Toward Understanding Massive Star Formation

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ARI ITA LSW

Overview

Massive star formation

1. Introduction
2. Key observations
3. Theoretical description
4. Differences to low-mass star formation

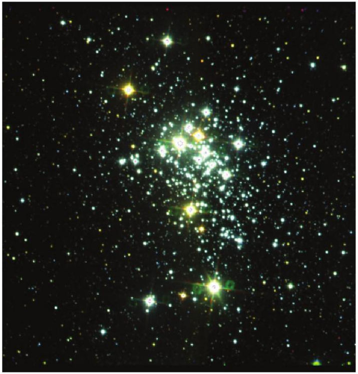

Figure: Composite image of Westerlund 1 obtained by ESO NTT. Probably the most massive young star cluster in our galaxy ($2 \times 10^4 \ M_\odot$)

Definitions

Massive star definitions (by the authors):

Mass	Designation	Sp. type
8–16 $M_\odot$	Early B-type massive stars	B3V to B0V
16–32 $M_\odot$	Late O-type massive stars	O9V to O6V
32–64 $M_\odot$	Early O-type massive stars	O5V to O2V[a]
64–128 $M_\odot$	O/WR-type massive stars	WNL-H[b]

Figure: Main-sequence massive star definitions. Focus of this talk.

and the even more massive ones,

- $100 < M_*/M_\odot < 1000$: very massive star (VMS)
- $1000 < M_*/M_\odot < 10^4$: ultramassive star (UMS)
- $10^4 < M_*/M_\odot < 10^8$: supermassive star (SMS)

which are expected not to play a role in the present epoch of star formation.

The importance of massive stars and the problems

Massive stars play a very important role in the evolution of the universe.

- Principal source of heavy elements
- Winds, massive outflows, expanding HII regions and SN explosions
- Principal source of heating in the ISM
- Cosmic rays, UV radiation
- Dissipation of turbulence

Observing massive stars is very difficult

- High dust extinction
- Massive stars are rare
- Extremely fast evolution
- Mostly non-isolated objects

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Observations: Birthplaces

Massive star formation takes place in giant molecular clouds.
Dense, compact clumps with high column densities are needed. $(10^{23} - 10^{24} \mathrm{cm}^{-2})$
One distinguishes:

1. IR dark clouds
2. Hot molecular cores
3. Hypercompact, ultracompact HII regions
4. Compact and classical HII regions

This sequence reflects the evolution of massive star formation.

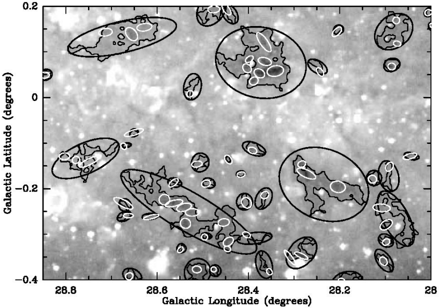


Figure: Simon et al. 2006, Identifying IRDC's from mid-IR background in the galaxy

Observations: Endproducts

The result of massive star formation reveals itself in different forms:

- OB star clusters
  - contain 1, 10 or 100 O-type stars per cluster
  - $M \sim 10^3, \; 10^4, \; 10^5 \; M_\odot$
- OB associations
  - widely spread OB stars
  - separated clusters
  - superposition of extended clusters?
- Field OB stars
  - Ejected runaway OB stars ($\mathrm{v} \sim 40\mathrm{km\ s}^{-1}$)
  - Isolated OB stars

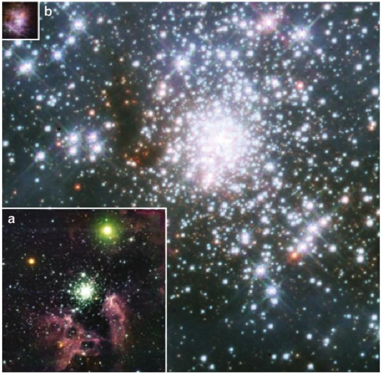


Figure: HST optical/IR image of R136/30Dor, a massive young cluster. a.) VLT image of NGC 3603, b.) VLT image of the Trapezium cluster in Orion

Observations: Further Implications

Observations indicate:

- Massive stars seem to have a high multiplicity
- The IMF seems to follow the Salpeter slope $\left(\frac{dN}{d\log M} \sim M^{-x} \text{ with } x = 1.35\right)$
- Different studies agree on the existence of an upper mass limit ($\sim 150\ M_\odot$)
- The role of feedback and triggering is very important but not well understood

