The Origin of Binary Stars

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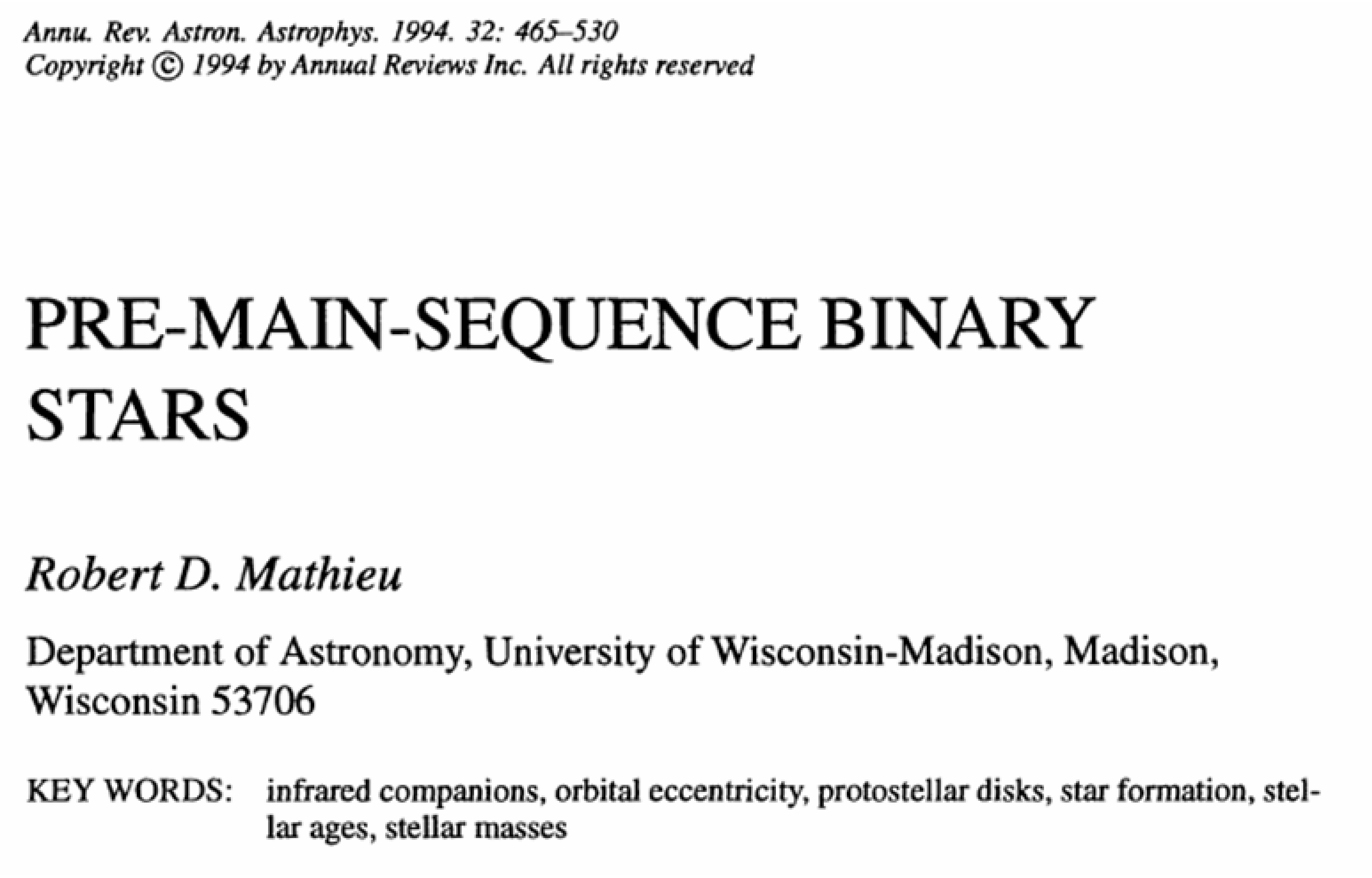
Jianfeng Wu

Instructor: Robin Ciardullo

Dept. of Astronomy & Astrophysics, The Pennsylvania State University

jfwu@astro.psu.edu

References



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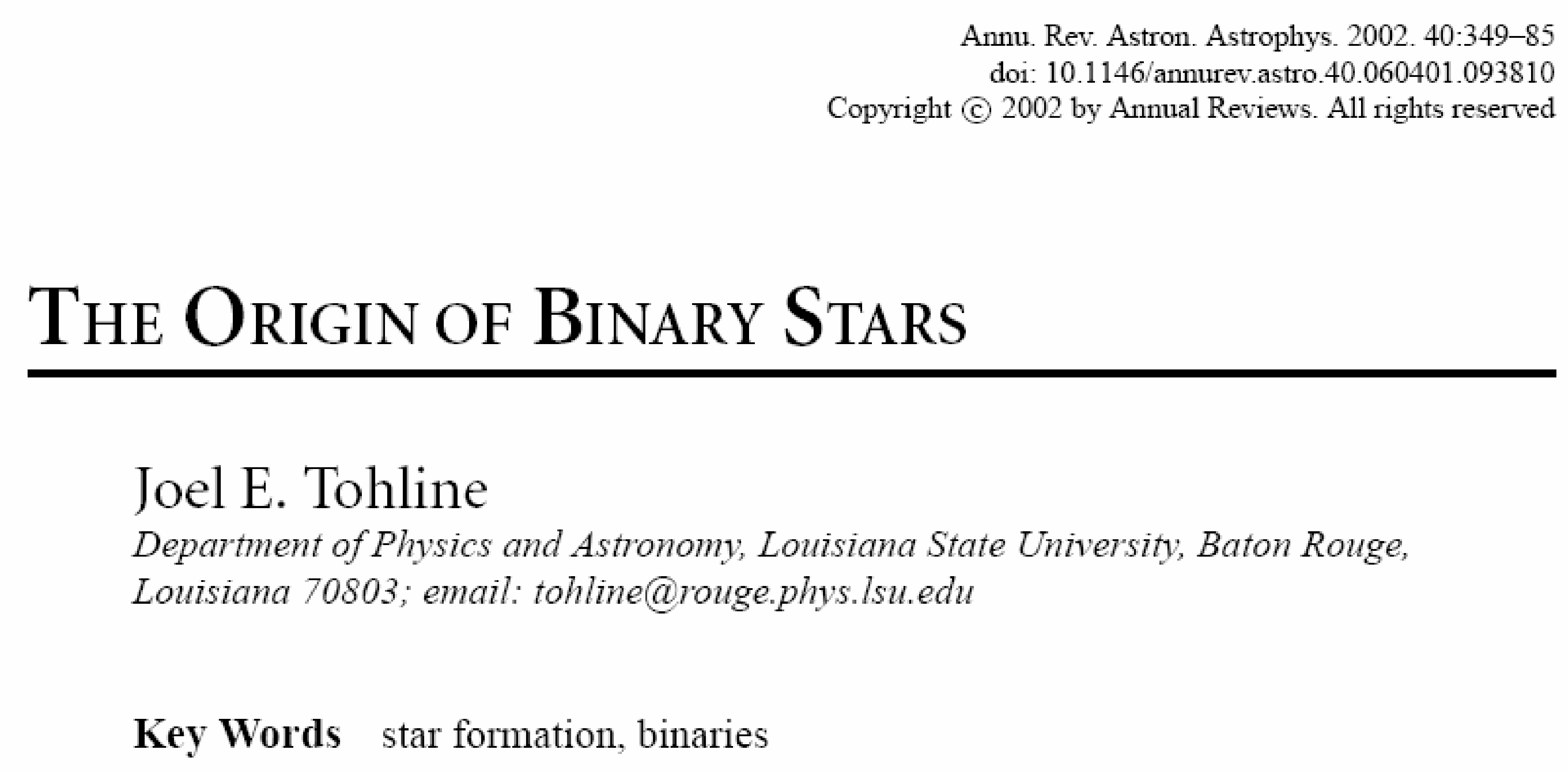
PRE-MAIN-SEQUENCE BINARY STARS

