Massive Stars – Formation and Feedback

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Outline

Introduction

Why to study massive stars?

Massive stars are interesting subject to study

- short lifetime (order of Myr, compare to Sun's 10^{10} years)
- strong influence on the surrounding environment
- can work as triggers for further star formation

Upper mass limit is still unknown

- models of initial mass function are dependent on models of their formation
- observation show evidence for stars having about 150 $M_{\odot}$ (Figer 2005), but the upper limit suffers from uncertainty

What we know and what we don't

- what is the upper mass limit and which mechanisms determine it
- how do these massive stars form and what processes play role in their interactions with interstellar medium
- can the feedback processes succesfully prevent acretion onto forming star

Feedback processes

- stellar winds, collimated outflows
- disk accretion
- radiation field emerging from the star and from accretion flow

Spherically symetric accretion
Wolfire & Cassinelli 1986, 1987

- accretion flow in spherical symmetry onto main sequence star (which is good approximation as massive stars enter the MS while still accreting)
- radial structure of the model:
  - closest to star – region of ionised hydrogen (HII)
  - shell of neutral hydrogen (assumed zero opacity)
  - gas-dust mixture at radius with temperature low enough for dust grains to survive
- radiation field is split into stellar (accretion shock) and diffuse component
- dust grain (graphite, silicates) size distribution $n_i(a)\,\mathrm{d}a = C_i a^{-3.5}\,\mathrm{d}a$ from Mathis, Rumpl & Nordsieck 1977 (MRN)

Spherically symetric accretion (cont.)

Wolfire & Cassinelli 1986, 1987

Results

Conditions necessary for massive star formation

- the mechanism, which prevents accretion is radiative force acting on dust particles in the gas cloud
- to allow accretion, the abundance of dust shoud be about 4 times lower than its standard value in Galaxy and the maximal grain size must be decreased
- inflow rate must by higher than $10^{-3}\,\mathrm{M}_{\odot}\mathrm{y}^{-1}$ (turbulence in initial cloud)
- upper mass limit for standard conditions in star-forming clouds is about $30\,\mathrm{M}_{\odot}$

Breaking the symmetry - turbulent core accretion

Mc Kee & Tan 2003

- model of turbulent accreting core
  - inner part – thermal motions
  - outer part – turbulent (supersonic) motions
- time for massive star formation is about 10^5 y with very weak dependence on stellar mass
- accretion rate is increasing with time ($\dot{m}_* \propto t$) and reaches $10^{-3}\,\mathrm{M_\odot y^{-1}}$ for the most massive stars
- massive stars join the main sequence having the mass about $20\,\mathrm{M_\odot}$

Let's go further
Yorke & Sonnhalter 2002

- axisymmetric 2-D nested grid (3 levels)
  - outer boundary of the grid - inflow/outflow allowed
  - boundary of innermost grid cell - inflow adding the mass to accreting star
- initial slow rotation
- modelling the disk using α-prescription for viscosity (Shakura & Sunyayev 1973) with local sound speed c_s and angular velocity Ω

$$\nu = \alpha c_s(r) H(r) = \alpha c_s(r)^2 / \Omega(r)$$

- MRN dust distribution concerning carbon particles, silicates and ice-coated silicates
- flux limited diffusion
- two solutions are calculated: gray approximation, frequency-dependent solution (treating scattering coefficients for all species simultaneously for all frequencies)
- initial clump masses $30\,M_\odot$, $60\,M_\odot$ and $120\,M_\odot$

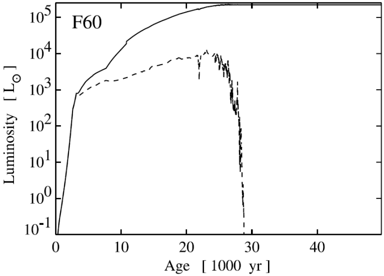
Let's go further (cont.)

