmented and the end result was a massive binary.

Source: M. Krumholz, R.I. Klein, C.F. McKee, S.S.R. Offner, A.J. Cunningham, Science **323,** 754 (2009)

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Case 2 (Small Cluster Formation)

- Small Cluster Formation
  - Extension of the single-core case to a larger core which contains **many times the mass** in a isolated core simulation
  - The general picture is that
    - Core is initially primarily **supported against collapse by turbulent** kinetic energy
    - Turbulent energy must be comparable to gravitational potential energy initially
  - However the turbulence, if not continuously driven by external effects, tends to decay
  - Once this occurs, the core begins to collapse and to develop into multiple fragments

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Case 2 (Small Cluster Formation): An Example

- Initial conditions
  - Cloud of $50M_{\odot}$
  - Diameter = 0.375 pc
  - Temperature = 10K
- The cloud is initially supported against collapse by a turbulent velocity field, with
  - RMS turbulent Mach number of 6.4
- Progression
  - Turbulence decays on a time scale of 1 initial free-fall time
  - Dense self-gravitating cores form
  - Star formation begins

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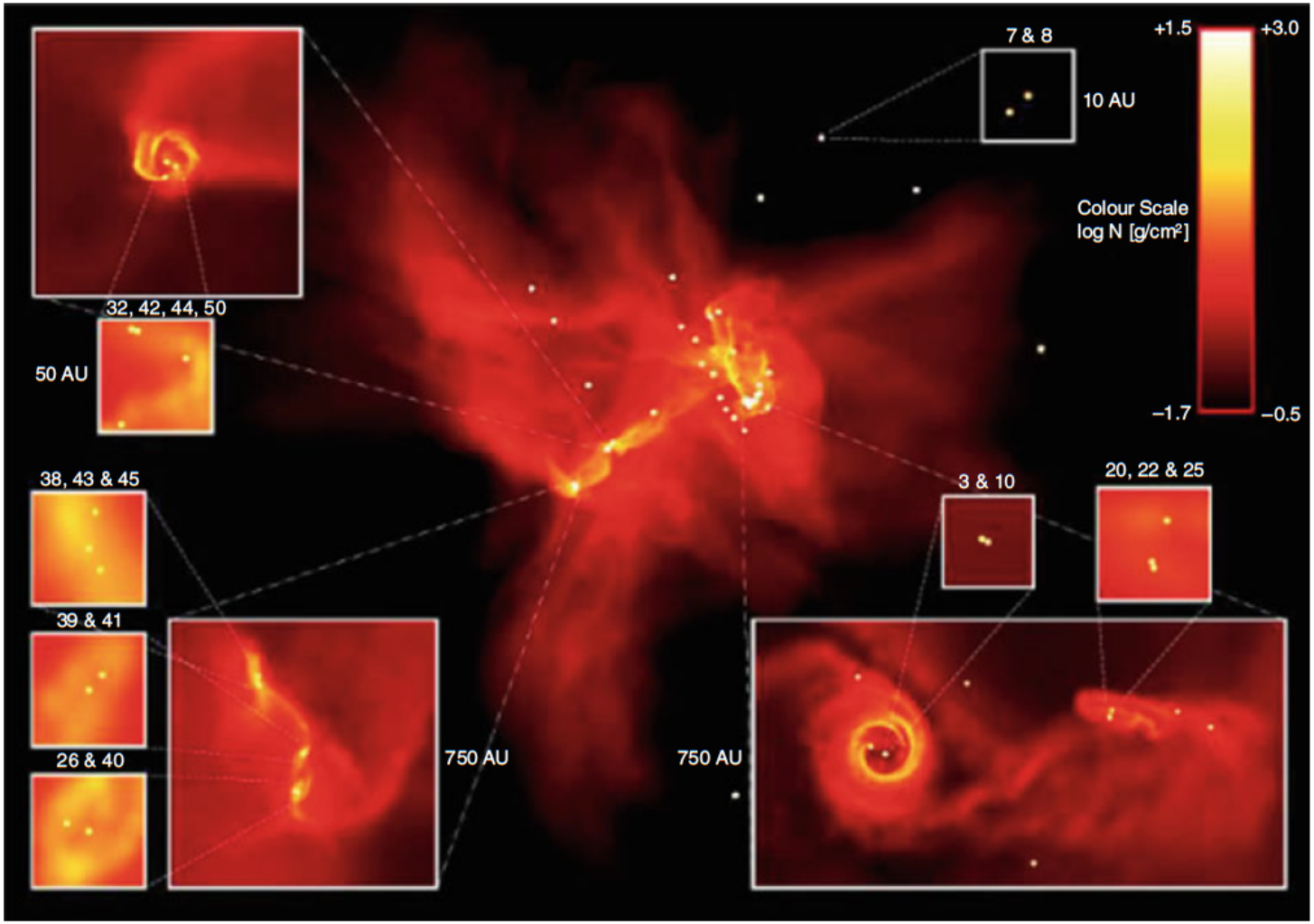
Case 2 (Small Cluster Formation): Example cont.