Robert D. Mathieu

Department of Astronomy, University of Wisconsin-Madison, Madison,
Wisconsin 53706

KEY WORDS: infrared companions, orbital eccentricity, protostellar disks, star formation, stellar ages, stellar masses

References



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THE ORIGIN OF BINARY STARS

Joel E. Tohline
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803; email: tohline@rouge.phys.lsu.edu

Key Words star formation, binaries

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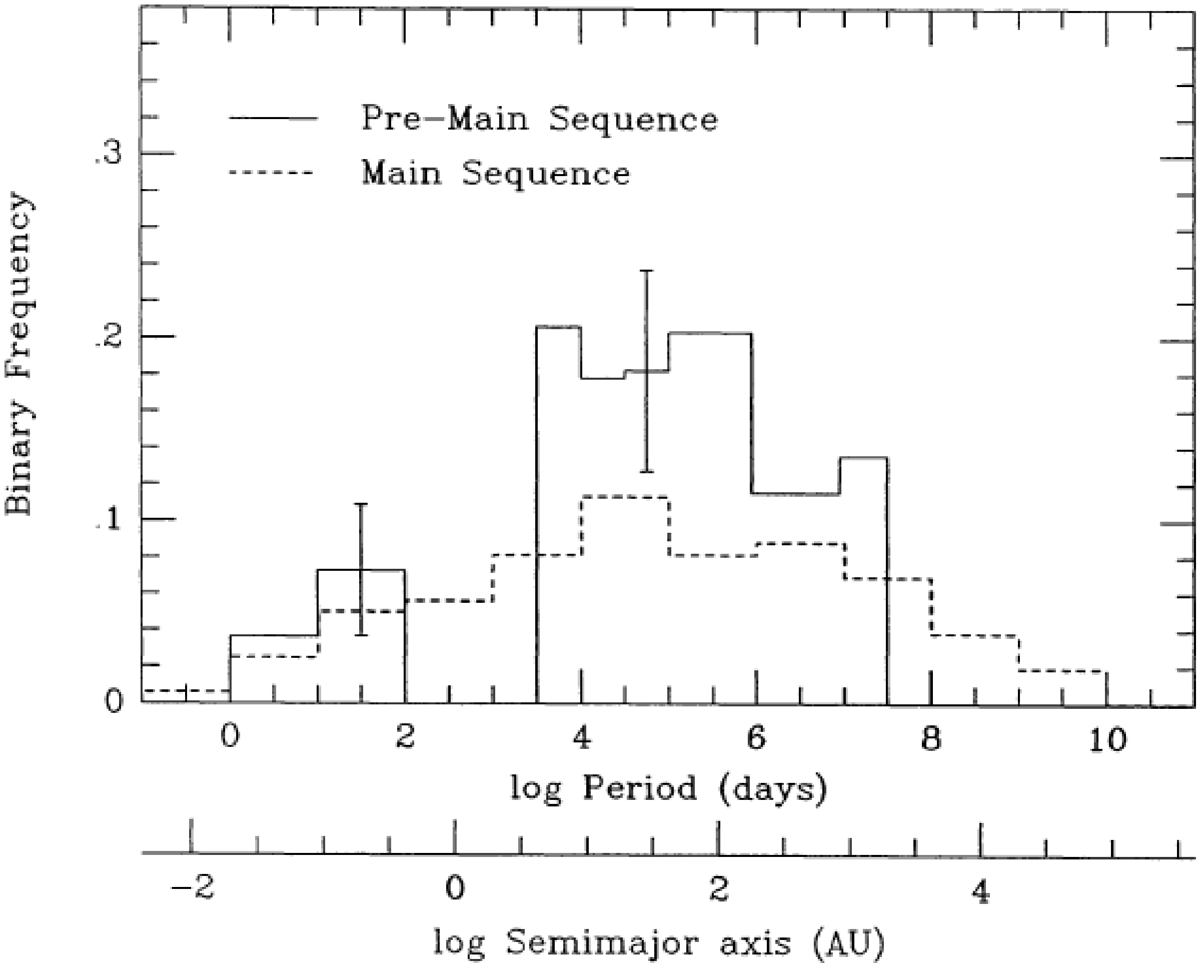
Observation

- Pre-Main-Sequence (PMS) Binary Frequency:
- Taurus-Auriga Association survey in infrared: 60% ± 9% between separations of 0.013” to 13”, or 1.8 AU to 1800 AU (Richichi et al. 1994).
- A factor of 1.9 ± 0.3 exceeds the Main-Sequence (MS) solar type binaries in the same range of separations
- Evident excess at intermediate periods

