The Diversity of Stellar Interactions in the ONC

Evolution of protoplanetary discs, binarity, and mass segregation

Christoph Olczak

ARI & MPIA, Heidelberg

NAOC & KIAA, Beijing

Collaborators:

Rainer Spurzem (ARI Heidelberg; NAOC, KIAA Beijing)

Thomas Henning (MPIA Heidelberg)

Susanne Pfalzner (MPIfR Bonn)

Some facts about star and planet formation

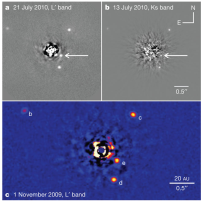
Planets and their hosts:

- stars form with dusty discs
  $\Rightarrow$ *protoplanetary discs*
- protoplanetary discs serve as hosts of planet formation
- protopl. discs last for $\lesssim 10\,\mathrm{Myr}$

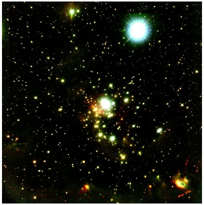
Stars and their hosts:

- up to 90 % of all stars form in clusters (Lada & Lada, 2003; Evans et al., 2009)
- 50 % of all stars form in *massive* clusters ($N > 1000$)
- star clusters last for $\gtrsim 10\,\mathrm{Myr}$

Ori 114-426
O'Dell & Beckwith (1997)



HR 8799
Marois et al. (2010)



IC 348
Muench et al. (2003)

NGC 3603
Brandl et al. (2001)

Some facts about star and planet formation

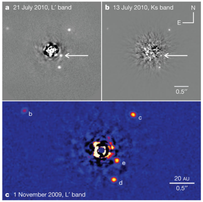
Planets and their hosts:

- stars form with dusty discs
  $\Rightarrow$ *protoplanetary discs*
- protoplanetary discs serve as hosts of planet formation
- protopl. discs last for $\lesssim$ 10 Myr

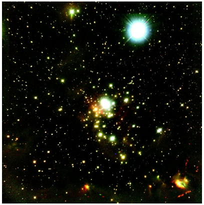
Stars and their hosts:

- up to 90 % of all stars form in clusters (Lada & Lada, 2003; Evans et al., 2009)
- 50 % of all stars form in *massive* clusters ($N > 1000$)
- star clusters last for $\gtrsim$ 10 Myr

Ori 114-426
O'Dell & Beckwith (1997)



HR 8799
Marois et al. (2010)



IC 348
Muench et al. (2003)

NGC 3603
Brandl et al. (2001)

$\Rightarrow$ formation and evolution of stars and planets potentially affected by the cluster environment

Some facts about star and planet formation

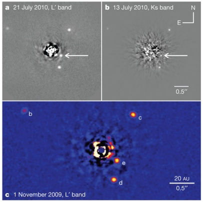
Planets and their hosts:

- stars form with dusty discs
  ⇒ *protoplanetary discs*
- protoplanetary discs serve as hosts of planet formation
- protopl. discs last for $\lesssim 10\,\mathrm{Myr}$

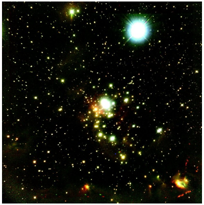
Stars and their hosts:

- up to 90 % of all stars form in clusters (Lada & Lada, 2003; Evans et al., 2009)
- 50 % of all stars form in *massive* clusters ($N > 1000$)
- star clusters last for $\gtrsim 10\,\mathrm{Myr}$

Ori 114-426
O'Dell & Beckwith (1997)



HR 8799
Marois et al. (2010)



IC 348
Muench et al. (2003)

NGC 3603
Brandl et al. (2001)

⇒ formation and evolution of stars and planets potentially affected by the cluster environment

⇒ investigation of the effect of stellar encounters on stars and their discs

The dynamically outstanding role of massive stars

The effect of stellar encounters is dominated by massive stars twofold:

Gravitational focusing

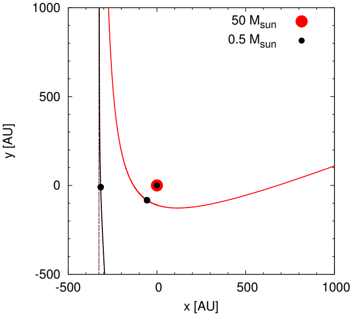
Mass-ratio dependent perturbation

The dynamically outstanding role of massive stars

The effect of stellar encounters is dominated by massive stars twofold:

Gravitational focusing

$$b^2 = r_{\mathrm{enc}}^2 \left(1 + \frac{2GMm}{\mu r_{\mathrm{enc}} v^2}\right) = r_{\mathrm{enc}}^2 (1+\Theta)$$



Orion: $M = 50\,\mathrm{M}_\odot$, $m = 0.5\,\mathrm{M}_\odot$
$\Rightarrow b \approx 330\,\mathrm{AU} \rightarrow r_{\mathrm{enc}} = 100\,\mathrm{AU}$

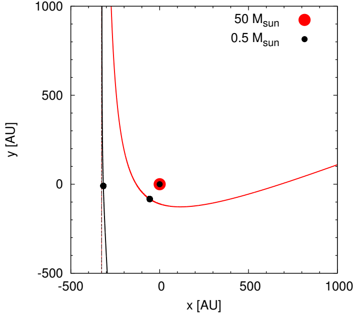
Mass-ratio dependent perturbation

The dynamically outstanding role of massive stars

The effect of stellar encounters is dominated by massive stars twofold:

Gravitational focusing

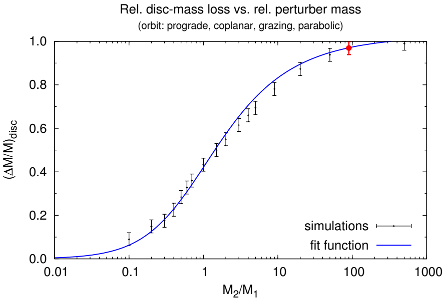
$$b^2 = r_{\mathrm{enc}}^2 \left(1 + \frac{2GMm}{\mu r_{\mathrm{enc}} v^2}\right) = r_{\mathrm{enc}}^2 (1+\Theta)$$



Orion: $M = 50\,\mathrm{M}_\odot$, $m = 0.5\,\mathrm{M}_\odot$

$\Rightarrow b \approx 330\,\mathrm{AU} \rightarrow r_{\mathrm{enc}} = 100\,\mathrm{AU}$

Mass-ratio dependent perturbation



Equivalent disc-mass loss:

$50\,\mathrm{M}_\odot$ perturber at $r_{\mathrm{enc}} = 500\,\mathrm{AU}$

$0.5\,\mathrm{M}_\odot$ perturber at $r_{\mathrm{enc}} = 100\,\mathrm{AU}$

Disc destruction (97 % mass loss):

$50\,\mathrm{M}_\odot$ perturber at $r_{\mathrm{enc}} = 100\,\mathrm{AU}$.

Protoplanetary discs at different wavelengths

Observations in a wide wavelength range, from near-infrared to millimeter, trace different spatial regimes of protoplanetary discs.

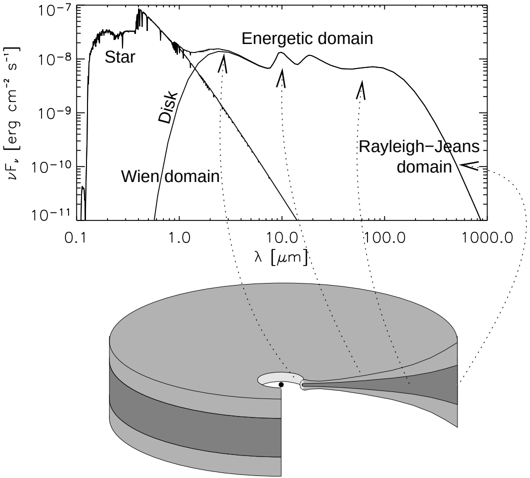
The correspondence of spatial regime and observed wavelength depends on

Protoplanetary discs at different wavelengths

Observations in a wide wavelength range, from near-infrared to millimeter, trace different spatial regimes of protoplanetary discs.

The correspondence of spatial regime and observed wavelength depends on

- dust temperature T
  → determines dominant wavelength
  $T \uparrow \Rightarrow \lambda \downarrow$
- size of dust grains R
  → determines scattering process
  $R \uparrow \Rightarrow \lambda \uparrow$
- density of dust grains ρ
  → determines optical depth
  $\rho \uparrow \Rightarrow \lambda \uparrow$



Dullemond et al. (2007)

Protoplanetary discs at different wavelengths

Observations in a wide wavelength range, from near-infrared to millimeter, trace different spatial regimes of protoplanetary discs.

The correspondence of spatial regime and observed wavelength depends on

- dust temperature T

  $\rightarrow$ determines dominant wavelength

  $T \uparrow \Rightarrow \lambda \downarrow$

- size of dust grains R

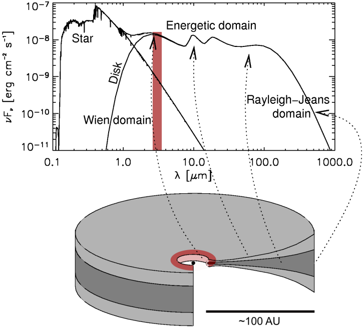
  $\rightarrow$ determines scattering process

  $R \uparrow \Rightarrow \lambda \uparrow$

- density of dust grains ρ

  $\rightarrow$ determines optical depth

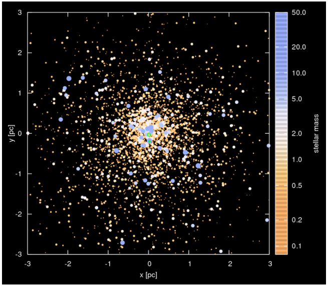
  $\rho \uparrow \Rightarrow \lambda \uparrow$



Dullemond et al. (2007)

Note: **near-infrared** $\sim 3\,\mu$ $\Rightarrow$ hot dust $\sim 1000\,\mathrm{K}$ $\Rightarrow$ **inner disc** $\lesssim 1\,\mathrm{AU}$

Realization of the numerical simulations

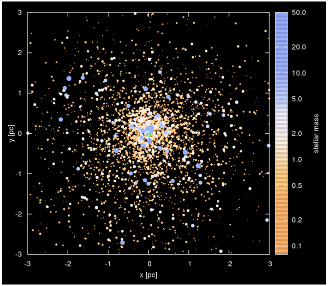


simulations of star cluster dynamics
(pure particle model, ∼1000 simulations, JUMP)
→ direct N-body code NBODY6++

tracking of encounters

record of encounter parameters

Realization of the numerical simulations

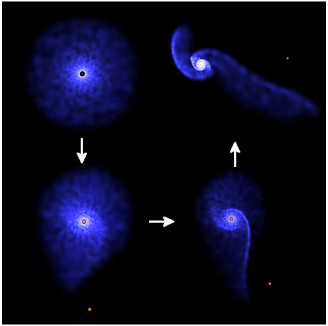


simulations of star cluster dynamics
(pure particle model, ∼1000 simulations, JUMP)
→ direct N-body code NBODY6++