Figure shows the configuration of gas and stars at the end of the simulation, 1.4 initial freefall times

Large number of binaries and multiple systems are formed

Varying separations down to about 1AU



Credit: M. R. Bate, I. Bonnell, V. Bromm: MNRAS 336, 705 (2002)

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Fragmentation Summary

- Does fragmentation during a rotating collapse explain the observed properties of binary systems?

1. A **wide range of orbital angular momenta** is predicted
2. Calculations do indicate presence of circumstellar and circumbinary **disks**
3. This process predicts that **components of young binaries are coeval**, in agreement with most comparisons of young binaries with pre-main-sequence evolutionary tracks
4. Calculations predict **eccentric orbits**, in qualitative agreement with observations
5. **Cloud core angular momenta** are of the **correct order of magnitude** to explain wide binary orbits.
6. Gives us **realistic initial conditions** for the isolated core fragmentation case

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Fragmentation Summary

- **Unsolved Problems:**

1. For standard core parameters, fragmentation sets in just at the density where the center of the cloud is beginning to heat
   - Many calculations have not treated **radiation transport** but have assumed adiabatic heating starting from an assumed transition density but radiation transfer is important
2. The role of **magnetic fields** in regulating the protostellar collapse and fragmentation phase has not been explored in sufficient detail
   - We will take a **closer look** at this
3. Since there are **so many possible initial conditions**, the statistics of mass ratio distributions, eccentricities, and multiplicity fraction will be difficult to derive from detailed three-dimensional calculations
4. It is **difficult to explain close binaries** (separations of <3AU) by the fragmentation processes
   - It appears that interactions in a cluster-forming environment may be the key to their formation
   - Even though the transition in observable properties between close binaries and wide binaries is smooth, there are likely to be a number of different physical processes that produce close binaries

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Magnetic Field Modeling

- Machida et al. 2008 study the formation of binary systems in the presence of magnetic fields
  - The simulate fragmentation using a 3D resistive MHD nested grid
  - Initial conditions
    - Isothermal rotation cloud with uniform magnetic field
    - Density ~ 10^4 cm^{-3}
    - They start with various
      - magnetic, rotational and thermal energies
      - non-axisymmetric perturbations

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Magnetic Fields

Fragmentation condition against parameters b and ω:

ω is the angular rotation velocity normalized by the free-fall timescale:

$$\omega = \frac{\Omega_{c,0}}{\sqrt{4\pi G \rho_{c,0}}}$$

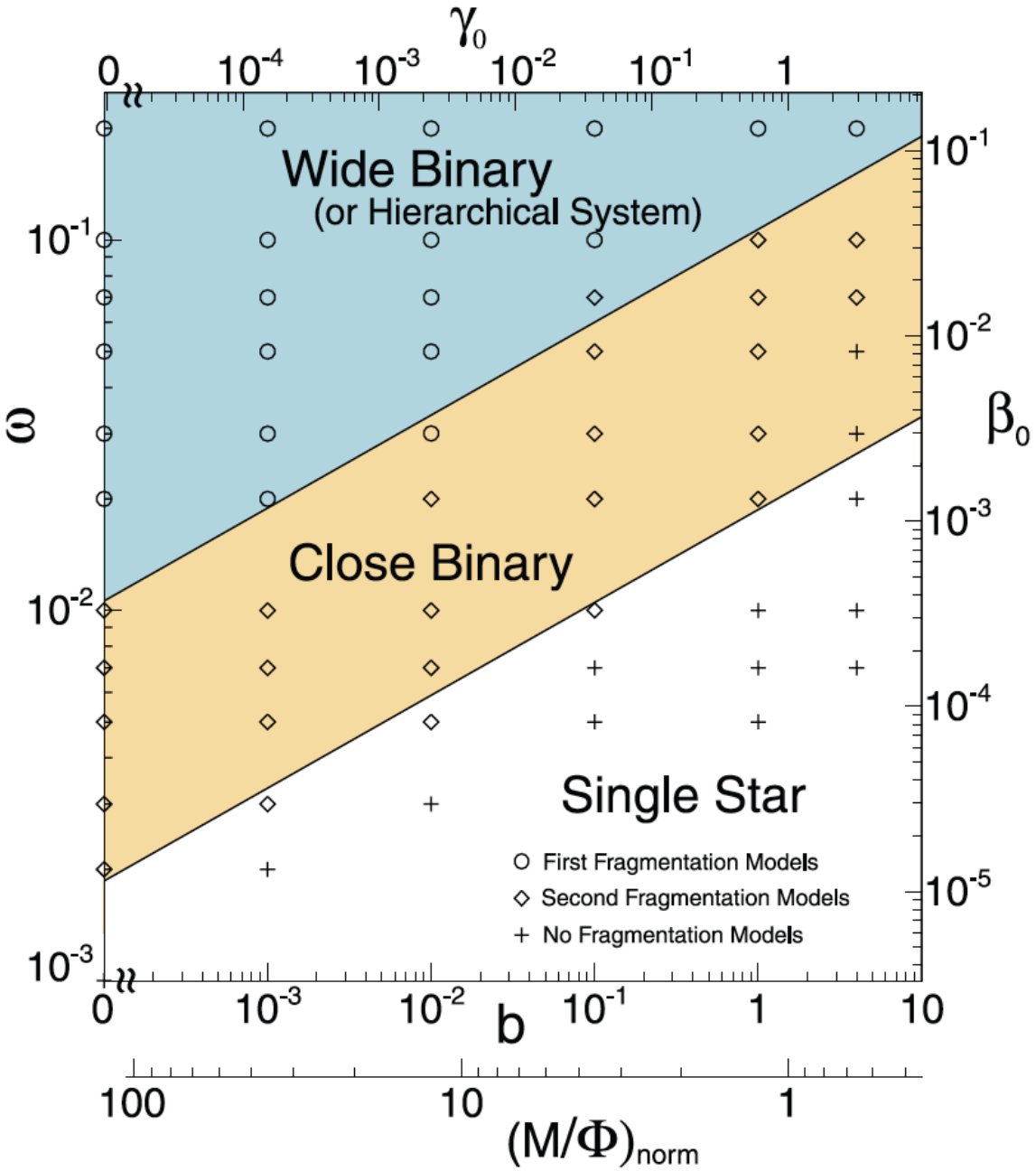
b is the magnetic-to-thermal pressure ratio:

$$b = \frac{B_{zc,0}^2}{4\pi \rho_{c,0} c_{s,0}^2},$$

Circles: fragmentation occurs in the adiabatic phase

Diamonds: fragmentation occurs in the second collapse phase

Plus signs: no fragmentation occurs through all phases of the cloud evolution



Machida et al. ApJ 677, 327 (2008)

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Magnetic Fields – Conclusions

- Machida et al. find that
  - Magnetic fields decay and sometimes completely suppress fragmentation
  - Three cases:
    - When the clouds have larger rotational energies in relation to magnetic energies
      - fragmentation occurs in the low-density phase
      - Create binaries with separations of 3-300AU
    - When initial clouds have larger magnetic energies in relation to the rotational energies
      - Fragmentation occurs only in the high density phase
      - Create very close binaries 0.007–0.3 AU
    - No fragmentation occurs in the case of sufficiently strong magnetic field, in which single stars are expected to be born

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Conclusions

- Numerical Simulations of **Fragmentation** have done a good job of **explaining observed binary star properties**
- From isolated star formation we saw that
  - The reduction in specific angular momentum of a fragment as compared with that of the initial rotating cloud is about a factor 15–20 → **angular momentum is the right order of magnitude**
- **Magnetic fields** are a problem – take all the angular momentum away making it hard to form disks
- Fission is not a likely to be a source of binary star formation
- Fragmentation theory & observations imply **binaries form rather efficiently**!