Mass range	Logarithmic slope		
	$x = 1$	$x = 1.35$	$x = 1.7$
0.5–1 $M_\odot$	128	700	3822
1–2 $M_\odot$	64	275	1176
2–4 $M_\odot$	32	108	362
4–8 $M_\odot$	16	42	111
8–16 $M_\odot$	8	16.6	34.3
16–32 $M_\odot$	4	6.5	10.6
32–64 $M_\odot$	2	2.55	3.25
64–128 $M_\odot$	1	1	1

Theoretical model of (massive) star formation

The formation process can be divided into four different phases:

Compression

Formation of molecular cores

Collapse

Gravity wins

Accretion

Towards the main-sequence

Disruption

A star in its habitat

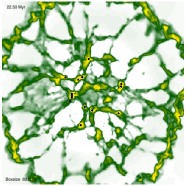
$$\text{CDMC} \rightarrow \text{HDMC} \rightarrow \text{DAMS} \rightarrow \text{FIMS}$$

This four phases can occur simultaneously in a big molecular cloud.
Modelling it altogether is impossible right now.

Compression

Production of cold dense cores or filaments.

- Main ingredients in this scenario are:
  - Gravity
  - Turbulence
  - Magnetic fields
- Turbulence produces localised, compressed pockets of gas
- Turbulence-supported quasi-equilibrium
- Gravitationally bound
- Starless cores: $M \sim 100 \ M_\odot$
- Starless clumps: $M \sim 1000 \ M_\odot$
- In simulations turbulence needs to be driven



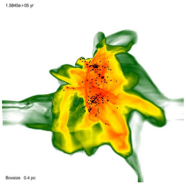


Figure: Simulations of the ITA star formation group. Thanks to Robi Banerjee.

Collapse

- In a cold dense core gravity fights against:
  - gas pressure
  - magnetic forces
  - turbulence
  - rotation
- In the simplest case the Jeans mass reads:

$$M_{\rm Jeans} \simeq 1.1 M_\odot \left[\frac{T_{\rm gas}}{10K}\right]^{3/2} \left[\frac{\rho}{10^{-19}\ \ {\rm g\ \ cm^{-3}}}\right]^{-1/2}$$

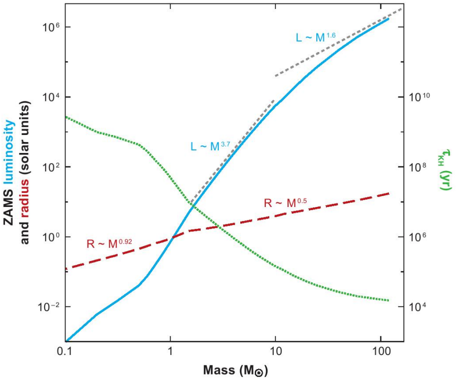
- The core collapses on a free-fall timescale:

$$t_{\rm ff} \simeq 2.1 \times 10^5\ \ {\rm yr} \left[\frac{\rho}{10^{-19}\ \ {\rm g\ \ cm^{-3}}}\right]^{-1/2}$$

- When the densest part become optically thick, the pressure increases dramatically

Accretion

- Due to angular-momentum conservation an accretion disk is built up
- The core reaches an accreting quasi-hydrostatic condition
- It starts contracting on the Kelvin-Helmholtz timescale, while further accreting
- The core may produce outflows and winds and to form a massive star we have:



$$M_* = \int_0^t \left[\dot{M}_{acc}(t') - \dot{M}_{wind}(t')\right] \mathrm{d}t' \gtrsim 8 M_\odot$$

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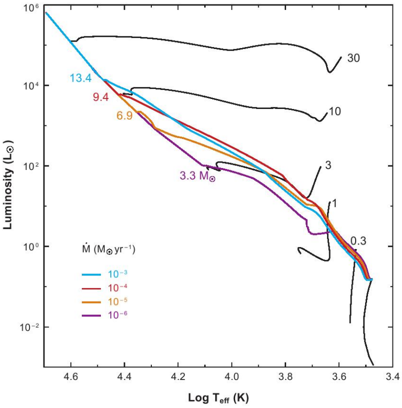

