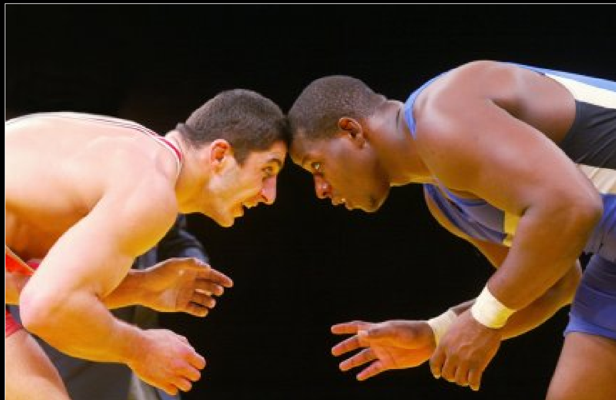


Australian Workshop
on Simulating the Dynamics
of Galaxies and the ISM

Australia Telescope National Facility (ATNF)

28 – 29 April 2005

Multiplicity of Massive Stars – a Clue to their Origin?

Hans Zinnecker (Astrophysical Institute Potsdam, Germany)

The coagulation theory of massive star formation (Bonnell, Bate, and Zinnecker 1998) predicts that most of the massive stars form in the central densest part of a protocluster by stellar collisions and tidal mergers. A further prediction is a high frequency of tight binary systems among massive stars due to tidal capture and the combination of tidal disruption followed by a star-disc encounter (failed stellar mergers). Recent observations have indeed confirmed this prediction (many young short-period SB2 systems among the O-stars in young clusters), but there is also observational evidence that seems to contradict the prediction (frequency of tight binaries higher in less dense young clusters). The jury is still out, whether stellar collisions are a viable theory for massive star formation. We will also briefly touch upon the implication of the observed very low binary frequency of O-type runaway stars and the high multiplicity of the four well-known Orion Trapezium high-mass OB stars.

outline of this talk

1. conditions for coalescence to occur
   in very dense young proto-clusters

2. multiplicity of massive stars -
   a clue to their origin (coalescence??)

3. the most massive star in the center
   of a very dense young cluster –
   a merger origin of GRB precursors
   (not discussed here, see AJ paper)

Origin of massive stars

two competing scenarios:

1. scaled-up version of low-mass star formation ("accretion") – but not quite (rad. pressure)

2. collisions of intermediate-mass stars/protostars in a dense gaseous protocluster ("coalescence")

how to discriminate between the two?
(Bally & Zinnecker 2005, AJ 129, 2281)

Origin of stellar masses

are stellar masses derived directly from pre-stellar core masses
hence related to the core physical conditions prior to grav. collapse

does "competetive accretion" play a role?
(the rich get richer, but the poor stay poor)

what about protostellar collisions and ejections?
photo-erosion?

triggering?
supernovae, stellar winds, expanding HII regions?
synchronisation (t = 0)?

The origin of massive stars: some questions

1. IRc2-I in Orion-KL:

nearest high-mass star in the making:
is there a hidden deeply embedded
cluster around it or is it a single object
with a massive disk and outflow
(H_2O masers, H_2 fingers: impulsive outflow)

2. Ultra-compact HII regions:

do they hide ($A_V > 100$) embedded
compact clusters where stellar
collisions / mergers are going on?
(science case for 30–100m class telescopes)

The origin of massive stars: some questions

3. NGC 3603 / R136:

how the hell do you form
10-100 O-stars within $1pc^3$?
(competitive accretion?
protostellar collision?)
are these massive clusters bound?
(depends on low-mass IMF)

4. massive clusters vs. OB associations:

same formation mechanism?
same stellar multiplicity?

5. field O-stars exist!

are there truly isolated massive stars
(i.e. no runaway stars, no ejections ...)?
clue to formation mechanism? EOS?

Stellar encounters in very dense clusters

„collision“ timescale

$$\tau_{coll} = \frac{1}{n_* \, \sigma_{grav} \, v_{rms}} = \left[16\sqrt{\pi}\, n_* \, v_{rms} \, R_*^2 \left(1 + \frac{v_{esc}^2}{v_{rms}^2} \right) \right]^{-1}$$

Require

$$\tau_{coll} < \tau_{evol} \qquad \left(\le 10^6 \, yr \right)$$

Ok, if

$$n_* \approx 5 \cdot 10^7 \; stars / pc^3$$

$$\sigma_{grav} \approx 10^4 \sigma_{geom,*}$$

$$\approx 10^{-8} \, pc^2 \quad for \quad 2R_* = 40 R_\odot$$

$$v_{rms} \approx 5 \, km / s$$

Stellar encounters in very dense clusters

such a situation can occur, if you shrink the Orion Trapezium Cluster core radius (0.2 pc) by a factor of 10 (0.02 pc), i.e. increase stellar number density by factor 1000!

$$v_{rms} = \sqrt{\frac{GM}{R_c}} \approx 5\, km/s \qquad for \qquad M = 200\, M_\odot$$

$$R_c = 0.02\, pc$$

$$\sigma_{grav} = \pi\, R_*^2 \left(\frac{v_{esc}}{v_\infty}\right)^2 = \sigma_{geom}\left(\frac{500}{5}\right)^2$$

grav. focusing


Orion Nebula and Trapezium Cluster (J,K,L true-colour composite)

Tight massive binaries
from dynamical dense star cluster evolution

massive central binary absorbing cluster B. E.