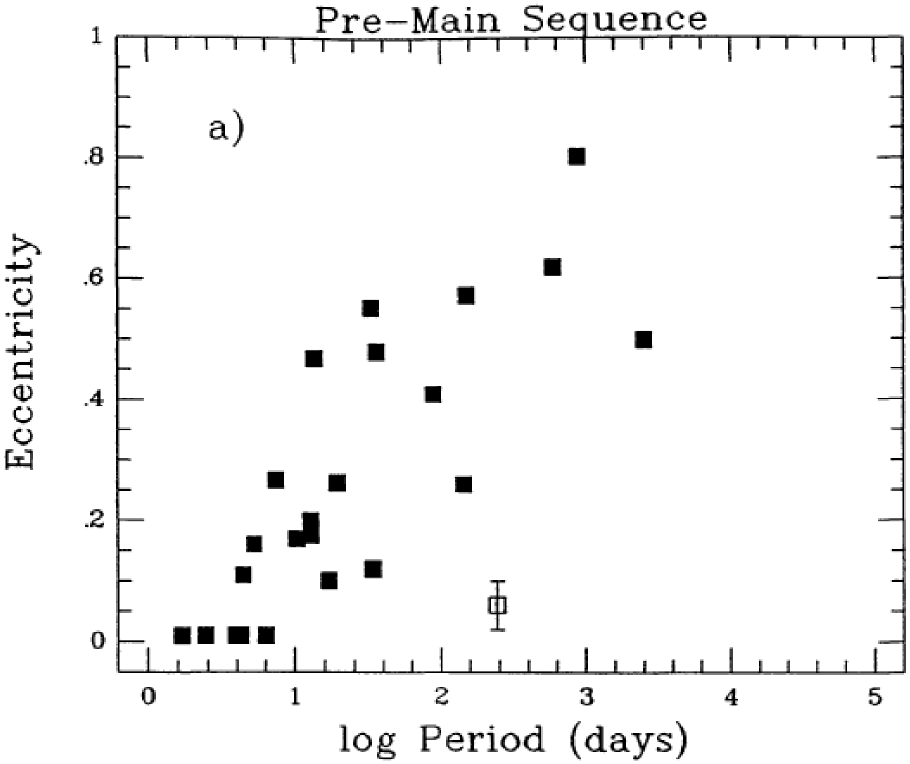


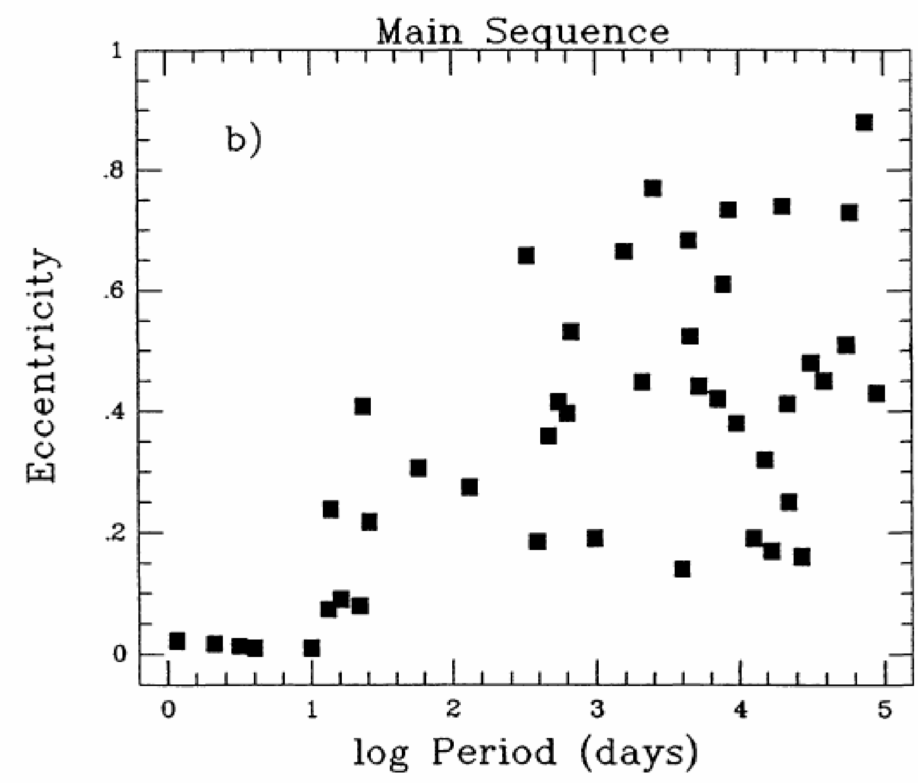
Observation

- Pre-Main-Sequence (PMS) Binary Frequency:
- Other similar results: 60% ± 17% (Ghez et al. 1993), 80% (Reipurth & Zinnecker 1993)
- Inconsistent result: no enhancement of PMS binary frequency in Trapezium (uncertainty, debatable)
- Multiples: 35% triples and quadruples within all multiple systems (Ghez 1993)
- Frequency of PMS binaries decreases with increasing separation (Reipurth & Zinnecker 1993; Leinert et al. 1993)

Observation

- Orbital Eccentricity Distribution:
  - —— *e*=0 to 0.8
  - —— shortest periods with circular orbits
  - —— similar to that of MS binaries