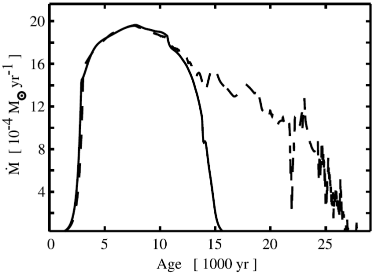
Yorke & Sonnhalter 2002

Luminosity and accretion rate (for 60 $M_\odot$ cloud)

Left figure: Total (solid line) and accretion (dashed line) luminosity vs. time(frequency dependent solution)

Right figure: Accretion rate vs. time for frequency dependent solution (dashed) and gray approximation solution (solid line)





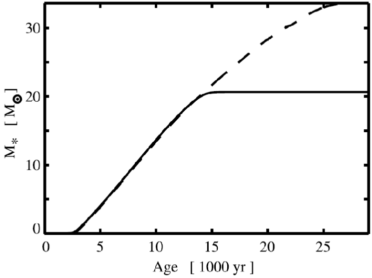
Let's go further (cont.)

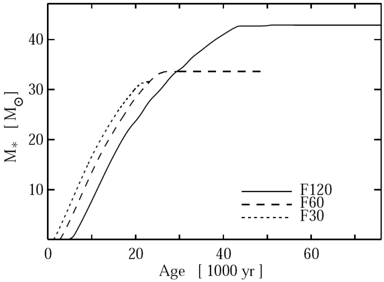
Yorke & Sonnhalter 2002

Evolution of stellar mass (for 60 $M_\odot$ cloud)

Left figure: Central mass of accreting object in grey approximation (solid line) and frequency dependent solution (dashed line)

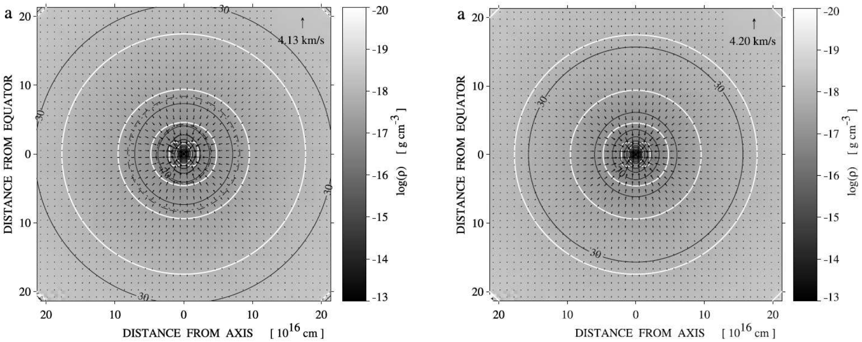
Right figure: Final mass (frequency dependent solution) for 30, 60 and 120 $M_\odot$ clumps





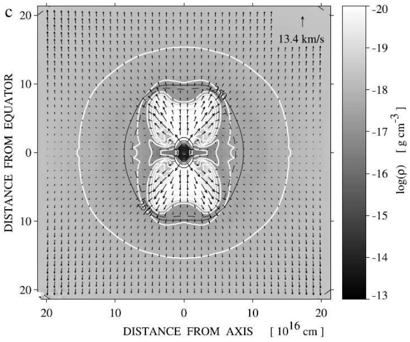
Let’s go further (cont.)
Yorke & Sonnhalter 2002

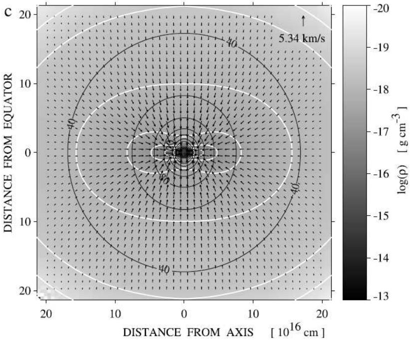
Density (grey scale, white contours), velocity and temperature of carbon (black contours) and silicate grains (dotted contour lines) for frequency dependent (left panel) at 10 ky and grey solution (right panel) at 10 ky.



Let's go further (cont.)
Yorke & Sonnhalter 2002

Density (grey scale, white contours), velocity and temperature of carbon (black contours) and silicate grains (dotted contour lines) for frequency dependent (left panel) at 25 ky and grey solution (right panel) at 35 ky.