→ **semi-major axis** $a_{bin} = R_{cl} / N_*^2$
for cluster radius R_{cl} , N_* number of OB stars

$$\begin{pmatrix} R_{cl} \sim 1pc, & N_* \sim 300: & a_{bin} \sim 1AU \\ R_{cl} \sim 0.1pc, & N_* \sim 100: & a_{bin} \sim 1AU \end{pmatrix}$$

⇒ **short-period massive spectroscopic binary, large eccentricity**
→ **tidal merger possible ***
→ **$M_* > 100\ M_\odot$ in the dense cluster center**

cf. HD 93129A in Carina (binary resolved by HST/FGS)
(60 mas, $\Delta V = 0.5$ mag, Walborn 2002)

*** Zinnecker 1986, IAU-Symp. 116, Lumin. Stars & Assoc. in Galaxies, p. 271**

Multiplicity of massive stars –
a clue to their origin

1. review of the observations
2. review of the theory / ideas

1. multiplicity data

Trapezium cluster, M16 cluster, NGC 6231 etc.
Sco-Cen OB association, runaway OB stars etc.
WR binaries in the Galaxy and the Mag. Clouds

2. massive binary formation

a) fragmentation of a massive circumstellar disk
b) Bondi/Hoyle accretion onto a lower-mass binary
c) coalescence: binaries as failed stellar mergers
d) N-body evolution in a dense stellar cluster

Definition „Multiplicity“

or companion star fraction (csf)

$$csf = \frac{B + 2T + 3Q}{S + B + T + Q}$$

Reipurth & Zinnecker 1993, A&A 278, 81

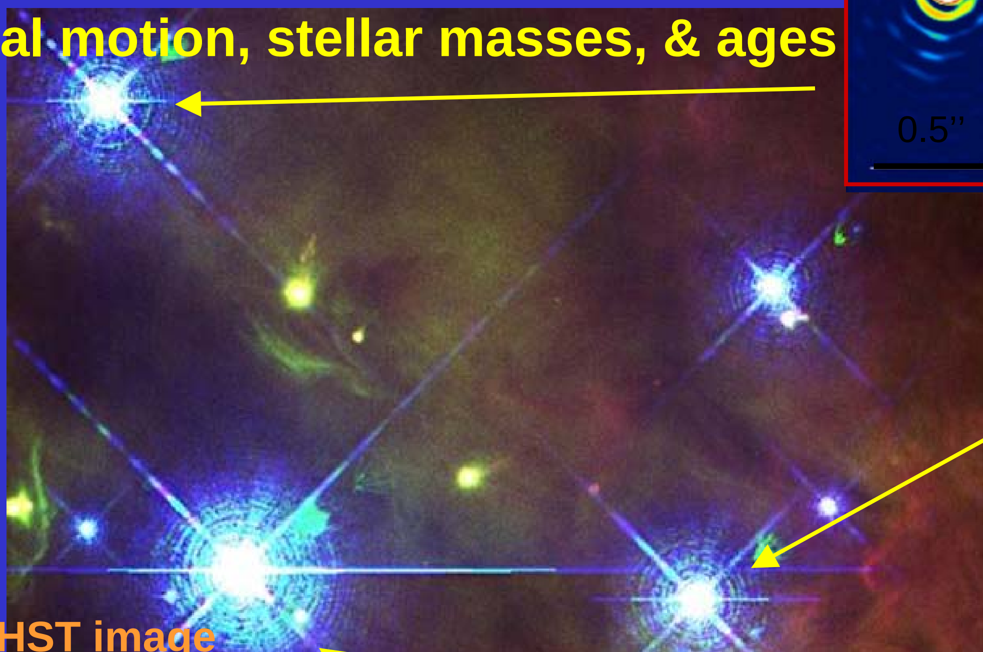
e.g. csf = 1.5 for Trapezium stars

*	1 single
* •	1double
* • •	1 triple
* • :	1 quadruple

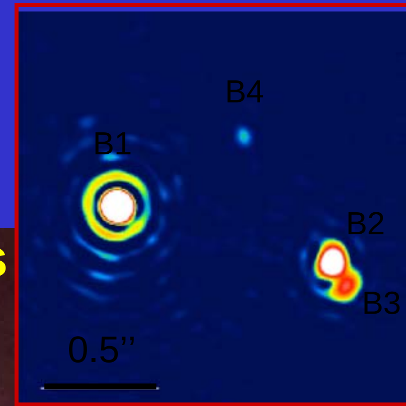
PS. csf = 0.5 for low-mass stars (T Tauri stars) in Orion Nebula Cluster