tracking of encounters

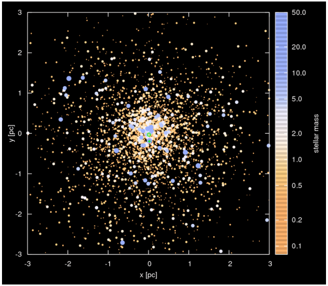
record of encounter parameters

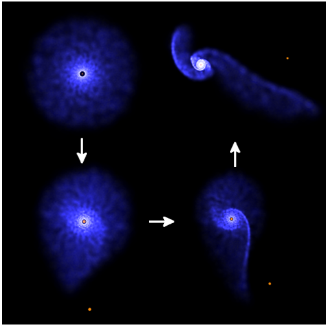
parameterized fit formula for effect of encounters:
- disc mass
- angular momentum



parameter study of star-disc encounters
(pure particle model, ∼2000 simulations, local)
→ tree code

Realization of the numerical simulations





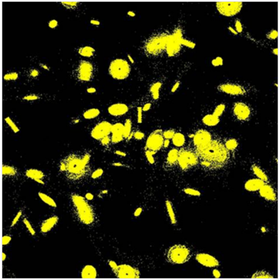
simulations of star cluster dynamics
(pure particle model, ∼1000 simulations, JUMP)
→ direct N-body code NBODY6++

tracking of encounters

record of encounter parameters

parameterized fit formula for effect of encounters:
- disc mass
- angular momentum

parameter study of star-disc encounters
(pure particle model, ∼2000 simulations, local)
→ tree code



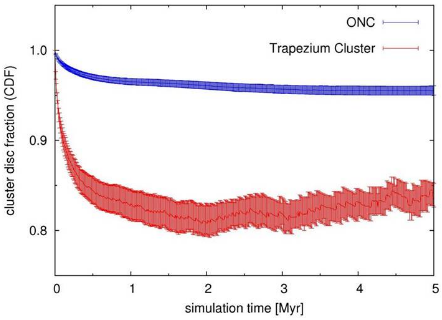
encounter-induced evolution of star-disc systems in a cluster environment

Encounter-induced disc destruction in the ONC

Numerical evolution of the dynamical model of the ONC ($t \approx 1$ Myr).
Investigation of the disc-mass loss over time (destruction: $> 90\,\%$ mass loss).

→ **Stellar encounters lead to significant disc destruction** (Olczak et al., 2006):

- ∼ 5 % discs destroyed in entire cluster ($R = 2.5$ pc)
- ∼ 20 % discs destroyed in cluster core ($R = 0.3$ pc, "Trapezium Cluster")



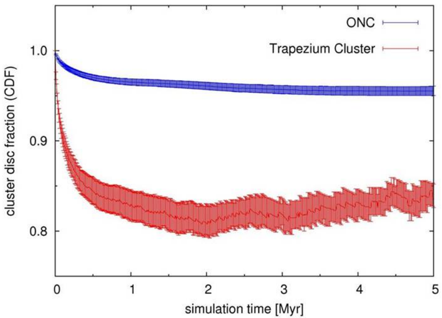
Encounter-induced disc destruction in the ONC

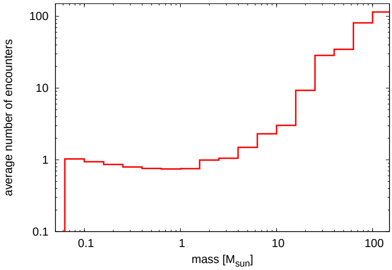
Numerical evolution of the dynamical model of the ONC ($t \approx 1$ Myr).
Investigation of the disc-mass loss over time (destruction: $> 90\,\%$ mass loss).

→ **Stellar encounters lead to significant disc destruction** (Olczak et al., 2006):

- ∼ 5 % discs destroyed in entire cluster ($R = 2.5$ pc)
- ∼ 20 % discs destroyed in cluster core ($R = 0.3$ pc, "Trapezium Cluster")

→ **High-mass stars dominate interactions: "gravitational foci"** (Pfalzner et al., 2006).





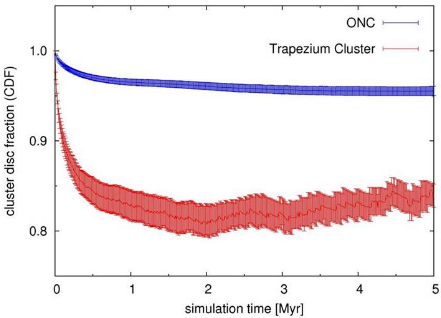
Encounter-induced disc destruction in the ONC

Numerical evolution of the dynamical model of the ONC ($t \approx 1\,\mathrm{Myr}$).
Investigation of the disc-mass loss over time (destruction: $> 90\,\%$ mass loss).

→ **Stellar encounters lead to significant disc destruction** (Olczak et al., 2006):

- $\sim$ 5 % discs destroyed in entire cluster ($R = 2.5\,\mathrm{pc}$)
- $\sim$ 20 % discs destroyed in cluster core ($R = 0.3\,\mathrm{pc}$, "Trapezium Cluster")

→ **High-mass stars dominate interactions: "gravitational foci"** (Pfalzner et al., 2006).