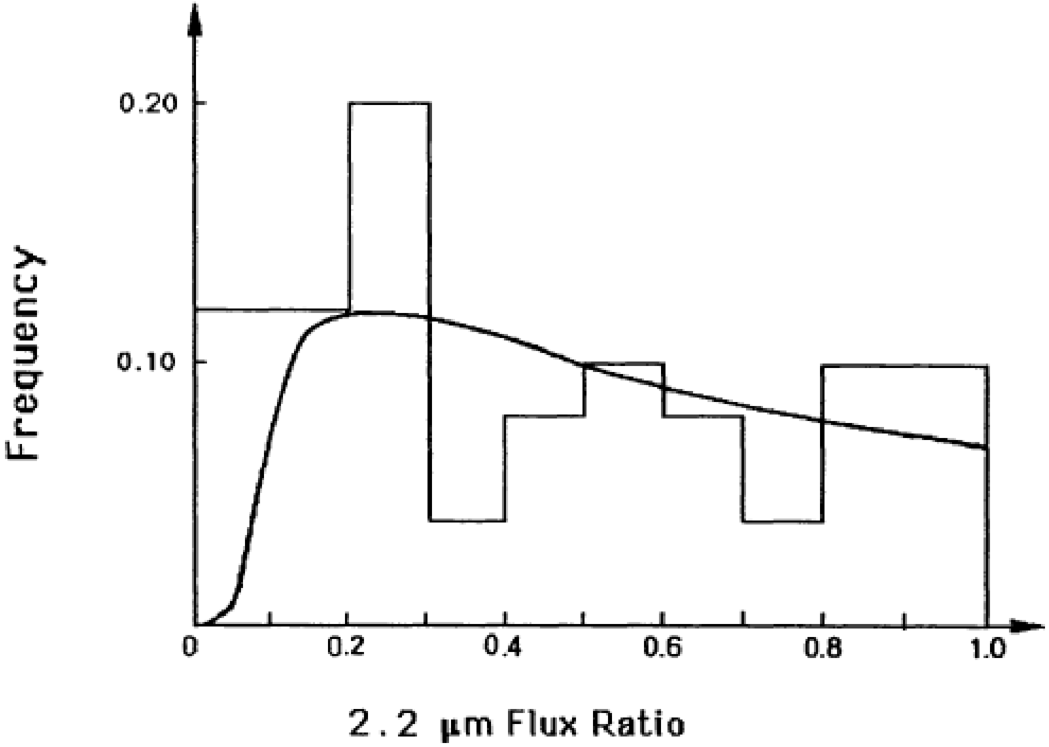


Observation

- Secondary Mass Distribution

—— secondary to primary ratio range from 1 to <<0.1

—— flux ratio distribution consistent with random pairings of stars from a single parent population similar to the initial mass function of the field



Observation

- Young Binary Environments
- Circumstellar disks:
- Disk frequency:

—— near and mid-infrared (2 μm and 10 μm) excess

—— 40% - 50% or more binaries show circumstellar disks

- Disk mass:

—— millimeter or submillimeter measurement

—— Tau-Aur Association: 0.004 M_{sun} to 0.3 M_{sun}

—— Large mass possibly: 1.8 M_{sun} (Z CMa), 1.5 M_{sun} (GW Ori)

- Disk accretion:

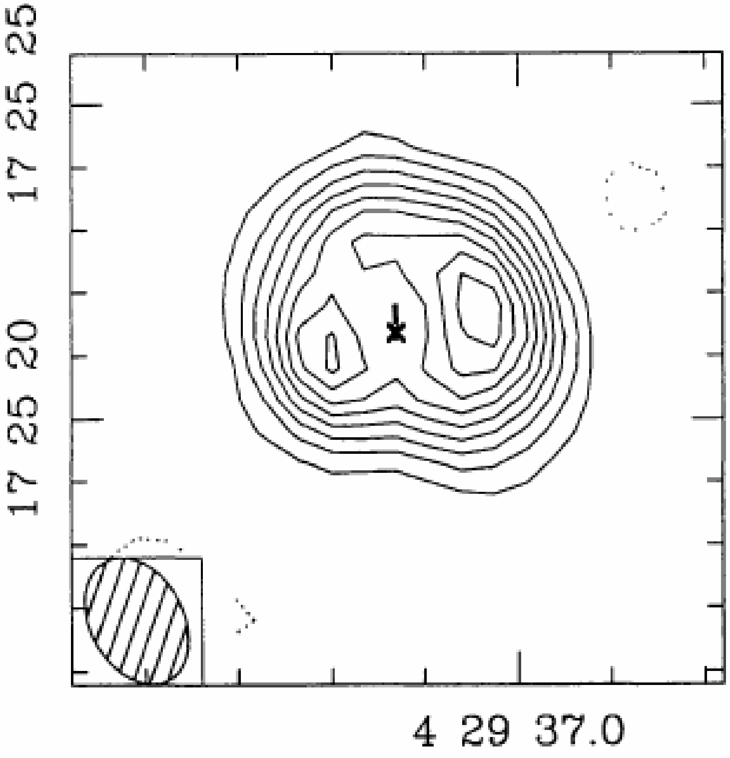
—— spectroscopy of Hα line

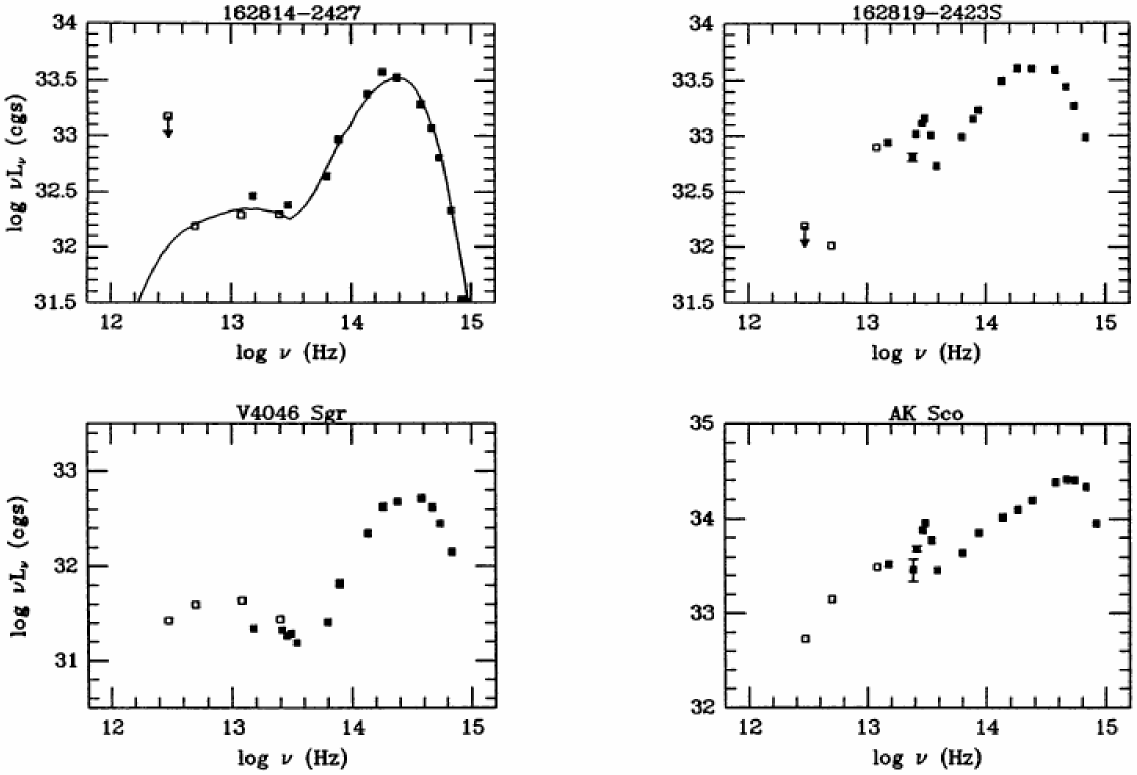
—— accretion rate: 10^{-7} M_{sun} yr^{-1}