Young, massive Orion Trapezium binaries:

orbital motion, stellar masses, & ages

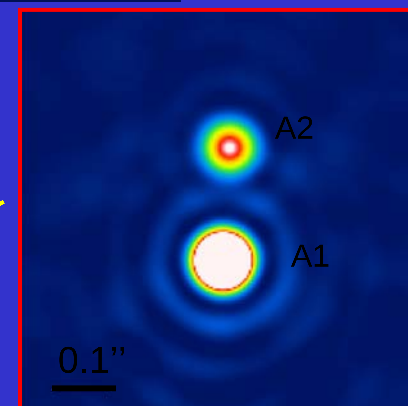


HST image

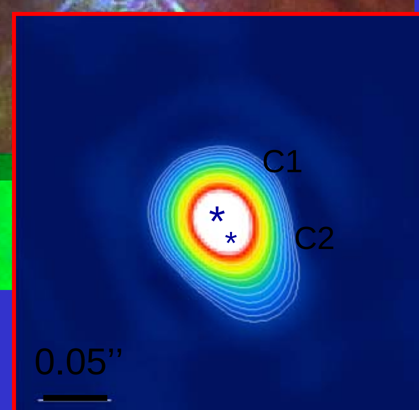


High-resolution infrared speckle reconstruction

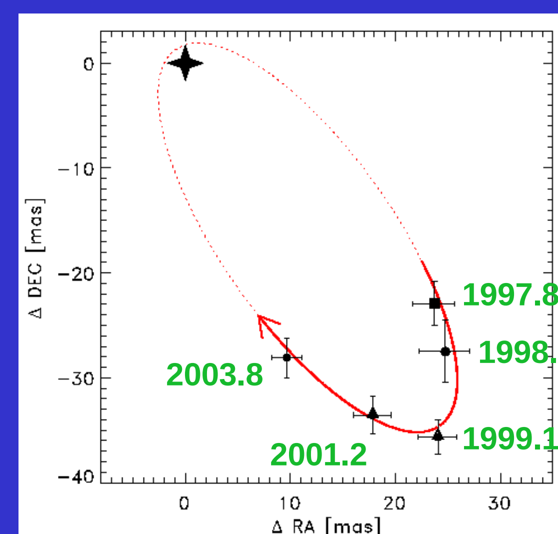
B2-3:
sep = 117 mas



sep = 215 mas



sep = 38 mas



Schertl et al. (2003, A&A)