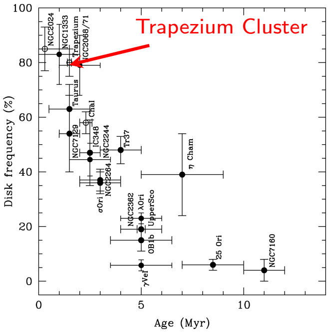


Figure: Hernández et al. (2007)

Encounter-induced disc destruction in the ONC

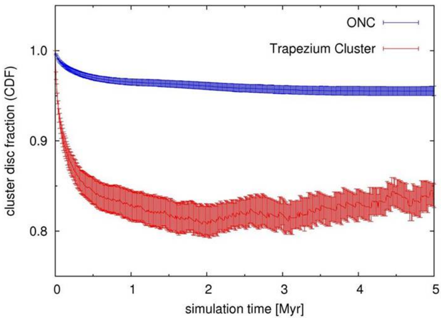
Numerical evolution of the dynamical model of the ONC ($t \approx 1\,\mathrm{Myr}$).

Investigation of the disc-mass loss over time (destruction: $> 90\,\%$ mass loss).

Conclusion

Gravitational interactions in star clusters

1. **cause very rapid disc destruction,**
2. **lower disc frequency close to massive stars** (independent of photoevaporation!),
3. **make planet formation around massive stars improbable.**



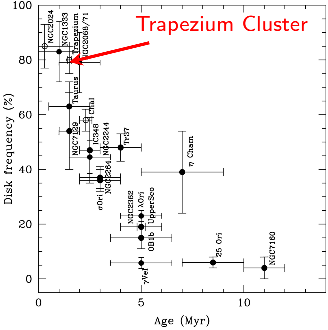


Figure: Hernández et al. (2007)

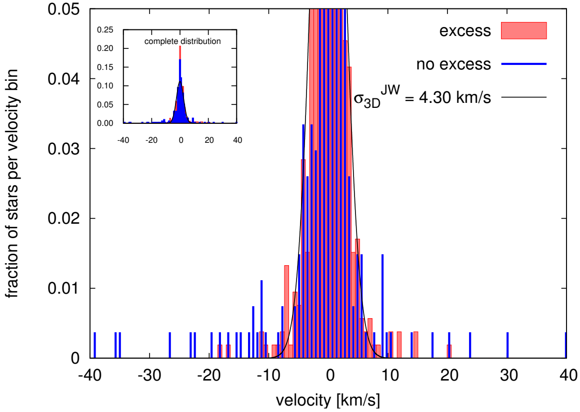
Observational imprints of encounter-induced disc destruction

How to identify stars that have been ejected in a three-body encounter?

→ High-velocity signature in cluster velocity distribution.

What influence do encounters have on the discs of ejected stars?

→ Combine disc signatures and cluster velocity distribution.



- Proper motions: Jones & Walker (1988)
- Disc signature (IR-excess): Hillenbrand et al. (1998)

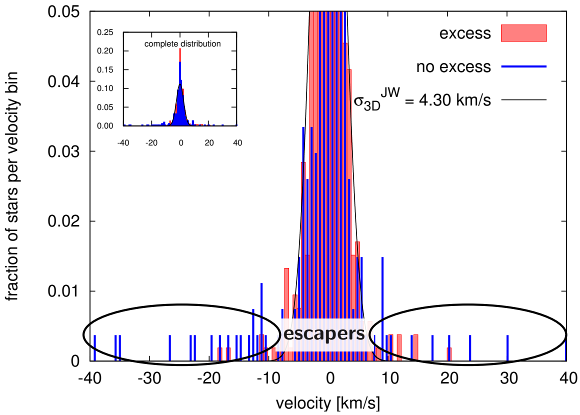
Observational imprints of encounter-induced disc destruction

How to identify stars that have been ejected in a three-body encounter?

→ High-velocity signature in cluster velocity distribution.

What influence do encounters have on the discs of ejected stars?

→ Combine disc signatures and cluster velocity distribution.



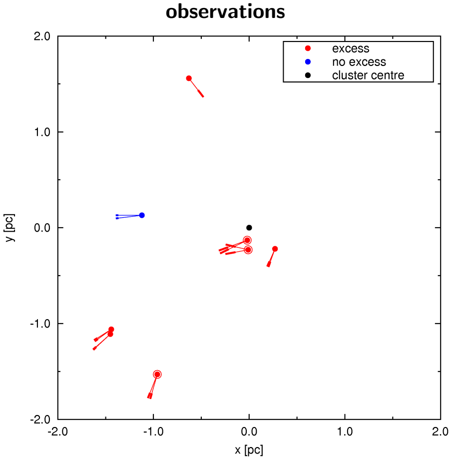
- Proper motions: Jones & Walker (1988)
- Disc signature (IR-excess): Hillenbrand et al. (1998)

Observational imprints of encounter-induced disc destruction

Are there characteristic positions and velocities of escapers?

→ Two features:

1. Star-disc systems do not seem to have been expelled from the cluster centre.

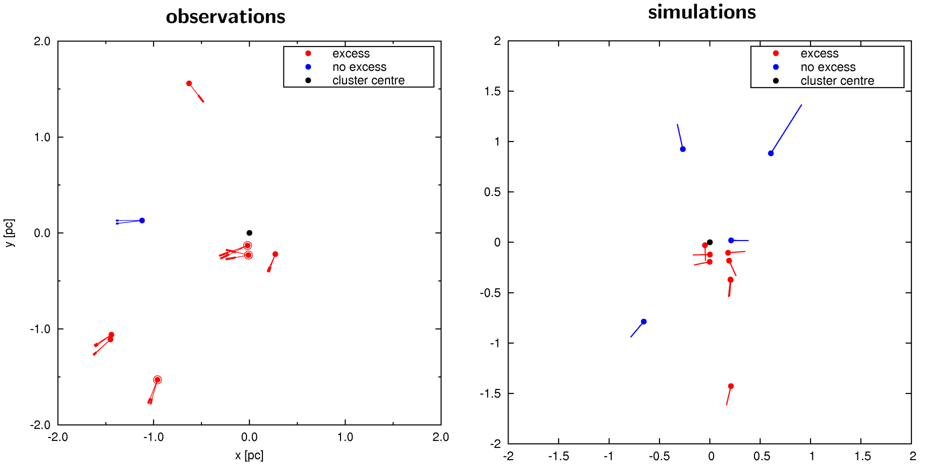


Observational imprints of encounter-induced disc destruction

Are there characteristic positions and velocities of escapers?