Observation

- Young Binary Environments
- Circumstellar disks:
- Disk structure: near infrared SED

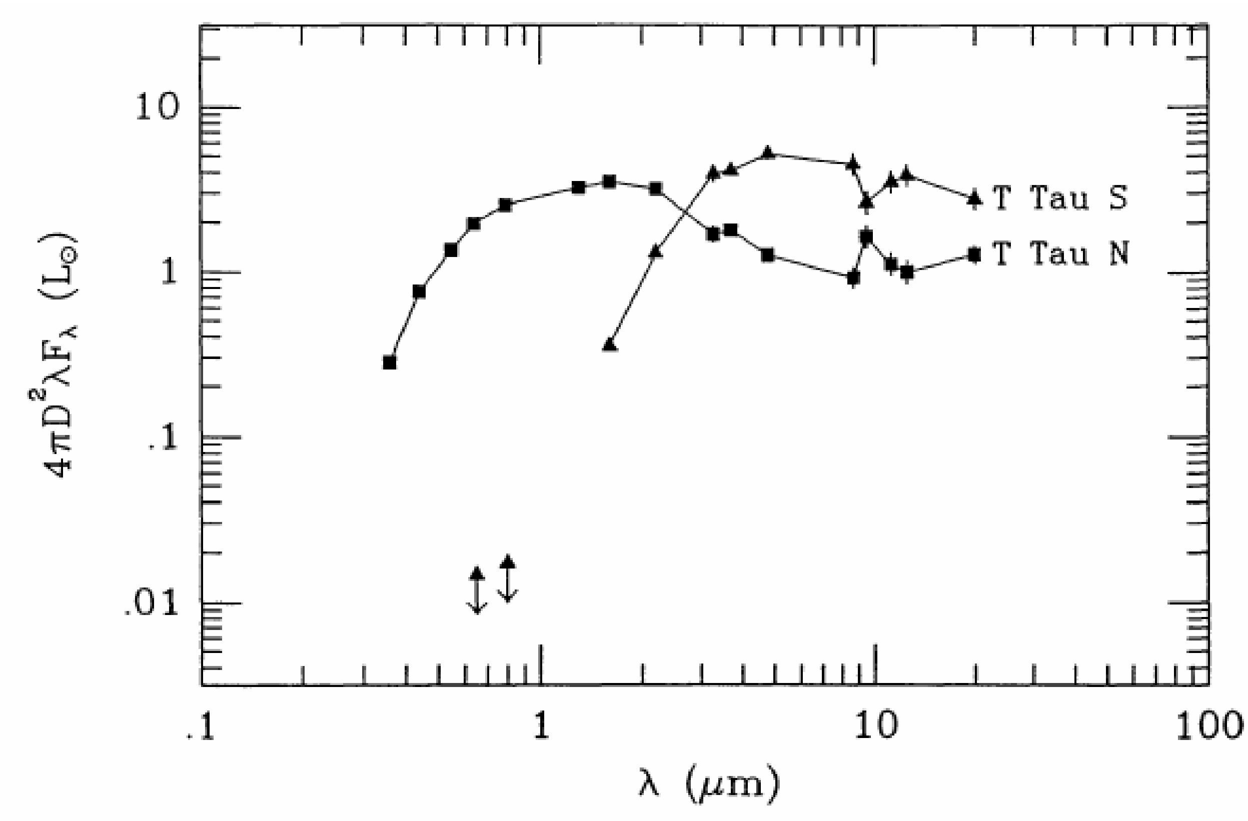
—— geometrically thin, optically thick disk with (0.3 AU – 10^2 AU)





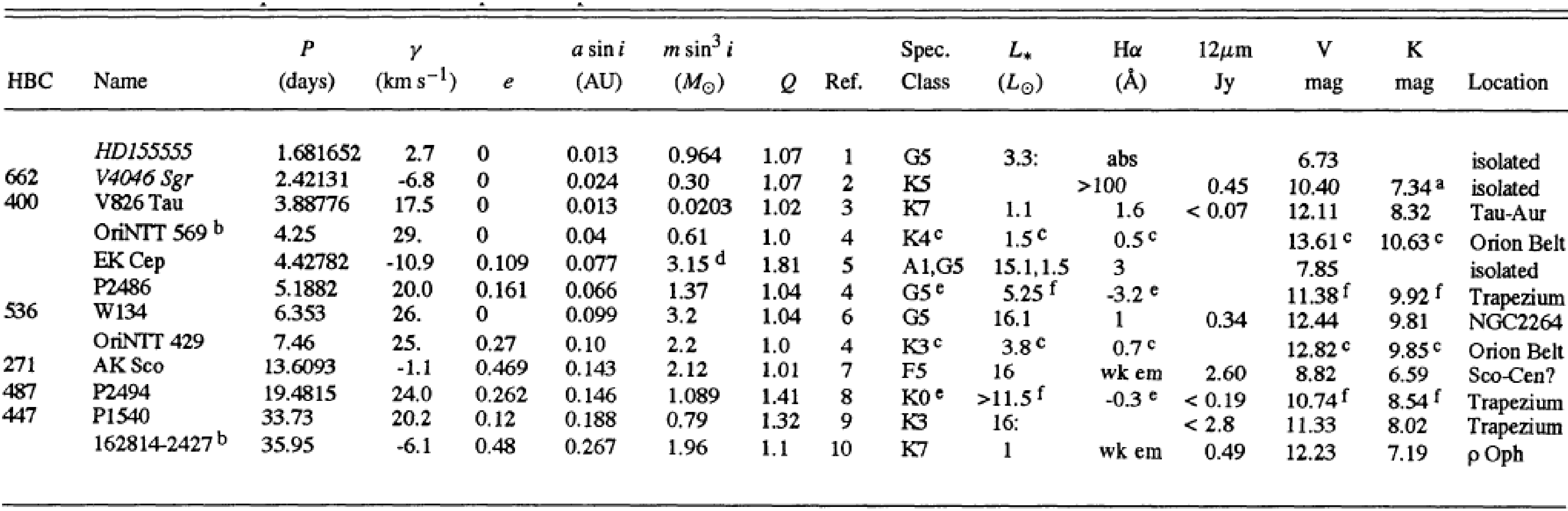
Observation

- Infrared Companions:
- Peaked at infrared, without optical —— large extinction
- Frequency: 10% at all T Tauri binary systems (Zinnecker & Wilking 1992)



Observation

- Implication
- Many of the properties of MS binaries are already at least approximately present in the PMS phase, and likely were established earlier.