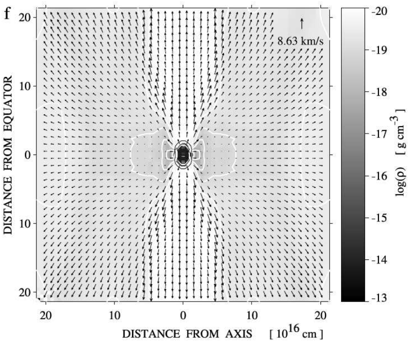




Let's go further (cont.)

Yorke & Sonnhalter 2002

Density (grey scale, white contours), velocity and temperature of carbon (black contours) and silicate grains (dotted contour lines) for frequency dependent (left panel) at 45 ky and grey solution (right panel) at 110 ky.



The flashlight effect
Krumholz, Mc Kee & Klein 2005

Motivation

Not only the polar concentration of radiation, but also the polar outflows are to be taken into account as shown from observations (Beuther & al. several papers).

- $50\,\mathrm{M}_\odot$ ZAMS ($\mathrm{R}_* = 10.8\,\mathrm{R}_\odot$, $\mathrm{T}_* = 4.3 \times 10^4\,\mathrm{K}$, $\mathrm{L}_* = 3.5 \times 10^5\,\mathrm{L}_\odot$) star placed in $50\,\mathrm{M}_\odot$ envelope (with bipolar cavity extending from the edge of the core)
- accretion rate $\dot{M}_* = 5 \times 10^{-4}\,\mathrm{M}_\odot \mathrm{y}^{-1}$
- accretion luminosity is negligible (order lower compared to L_*)
- given density and velocity distribution (neglecting turbulence) in the core

$$\rho = -\frac{\dot{M}_*}{4\pi r^2 u_r}\left[1 + 2\frac{R_{\mathrm{cen}}}{r} P_2(\cos\theta_0)\right]^{-1}, u_r = -\left(\frac{2GM_*}{r}\right)^{1/2}\left(1 + \frac{\cos\theta}{\cos\theta_0}\right)^{1/2},$$

$$\frac{R_{\mathrm{cen}}}{r} = \frac{\cos\theta_0 - \cos\theta}{\sin^2\theta_0 \cos\theta_0}$$

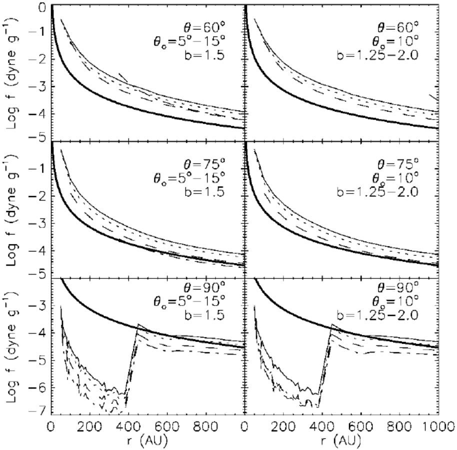
The flashlight effect (cont.)
Krumholz, Mc Kee & Klein 2005

Radiation transfer through the dust envelope

- Kurucz model atmosphere
- Monte Carlo diffusion
- solving radiation transfer eqn. along each ray, computing the flux
- examine flux convergence when increasing the number of rays
- calculating the radiative force integrating the flux over frequency
- changing parameters of cavity (which determine its shape)

The flashlight effect (cont.)
Krumholz, Mc Kee & Klein 2005

Dependence of radiation pressure force on radius r for different values of angle θ for model without wind cavity (thick solid line) and with the cavity (with changing opening angle θ_0 and curvature β)



3-D simulations – new effects comming in
AMR – Adaptive Mesh refinement

AMR is the technique which allow to perform simulation of fine details without increasing computational/memory demands over reasonable limits. Compared to nested grid, the grid in AMR is dynamical scalable structure.