→ Two features:

1. Star-disc systems do not seem to have been expelled from the cluster centre.
2. Disc-less stars are moving on radial tracks from the cluster centre.

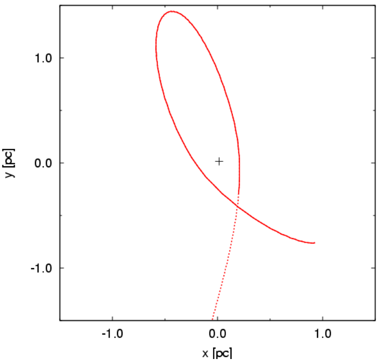


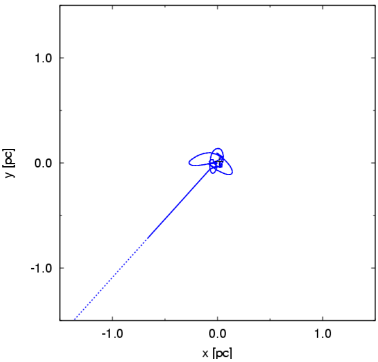
Observational imprints of encounter-induced disc destruction

What is the dynamical history of the escapers?

→ Two scenarios:

1. Star-disc: formation in outer cluster → escape on wide non-closed orbit
2. Disc-less: formation in cluster core → escape on radial trajectory



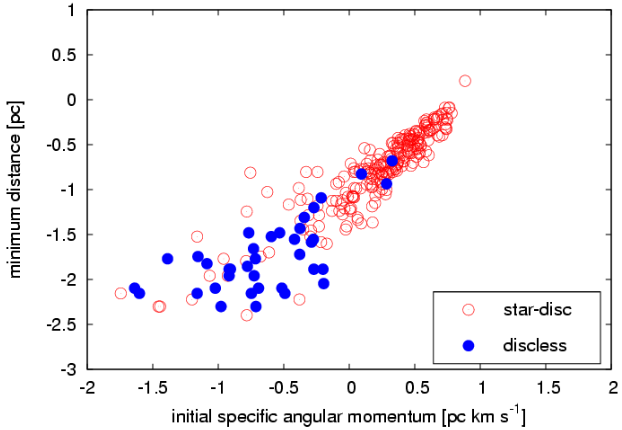


Observational imprints of encounter-induced disc destruction

Conclusion

Two fundamental classes of ONC escapers in terms of dynamics and stellar properties:

1. formation in outer cluster ↔ star-disc system ↔ wide non-closed orbit
2. formation in cluster core ↔ disc-less ↔ radial trajectory

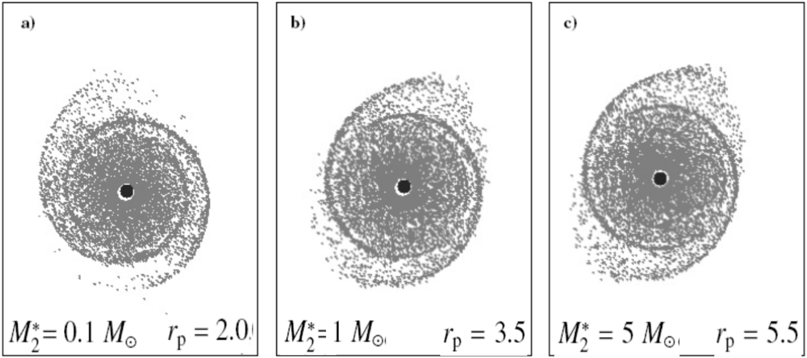


Encounter-induced angular momentum loss in the ONC

Investigation of the angular momentum loss (AML) in the ONC over time ($t \approx 1$ Myr).

→ **Stellar encounters lead to 3-5 % average AML in the ONC** (Pfalzner & Olczak, 2007a).

⇒ Pronounced spiral arm structure triggered by encounters in most of the cluster stars.



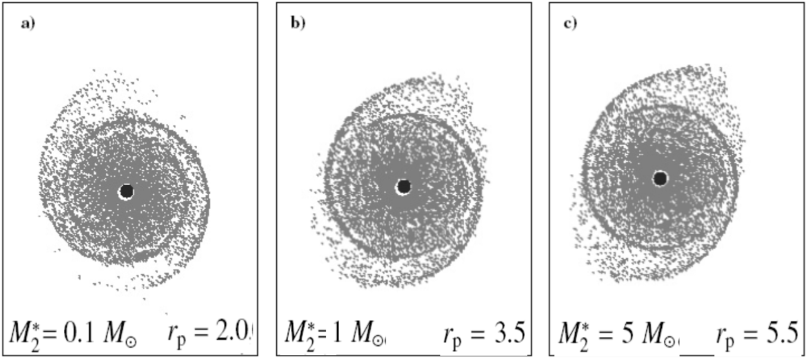
Encounter-induced angular momentum loss in the ONC

Investigation of the angular momentum loss (AML) in the ONC over time ($t \approx 1$ Myr).