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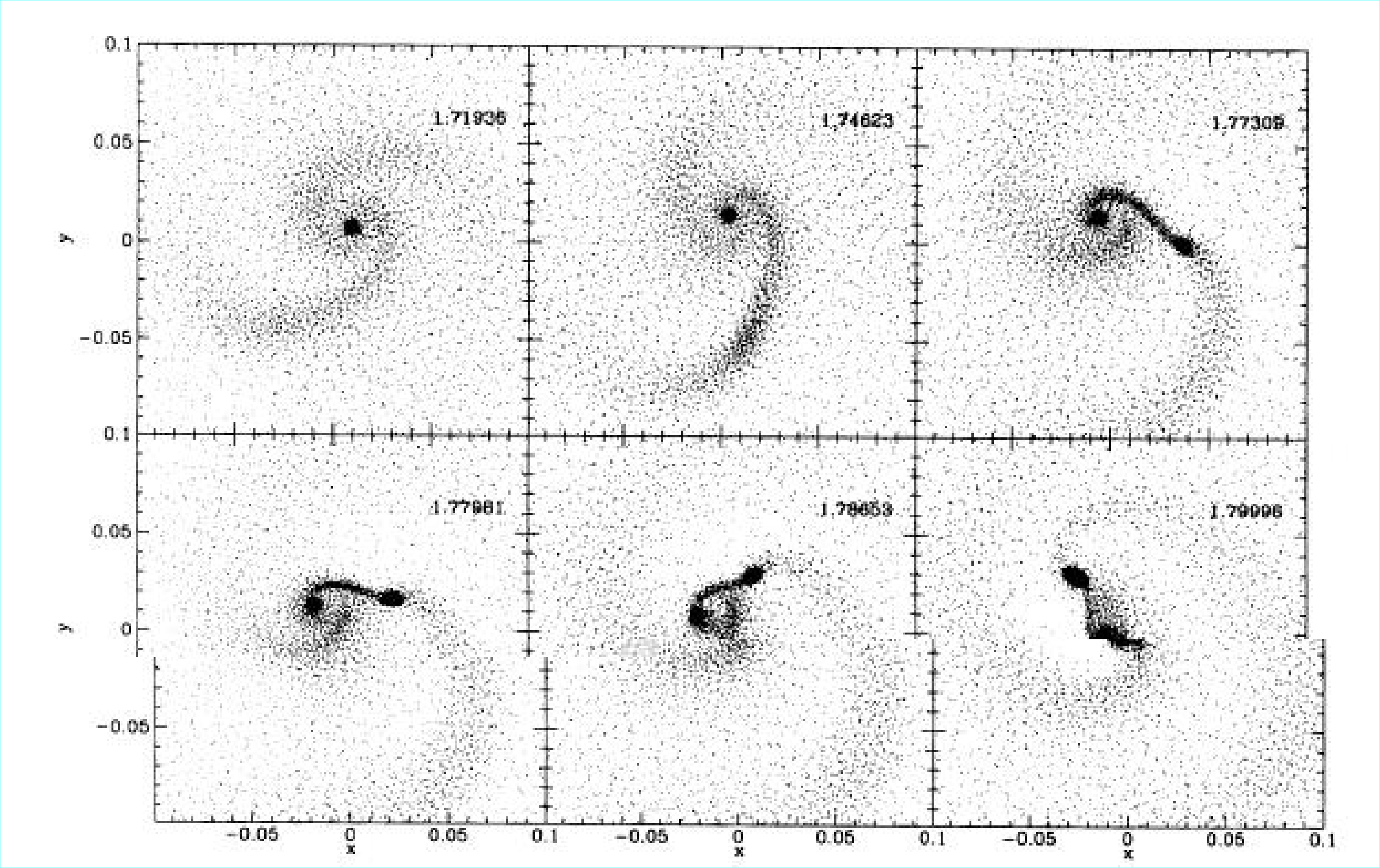
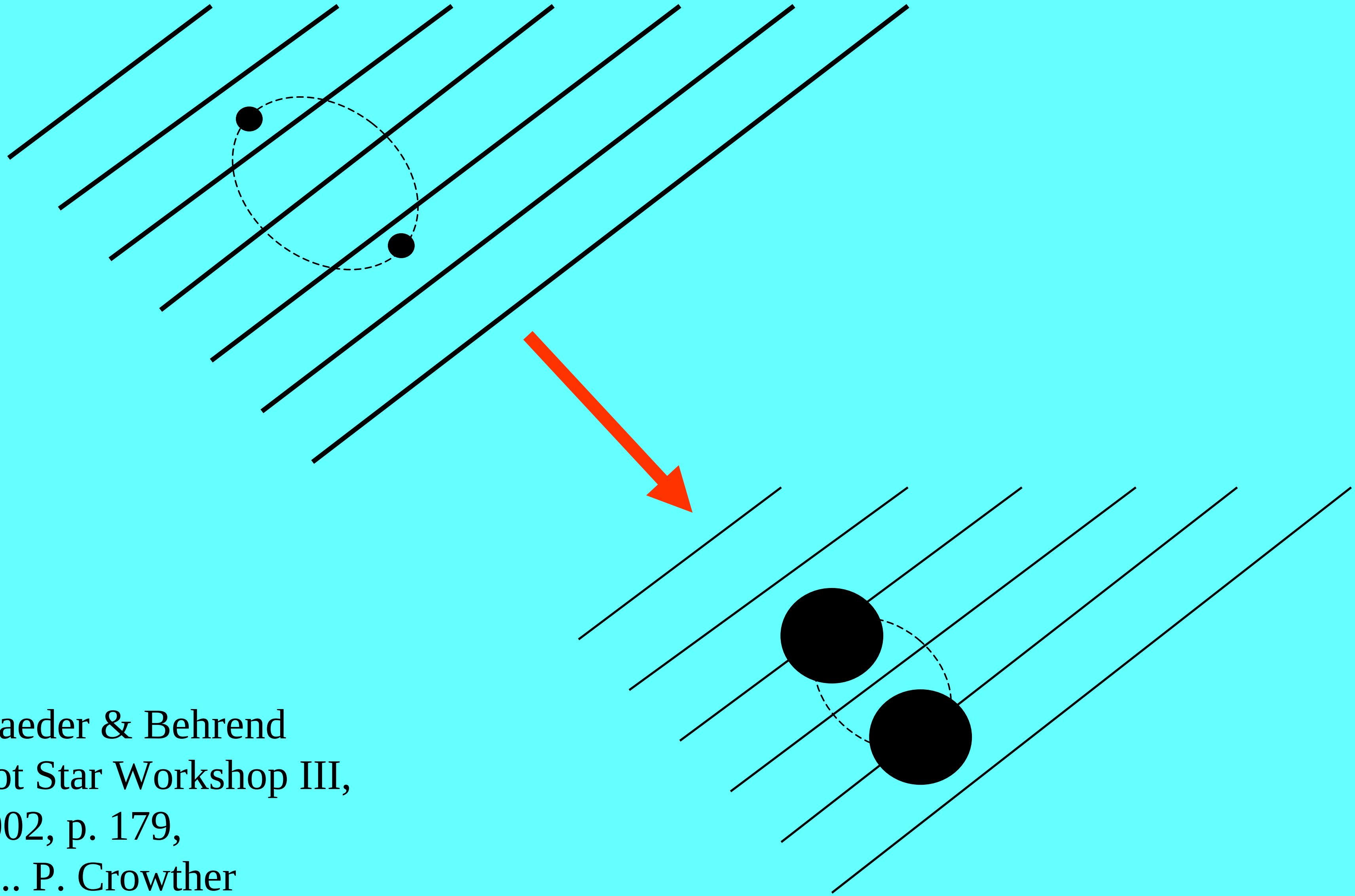
Rotationally driven disk fragmentation