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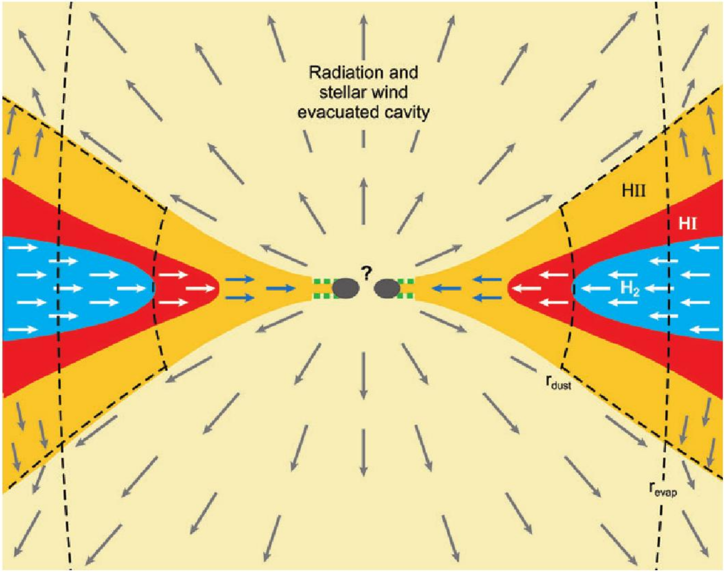
Disruption


Radiation and
stellar wind
evacuated cavity
?
HII
HI
H_2
r_{dust}
r_{evap}

Competing models

Monolithic collapse

- "Standard" isolated formation, via accretion disk.
- Yorke & Sonnhalter (2002): "production" of massive stars.
- All mass is gathered before the formation process.
- Photoevaporation finally destroys the disk.

Competitive accretion

- The cloud environment is taken into account.
- Real estate and capitalism: *location, location, location* *the rich get richer*.
- Can explain the IMF (Bondi-Hoyle rate)
- Stellar collisions and mergers may also play a role.

The truth, as usual, seems to lie somewhere in between.

Differences to low-mass star formation

High-mass star formation is not a scaled-up version of low-mass star formation:

- Radiative forces on gas and dust play an important role:
  - Substantial fraction of the total luminosity.
  - Photoevaporation of the envelope and accretion disk.

  ⇒ Producing massive stars is difficult.

  ⇒ Upper mass limit might only be beaten by star collisions and mergers.
- High-mass stars are immediately born on the main sequence.
- Competitive accretion might play a bigger role.
- Massive stars have a much bigger influence on the environment and can trigger star formation.
  - Expanding HII regions.
  - Stellar winds.
  - Supernovae explosions.

NGC 3603

Figure: HST/ACS

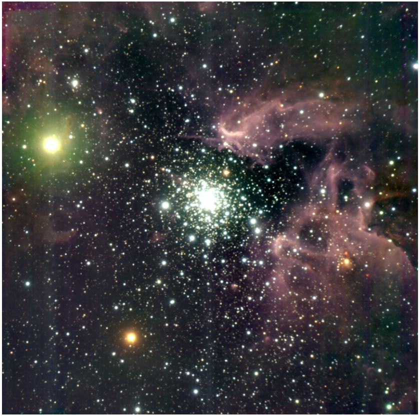


Figure: VLT/ISAAC

Thanks to Stefan Vehoff (ITA).

NGC 3603

Figure: HST/ACS

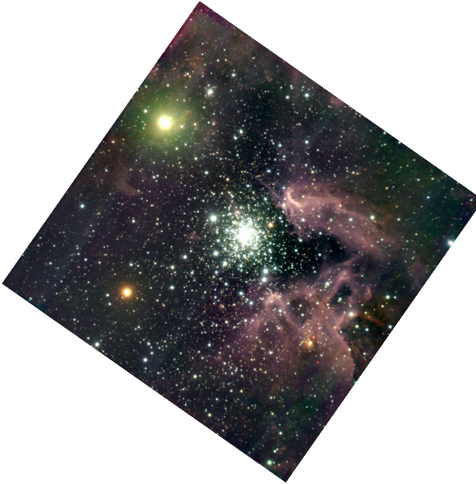


Figure: VLT/ISAAC

Summary

1. Massive stars have masses of 8 to $\sim 150\ M_\odot$.
2. Due to feedback processes, they have huge influence on their environment
3. They are born in molecular clouds and often end up in star clusters, but also in isolation.
4. Theoretical models which produce massive stars exist, but details are still unclear
5. Massive star formation is very different from low-mass star formation, mostly due to rapid evolution and feedback.