→ **Stellar encounters lead to 3-5 % average AML in the ONC** (Pfalzner & Olczak, 2007a).

⇒ Pronounced spiral arm structure triggered by encounters in most of the cluster stars.

→ **Planet formation via gravitational instabilities might be common**.
(see Rice et al., 2004, 2006; Clarke & Lodato, 2009)



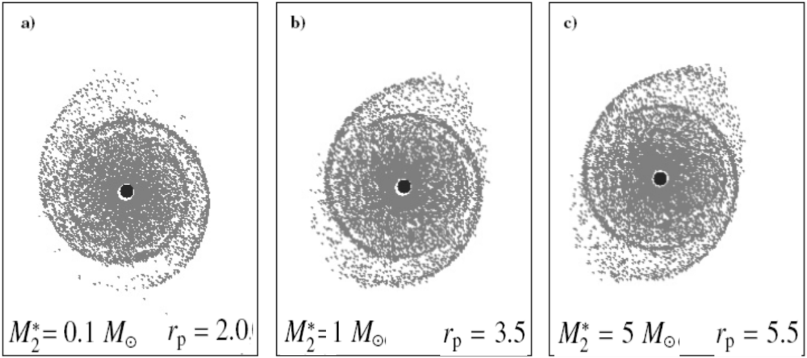
Encounter-induced angular momentum loss in the ONC

Investigation of the angular momentum loss (AML) in the ONC over time ($t \approx 1$ Myr).

Conclusion

Gravitational interactions in star clusters

1. **cause significant perturbations of most protoplanetary discs,**
2. **potentially trigger "synchronous" (giant?) planet formation.**

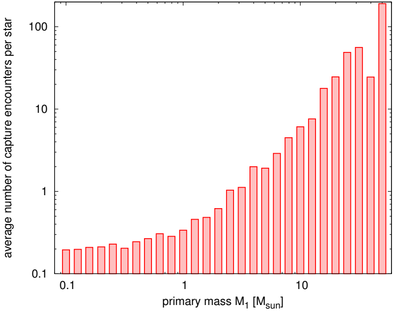


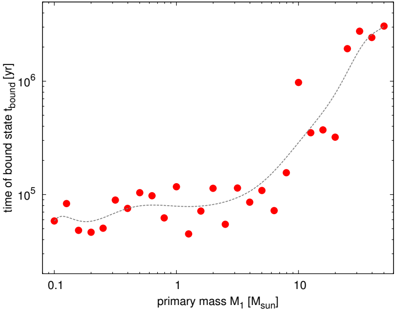
Capture-induced binarity in the ONC

Investigation of three-body encounters in pure single star models (Pfalzner & Olczak, 2007b).

Temporary capture events lead to the formation of **Transient Bound Systems (TBS)**.

→ Massive stars are affected the most (see also Moeckel & Bally, 2007a,b).





Capture-induced binarity in the ONC

Investigation of three-body encounters in pure single star models (Pfalzner & Olczak, 2007b).

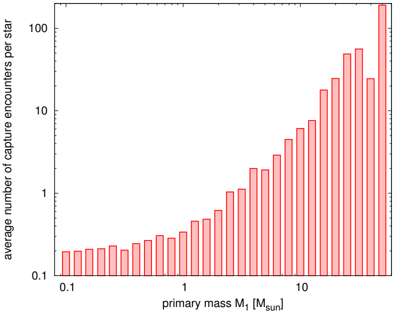
Temporary capture events lead to the formation of **Transient Bound Systems (TBS)**.

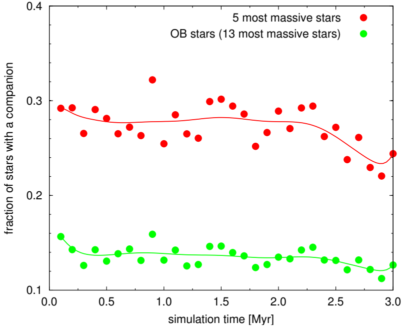
→ Massive stars are affected the most (see also Moeckel & Bally, 2007a,b).

→ **Formation of TBS highly affects the (apparent/observed) binary rate**.

- 15 % of the 13 OB stars
- 30 % of the five most massive stars

are in a bound state on average





A new efficient measure of mass segregation

Problem

- Do young star clusters really show evidence for mass segregation?
- Is the observed mass segregation in young clusters due to initial conditions (i.e. *primordial*)?
- Does the observed degree of (*dynamical*) mass segregation in old clusters agree with theory?

A new efficient measure of mass segregation

Problem

- Do young star clusters really show evidence for mass segregation?
- Is the observed mass segregation in young clusters due to initial conditions (i.e. *primordial*)?
- Does the observed degree of (*dynamical*) mass segregation in old clusters agree with theory?

Goal

Efficient measure of mass segregation for observational and numerical data.

- Geometrically independent.
- Independence of quantitative mass measurement.
- Numerical robustness.
- Simple, intuitive measure.

A new efficient measure of mass segregation

Problem

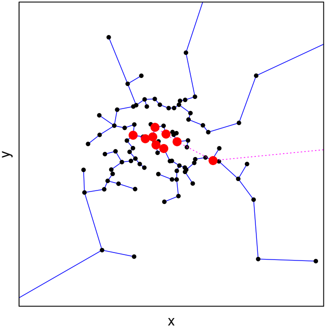
- Do young star clusters really show evidence for mass segregation?
- Is the observed mass segregation in young clusters due to initial conditions (i.e. *primordial*)?
- Does the observed degree of (*dynamical*) mass segregation in old clusters agree with theory?