with continued infall of gas (mass)



Bonnell & Bate (1994, MNRAS)

Bondi/Hoyle accretion onto a binary system

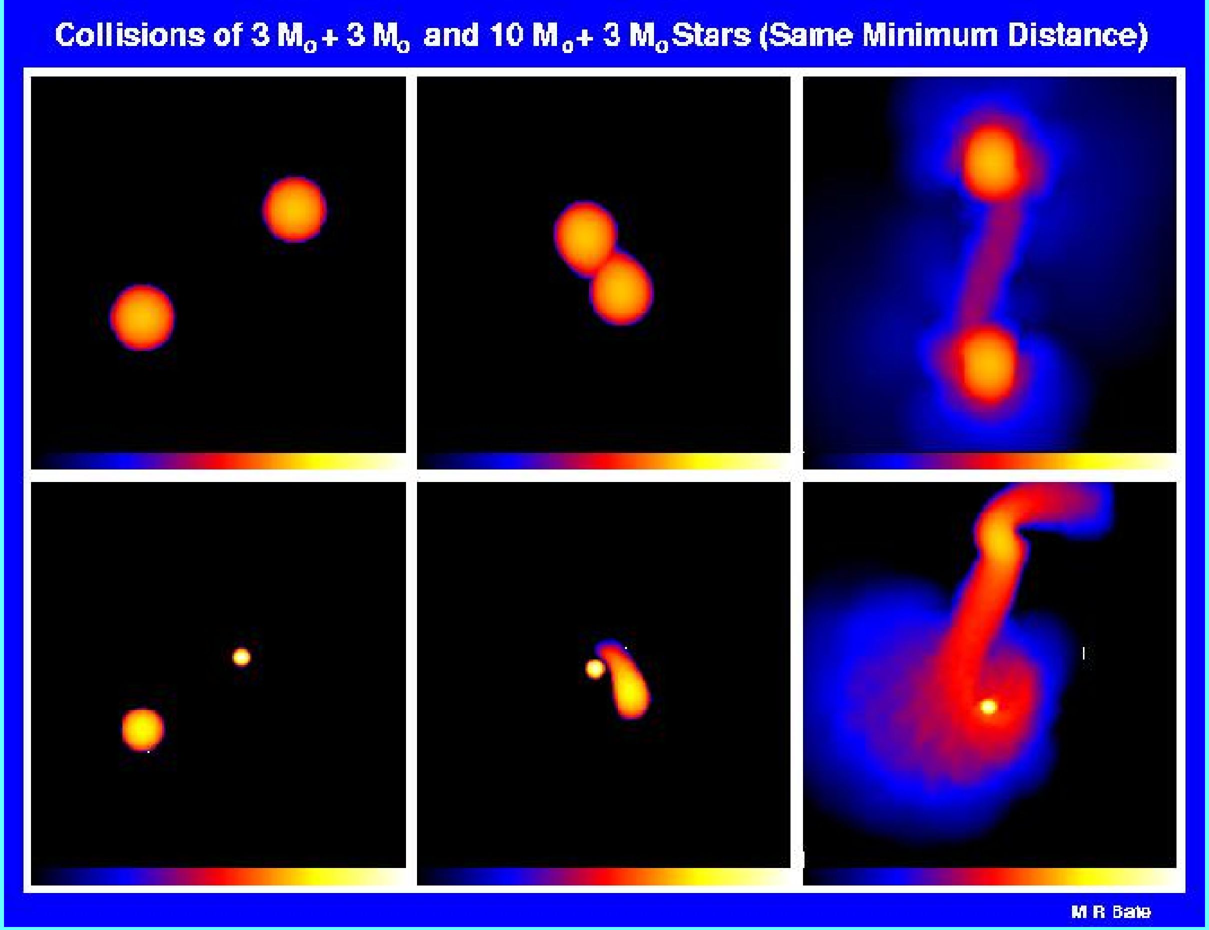


Maeder & Behrend
Hot Star Workshop III,
2002, p. 179,
ed.. P. Crowther

The fundamental role of grav. focusing

3 situations: see Bate et al. Simulations

1.	$r_{peri\text{-}astron}$	$\leq$	**R_* collisional merger**
2.	$r_{peri\text{-}astron}$	$\approx$	**$2\ R_*$ grazing collision: tidal capture (binary) or tidal disruption (disk)**
3.	$r_{peri\text{-}astron}$	$\geq$	**$4\ R_*$ near-miss**



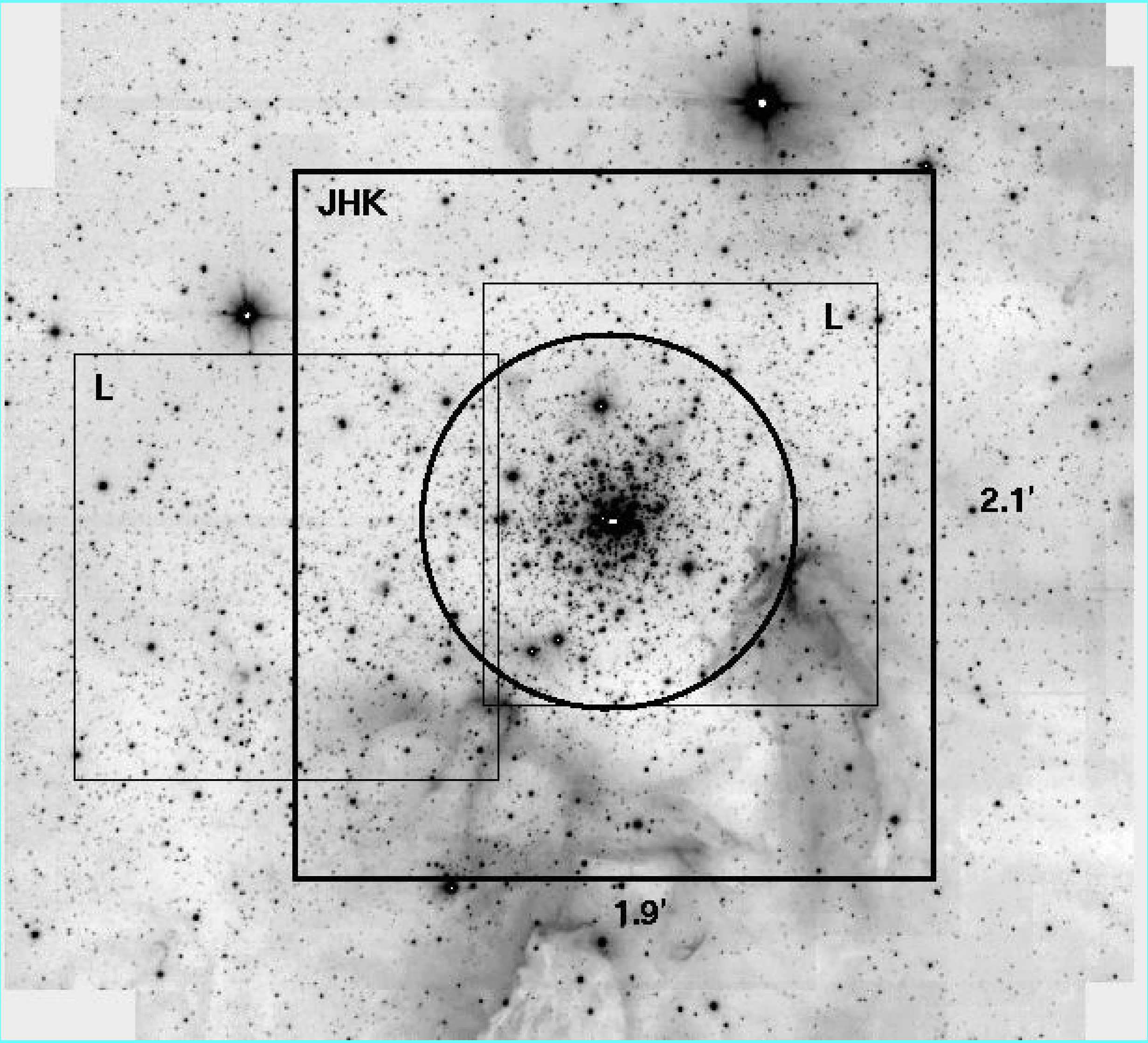
Top: A grazing encounter between two 3-$M_{\odot}$ pre-main-sequence stars that results in the formation of a binary (r_{min}=25.8solar radii).
Bottom: A detached encounter between a 3-$M_{\odot}$ pre-main-sequence Star and a 10-$M_{\odot}$ zero-age main-sequence star with the same minimum periastron distance as the top encounter. The stars have radii of 12.9 and 3.92 solar radii respectively. The greater density of the 10-$M_{\odot}$ star results in tidal disruption of the low-density 3-$M_{\odot}$ star to form a disc around the massive star. The encounters have zero relative velocity at infinity (i.e. parabolic encounters).