HBC	Name	P (days)	γ (km s^{-1})	e	$a \sin i$ (AU)	$m \sin^3 i$ ($M_\odot$)	Q	Ref.	Spec. Class	L_* ($L_\odot$)	Hα (Å)	12μm Jy	V mag	K mag	Location
	HD155555	1.681652	2.7	0	0.013	0.964	1.07	1	G5	3.3:	abs		6.73		isolated
662	*V4046 Sgr*	2.42131	-6.8	0	0.024	0.30	1.07	2	K5		>100	0.45	10.40	7.34[a]	isolated
400	V826 Tau	3.88776	17.5	0	0.013	0.0203	1.02	3	K7	1.1	1.6	< 0.07	12.11	8.32	Tau-Aur
	OriNTT 569[b]	4.25	29.	0	0.04	0.61	1.0	4	K4[c]	1.5[c]	0.5[c]		13.61[c]	10.63[c]	Orion Belt
	EK Cep	4.42782	-10.9	0.109	0.077	3.15[d]	1.81	5	A1,G5	15.1,1.5	3		7.85		isolated
	P2486	5.1882	20.0	0.161	0.066	1.37	1.04	4	G5[e]	5.25[f]	-3.2[e]		11.38[f]	9.92[f]	Trapezium
536	W134	6.353	26.	0	0.099	3.2	1.04	6	G5	16.1	1	0.34	12.44	9.81	NGC2264
	OriNTT 429	7.46	25.	0.27	0.10	2.2	1.0	4	K3[c]	3.8[c]	0.7[c]		12.82[c]	9.85[c]	Orion Belt
271	AK Sco	13.6093	-1.1	0.469	0.143	2.12	1.01	7	F5	16	wk em	2.60	8.82	6.59	Sco-Cen?
487	P2494	19.4815	24.0	0.262	0.146	1.089	1.41	8	K0[e]	>11.5[f]	-0.3[e]	< 0.19	10.74[f]	8.54[f]	Trapezium
447	P1540	33.73	20.2	0.12	0.188	0.79	1.32	9	K3	16:		< 2.8	11.33	8.02	Trapezium
	162814-2427[b]	35.95	-6.1	0.48	0.267	1.96	1.1	10	K7	1	wk em	0.49	12.23	7.19	ρ Oph

Theoretical Models

- Stages of Single Star Formation (Shu et al. 1987)

—— Begin with a molecular cloud supported by magnetic field

I. Magnetic field diffused, and molecular cloud cores formed

II. collapse begins, central protostar formed

III. direct infall weakens, stellar wind creates bipolar outflow

IV. Direct infall continues to decrease, wind opening angle widens until the central young star reveals as a PMS star

V. nebular disk finally disappears

Theoretical Models

- Basic Physical Principles:

—— ignoring the magnetic field (decoupled at the high density of binary forming process), using thermal Jeans instability instead

- Physical parameter:

—— total mass M

—— radius R

—— mean temperature T

—— mean molecular weight μ

—— mean angular velocity ω

Theoretical Models

- Basic Physical Principles:
- Physical parameters:

mean mass density

$$\bar{\rho} \equiv \frac{3M}{4\pi R^3}$$

number density

$$n = \frac{\bar{\rho}}{\mu m_{\rm p}}$$

temperature

$$T \propto \bar{\rho}^{\gamma - 1}$$

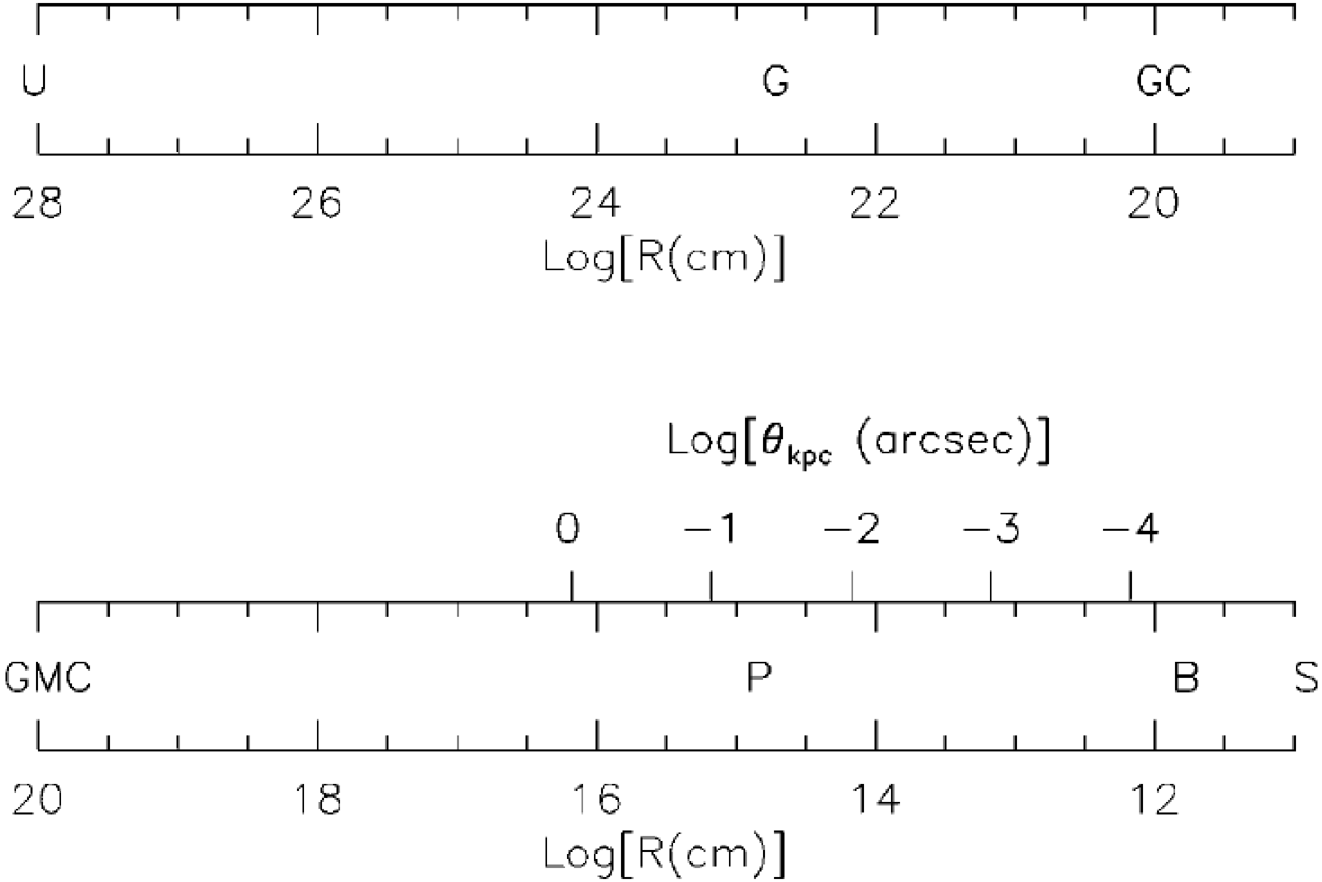
mean sound speed

$$c_{\rm s} = \left[\gamma \frac{\Re T}{\mu}\right]^{1/2}$$

Theoretical Models

- Basic Physical Principles:
- Physical parameters:

scale: angular resolution of 10^{-4} arcsec needed



Theoretical Models

- Basic Physical Principles:
- Key timescales:

free-fall time:

$$\tau_{\rm ff} = \left[\frac{3\pi}{32G\bar{\rho}}\right]^{1/2}$$

sound-crossing time:

$$\tau_{\rm s} = \frac{R}{c_{\rm s}}$$

rotation period:

$$\tau_{\rm rot} = \frac{2\pi}{\omega}$$

binary orbital period:

$$P = \left[\frac{4\pi^2 a^3}{GM_{\rm tot}}\right]^{1/2}$$

$$P = 32^{1/2}\tau_{\rm ff} \approx 5.7\tau_{\rm ff}$$

accretion timescale:

$$\tau_{\rm accrete} = \frac{m_0}{\dot{M}}$$

Theoretical Models

- Basic Physical Principles:
- Virial theorem: $2(E_{\text{therm}} + E_{\text{rot}}) + E_{\text{grav}} = 0$

$$\alpha + \beta = \frac{1}{2}, \qquad \alpha \equiv \frac{E_{\text{therm}}}{|E_{\text{grav}}|} \sim \frac{5}{2}\frac{\Re}{\mu}T\frac{R}{GM}, \qquad \beta \equiv \frac{E_{\text{rot}}}{|E_{\text{grav}}|} \sim \frac{1}{3}\frac{R^3\omega^2}{GM}.$$

thermal dominated: $\alpha \approx 1/2$

$$M_{\text{equil}} \sim 5\frac{\Re}{\mu}T\frac{R}{G}. \qquad \tau_{\text{s}} \approx \tau_{\text{ff}}.$$

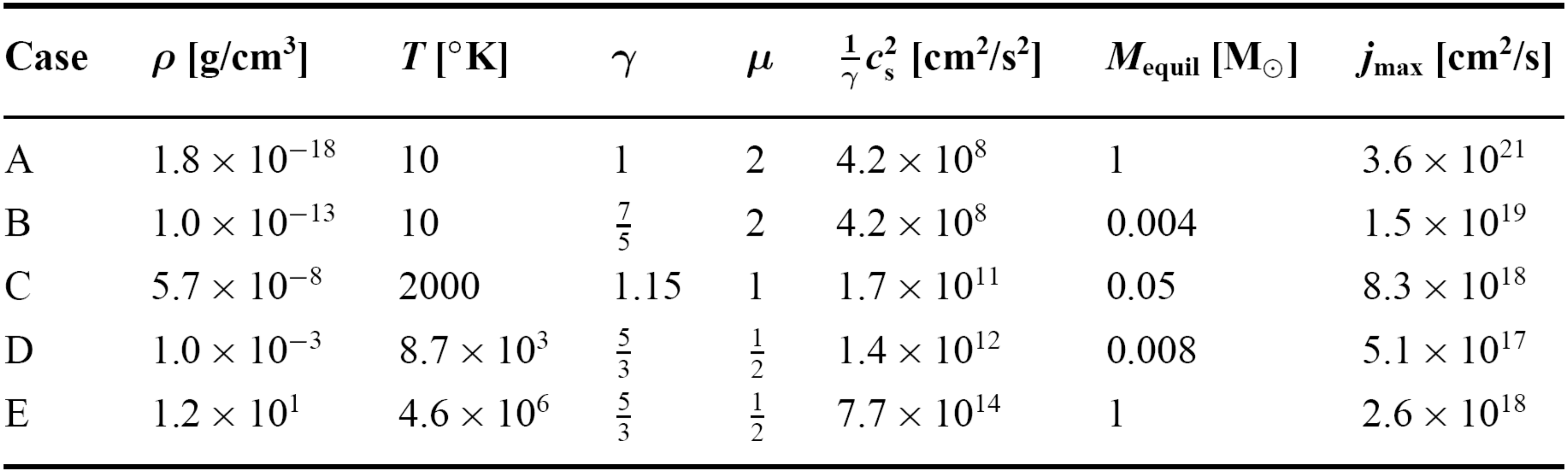
rotation dominated: $\beta \approx 1/2$

$$\omega \approx \omega_{\max} \approx [2\pi G\bar{\rho}]^{1/2} \qquad \tau_{\text{rot}} = \frac{2\pi}{\omega} \approx 4.6\tau_{\text{ff}}$$

Theoretical Models

- Basic Physical Principles:
- Jeans instability: $\alpha + \beta < 1/2$

$$M > M_{\mathrm{equil}} \qquad M_{\mathrm{J}} \sim 5 \frac{\Re}{\mu} T \frac{R}{G} \sim 5.5 \left[\frac{\Re}{\mu} \frac{T}{G} \right]^{3/2} \bar{\rho}^{-1/2}$$