Goal

Efficient measure of mass segregation for observational and numerical data.

- Geometrically independent.
- Independence of quantitative mass measurement.
- Numerical robustness.
- Simple, intuitive measure.

$\Rightarrow$ **Minimum Spanning Tree (MST)**



Definition

MST $\equiv$ shortest connecting graph $G = (V, E)$ of all vertices $v_i \in V$ without closed loops,

where $V := \{v_1, ..., v_N\} \subset \mathbb{R}^2$, $E := \{\{v_i, v_j\} \mid v_i, v_j \in V\}$.

Measuring mass segregation via the MST

Construction

1. Construct sub-MST, i.e. shortest connecting subgraph $G' = (V', E')$ of $n < N$ stars, where $V' := \{v'_1, ..., v'_n\} \subset V$, $E' := \{\{v'_i, v'_j\} \mid v'_i, v'_j \in V'\}$.
2. Assign to each edge $e = \{v'_i, v'_j\} \in E'$ the weight $w_e \equiv w_{ij} \equiv ||v'_i - v'_j||$.

Measuring mass segregation via the MST

Construction

1. Construct sub-MST, i.e. shortest connecting subgraph $G' = (V', E')$ of $n < N$ stars, where $V' := \{v'_1, ..., v'_n\} \subset V$, $E' := \{\{v'_i, v'_j\} \mid v'_i, v'_j \in V'\}$.
2. Assign to each edge $e = \{v'_i, v'_j\} \in E'$ the weight $w_e \equiv w_{ij} \equiv ||v'_i - v'_j||$.

Quantifying mass segregation

	Allison et al. (2009)
1. Define a measure L of the sub-MST:	$\boxed{\lambda = \sum_{e \in E'} w_e}$
2. Calculate L of the n most massive stars:	$l_{\mathrm{MST}}^{\mathrm{mass}}$
3. Calculate $\bar{L}$, ΔL of k sets of n random stars:	$l_{\mathrm{MST}}^{\mathrm{ref}}$, $\Delta l_{\mathrm{MST}}^{\mathrm{ref}}$
4. Normalize L (**signature** if $L > 1$):	$\boxed{\Lambda_{\mathrm{MST}} = \frac{l_{\mathrm{MST}}^{\mathrm{ref}}}{l_{\mathrm{MST}}^{\mathrm{mass}}}}$
5. Normalize ΔL (**significance** $\kappa = \frac{L-1}{\Delta L}$):	$\boxed{\Delta\Lambda_{\mathrm{MST}} = \frac{\Delta l_{\mathrm{MST}}^{\mathrm{ref}}}{l_{\mathrm{MST}}^{\mathrm{mass}}}}$

Measuring mass segregation via the MST

Construction

1. Construct sub-MST, i.e. shortest connecting subgraph $G' = (V', E')$ of $n < N$ stars, where $V' := \{v'_1, ..., v'_n\} \subset V$, $E' := \{\{v'_i, v'_j\} \mid v'_i, v'_j \in V'\}$.
2. Assign to each edge $e = \{v'_i, v'_j\} \in E'$ the weight $w_e \equiv w_{ij} \equiv ||v'_i - v'_j||$.

Quantifying mass segregation

	Allison et al. (2009)	Olczak et al. (2011)
1. Define a measure L of the sub-MST:	$\lambda = \sum_{e \in E'} w_e$	$\gamma = \sqrt[n]{\prod_{e \in E'} w_e}$
2. Calculate L of the n most massive stars:	$l_{\mathrm{MST}}^{\mathrm{mass}}$	$\gamma_{\mathrm{MST}}^{\mathrm{mass}}$
3. Calculate $\bar{L}$, ΔL of k sets of n random stars:	$l_{\mathrm{MST}}^{\mathrm{ref}}$, $\Delta l_{\mathrm{MST}}^{\mathrm{ref}}$	$\gamma_{\mathrm{MST}}^{\mathrm{ref}}$, $\Delta\gamma_{\mathrm{MST}}^{\mathrm{ref}}$
4. Normalize L (**signature** if $L > 1$):	$\Lambda_{\mathrm{MST}} = \frac{l_{\mathrm{MST}}^{\mathrm{ref}}}{l_{\mathrm{MST}}^{\mathrm{mass}}}$	$\Gamma_{\mathrm{MST}} = \frac{\gamma_{\mathrm{MST}}^{\mathrm{ref}}}{\gamma_{\mathrm{MST}}^{\mathrm{mass}}}$
5. Normalize ΔL (**significance** $\kappa = \frac{L-1}{\Delta L}$):	$\Delta\Lambda_{\mathrm{MST}} = \frac{\Delta l_{\mathrm{MST}}^{\mathrm{ref}}}{l_{\mathrm{MST}}^{\mathrm{mass}}}$	$\Delta\Gamma_{\mathrm{MST}} = \frac{\Delta\gamma_{\mathrm{MST}}^{\mathrm{ref}}}{\gamma_{\mathrm{MST}}^{\mathrm{mass}}}$

Use the *geometric mean* Γ_{MST} of the edges rather than their sum Λ_{MST}.
$\Rightarrow$ Acts as an intermediate pass that damps contributions from extreme edge lengths.

Mass-segregation in the ONC

Application of Γ_{MST}:

- **Observational data** of the ONC obtained by Hillenbrand (1997).
  Analysis via cumulative and differential mass groups:
  → Very strong segregation of the five most massive stars.