Zinnecker & Bate (2002)

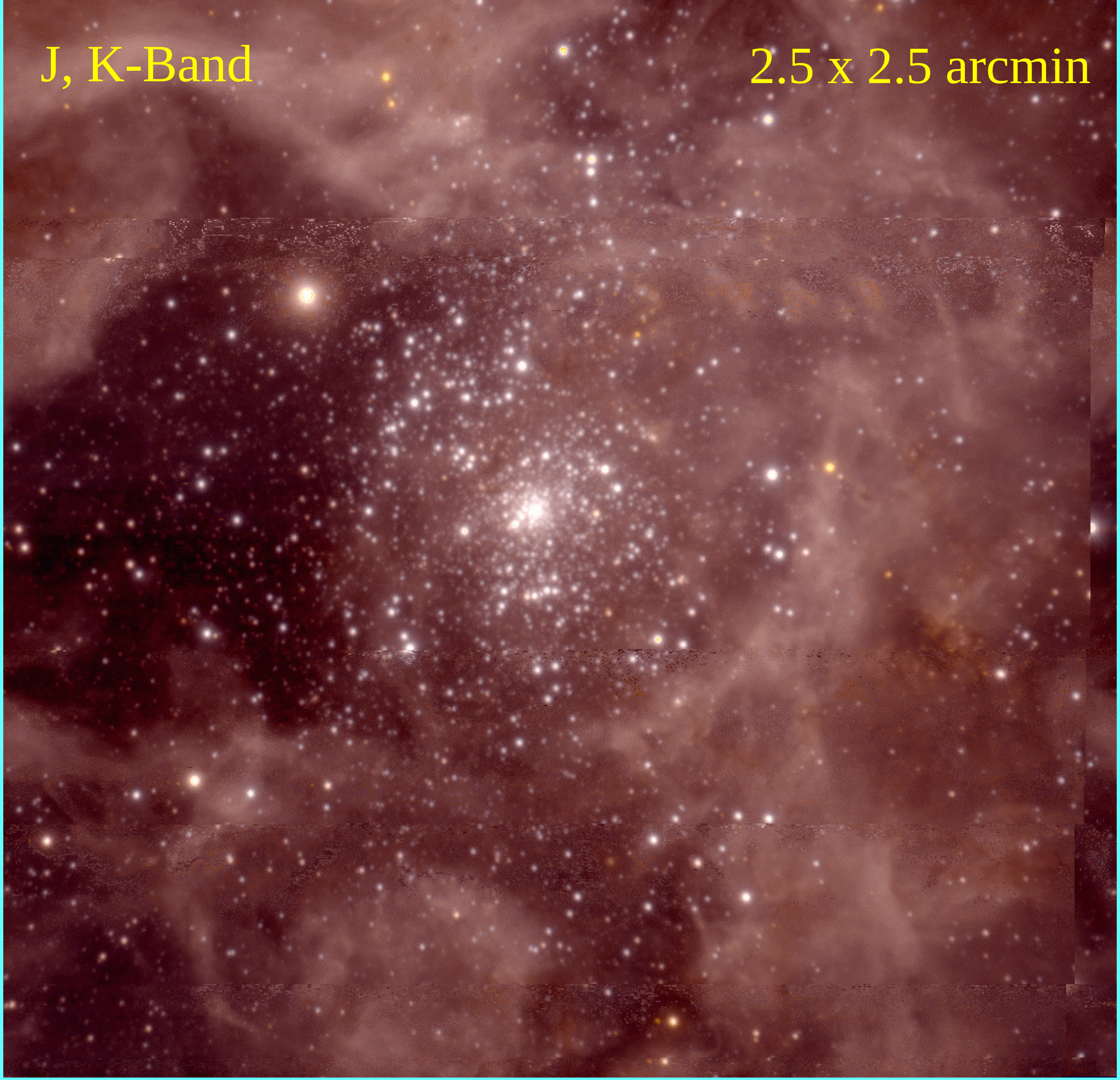
The Mon R2 young stellar cluster

A false, three color composite image of the SQIID mosaics (J band = blue, H band = green, K band = red). The field of view of the mosaic is approximately 15' x 15'. The embedded cluster is located near the center of the mosaic, and the two blue, nebulous regions are reflection nebula associated with early B type stars .