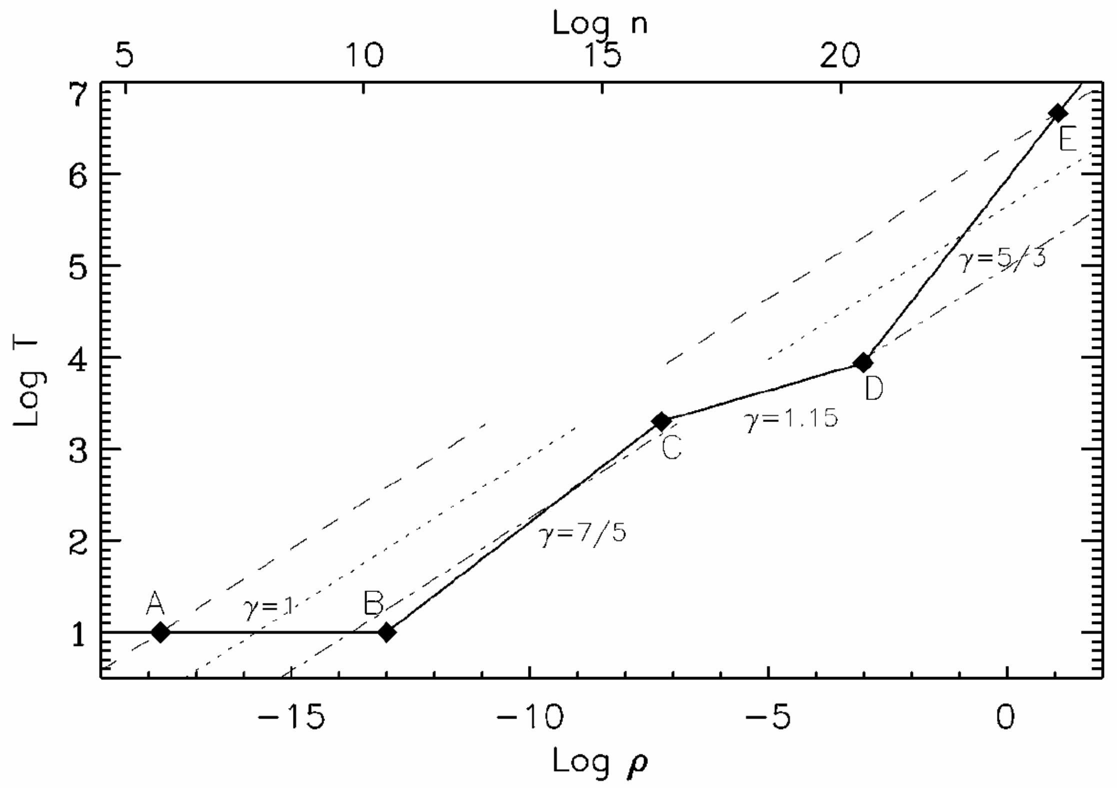
Case	ρ [g/cm^3]	T [°K]	γ	μ	$\frac{1}{\gamma} c_s^2$ [cm^2/s^2]	M_{equil} [$M_\odot$]	$j_{\max}$ [cm^2/s]
A	1.8×10^{-18}	10	1	2	4.2×10^{8}	1	3.6×10^{21}
B	1.0×10^{-13}	10	$\frac{7}{5}$	2	4.2×10^{8}	0.004	1.5×10^{19}
C	5.7×10^{-8}	2000	1.15	1	1.7×10^{11}	0.05	8.3×10^{18}
D	1.0×10^{-3}	8.7×10^{3}	$\frac{5}{3}$	$\frac{1}{2}$	1.4×10^{12}	0.008	5.1×10^{17}
E	1.2×10^{1}	4.6×10^{6}	$\frac{5}{3}$	$\frac{1}{2}$	7.7×10^{14}	1	2.6×10^{18}

Theoretical Models

- Basic Physical Principles:
- Effective adiabatic exponent γ:

$$\beta \propto R^{-1} \propto \bar{\rho}^{1/3}, \qquad \alpha \propto TR \propto \bar{\rho}^{\gamma-4/3}$$

$$\gamma > \gamma_{\mathrm{crit}} \approx \frac{2}{3}\frac{(2-5\beta)}{(1-2\beta)}$$



Theoretical Models

- Possible Formation Mechanisms:
  - —— Capture
  - —— Prompt Fragmentation
  - —— Delayed Breakup

- Capture: unlikely
  - —— encounter probability is extremely slow in large cluster or field
  - —— typical velocity of approaching unpaired stars is hyperbolic
  - —— interaction not purely gravitational, but no other effective mechanism

Theoretical Models

- Possible Formation Mechanisms:
- Prompt fragmentation: most noticed

—— fully three-dimensional, nonlinear hydrodynamical simulation

—— isothermal equation of state assumed, some including adiabatic compression or focusing on the adiabatic collapse

- Nearly Homologous Collapse: uniform in density, significantly larger than Jeans mass, i.e. $\alpha << ½$

—— reach flattened configuration after one free-fall time

- Nonhomologous Collapse: centrally condensed and/or cloud initially only marginally Jeans unstable

—— central region collapse ahead of the rest

—— core equilibrium first, and then mass accretion follow

Theoretical Models

- Possible Formation Mechanisms:
- Prompt fragmentation:
- Results

—— fragmentation occur immediately after one free-fall time, instead of during the free-fall collapse

—— homologous collapse with more than one Jeans mass material favorable for fragmentation, high β causes instability

—— nonhomologous collapse discourages collapse

—— not yet clear how often this process will directly produce a binary

Theoretical Models

- Possible Formation Mechanisms:
- Delayed breakup:
- Instability leading to breakup
- Direct breakup from an axisymmetric state: unlikely

—— only form bar-like structure with a slight two-armed spiral character

—— fission may occur only after the triaxial configuration undergoes further slow contraction

- Substantial disk

—— form around the central core through the additional infall of high specific angular momentum material

—— grow to a mass comparable or even larger than the mass of the core

—— then disk instabilities lead to nonaxisymmetric structure which may break up

Conclusions

- Many of the properties of MS binaries are already at least approximately present in the PMS phase, which indicates young stars have paired themselves during early stage of star formation
- Capture are not likely to be a binary formation mechanism
- Prompt fragmentation may work immediately after the free-fall collapse, rather than during the free-fall phase
- Prompt fragmentation may occur in a homologous pattern, instead of inhomologous pattern
- Rapidly rotating axisymmetric cores do not break up due to instability; instead, they form bar-like structure
- Substantial disk around the core may break up into pieces containing material comparable to core mass