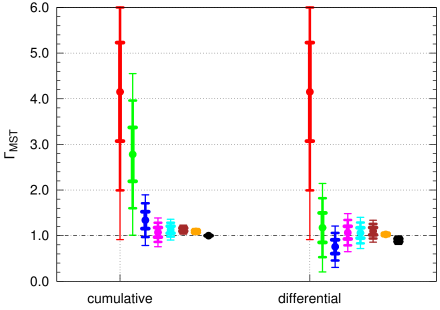


Figure: 5, 10, 20, 50, 100, 200, 500, 700 most massive stars.

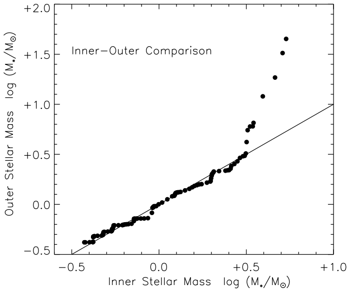


Figure: Huff & Stahler (2006), Fig. 4

Mass-segregation in the ONC

Application of Γ_{MST}:

- **Observational data** of the ONC obtained by Hillenbrand (1997).
  Analysis via cumulative and differential mass groups:
  → Very strong segregation of the five most massive stars.
- **Numerical simulations** of dynamical models of the ONC.
  → Subvirial initial conditions drive very rapid segregation of the most massive stars.

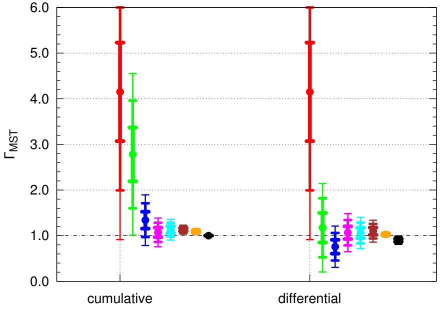


Figure: 5, 10, 20, 50, 100, 200, 500, 700 most massive stars.

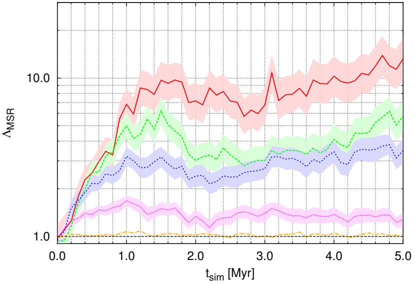


Figure: 5, 10, 20, 50, 500 most massive stars.

Summary

Stellar interactions in the ONC

Stellar encounters affect the formation and evolution of stars and planets in a huge variety:

- Massive stars act as gravitational foci of **very rapid** encounter-induced disc destruction.
  $\rightarrow$ Escapers provide observational signatures.
- Most star-disc systems are (weakly) perturbed: triggering of planet formation?
- Very efficient dynamical formation of **massive transient binary systems** (TBS).

Mass segregation in the ONC

Mass segregation in young star clusters is a key observable of the star formation process:

- New measure of mass segregation: Γ_{MST} = Minimum Spanning Tree + geometrical mean.
  $\rightarrow$ Γ_{MST} **highly advantageous over previous methods**.
- The ONC shows significant segregation of the five most massive members.
- Very rapid mass segregation induced by subvirial initial conditions.

Allison, R. J., Goodwin, S. P., Parker, R. J., et al. 2009, MNRAS, 395, 1449

Brandl, B., The Ngc 3603 Team, & The 30 Doradus Team. 2001, in Astronomical Society of the Pacific Conference Series, Vol. 243, From Darkness to Light: Origin and Evolution of Young Stellar Clusters, ed. T. Montmerle & P. André, 505–+

Clarke, C. J. & Lodato, G. 2009, MNRAS, 398, L6

Dullemond, C. P., Hollenbach, D., Kamp, I., & D'Alessio, P. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil, 555–572

Evans, N. J., Dunham, M. M., Jørgensen, J. K., et al. 2009, ApJS, 181, 321

Hernández, J., Hartmann, L., Megeath, T., et al. 2007, ApJ, 662, 1067

Hillenbrand, L. A. 1997, AJ, 113, 1733

Hillenbrand, L. A., Strom, S. E., Calvet, N., et al. 1998, AJ, 116, 1816

Huff, E. M. & Stahler, S. W. 2006, ApJ, 644, 355

Jones, B. F. & Walker, M. F. 1988, AJ, 95, 1755

Lada, C. J. & Lada, E. A. 2003, ARA&A, 41, 57

Marois, C., Zuckerman, B., Konopacky, Q. M., Macintosh, B., & Barman, T. 2010, Nature, 468, 1080

Moeckel, N. & Bally, J. 2007a, ApJ, 661, L183

Moeckel, N. & Bally, J. 2007b, ApJ, 656, 275

Muench, A. A., Lada, E. A., Lada, C. J., et al. 2003, AJ, 125, 2029

O'Dell, C. R. & Beckwith, S. V. W. 1997, Science, 276, 1355

Olczak, C., Pfalzner, S., & Spurzem, R. 2006, ApJ, 642, 1140

Olczak, C., Spurzem, R., & Henning, T. 2011, A&A, 532, A119+

Pfalzner, S. & Olczak, C. 2007a, A&A, 462, 193

Pfalzner, S. & Olczak, C. 2007b, A&A, 475, 875

Pfalzner, S., Olczak, C., & Eckart, A. 2006, A&A, 454, 811

Rice, W. K. M., Lodato, G., Pringle, J. E., Armitage, P. J., & Bonnell, I. A. 2004, MNRAS, 355, 543

Rice, W. K. M., Lodato, G., Pringle, J. E., Armitage, P. J., & Bonnell, I. A. 2006, MNRAS, 372, L9