(Carpenter et al. 1997, AJ 114, 198)



NGC 3603 massive young cluster (VLT)



30 Dor star burst cluster (VLT)

30Dor cluster

Is it bound? **Is it a proto-globular cluster?**

$v^2 = (G \cdot M / R)^{1/2}$

$v = 20\ km / s$

G = $4{\cdot}10^{-3}$
M = $10^5\ M_\odot$
R = 1 pc

velocity dispersion measures the depth of the potential well

to be compared with the sound speed (expansion velocity) of an HII region

~ 10 km/s

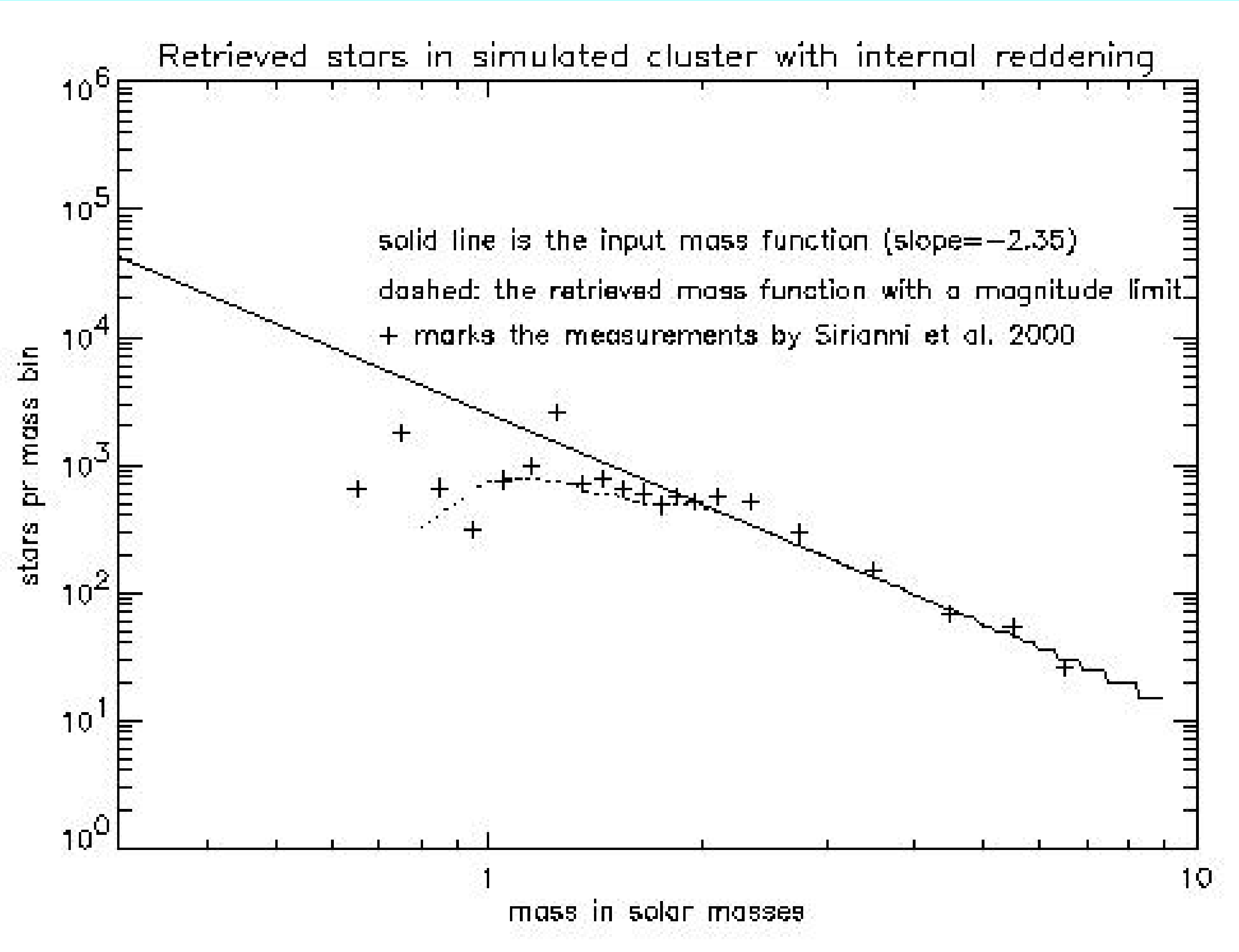
30Dor cluster will be bound,
if $M_{tot} = 10^5\ M_\odot$

(trapped HII region)

but unbound,
if $M_{tot} = 2.5 \cdot 10^4\ M_\odot$

(expanding HII region)

30 Dor cluster IMF-simulation



M. Andersen 2004 (PhD)