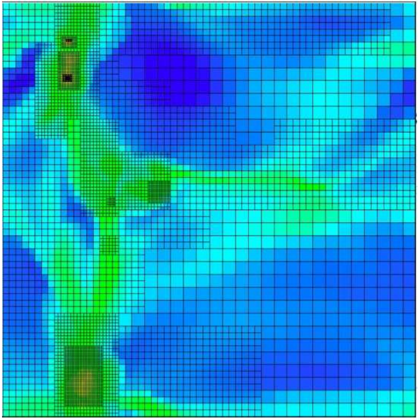


image courtesy: http://www.isgtw.org/?pid=1001250

3-D simulations – new effects comming in
Krumholz, Klein & Mc Kee 2005

- 3-D simulation of slowly rotating centrally condensed cores having 100–200 $M_\odot$ using AMR
- gray, flux-limited diffusion approximation of radiation transfer
- 6 components of dust according (Pollack et al. 1994)

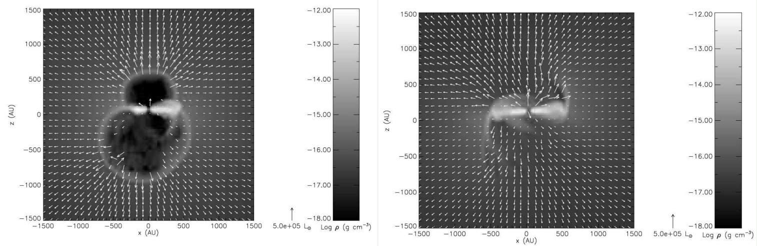
Key findings

- stellar luminosity begins repeling gas at 17–20 $M_\odot$
- radiation bubble is created
  - the bubble is growing asymmetrically (no such evidence in 2-D models)
  - collimation of radiation into the cavity (optically thin)
  - infall of the matter around the bubble to (optically thick) disk in equatorial plane

3-D simulations – new effects comming in

Krumholz, Klein & Mc Kee 2005

Radiation driven bubble



- when star grows to 22–26 $M_{\odot}$, the bubble tends to collapse due to Rayleigh-Taylor instability and allows additional matter to acrete
- the radiation is still beamed to polar directions

State-of-the-art simulations, creation of multiple stars

Krumholz et al. 2009

Simulation setup

- initial cloud with 100 $M_\odot$, radius 0.1 pc and density profile $\rho \propto r^{-1.5}$, initial temperature T=20 K slowly rotating (rotational kinetic to gravitational binding energy ratio 0.02)
- turbulence was not included
- full 3-D AMR treatment, gray flux-limited diffusion approximation of radiative transfer (lower computational complexity)
- grid cells at highest resolution with density exceeding the Jeans density were treated as (proto)stars (additional luminosity sources)

State-of-the-art simulations (cont.)

Krumholz et al. 2009

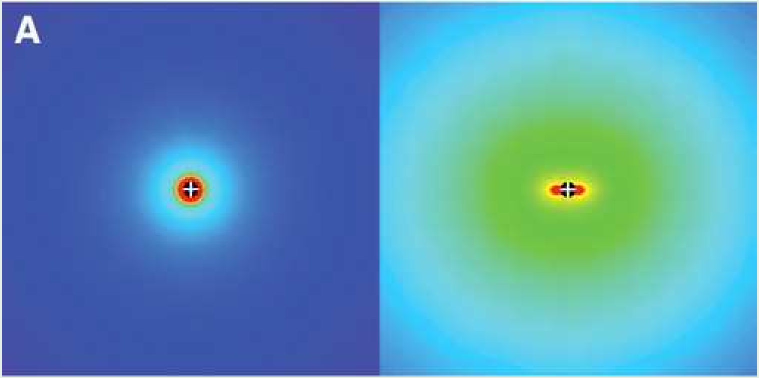
Simulation evolution and output

1. immediate collapse of initial cloud, formation of central protostar at 3.6 ky
2. smooth accretion via disk for following 17 ky increasing the central star mass to 11 $M_\odot$ (luminosity bellow 10^4 $L_\odot$, radiation pressure negligible)
3. after 20 ky the disk starts to become gravitationally unstable forming two spiral arms
4. accretion remains smooth, at approx. 17 $M_\odot$ (at about 25 ky) the radiation pressure exceeds the gravity and the bubble is formed in polar directions
5. at this phase, the matter accretes along the bubble walls, in disk small secondary stars are created, but due to dynamical friction, they advect in the center collide with the central star (accretion rate is now variable, but its mean value is unchanged)

State-of-the-art simulations (cont.)

Krumholz et al. 2009

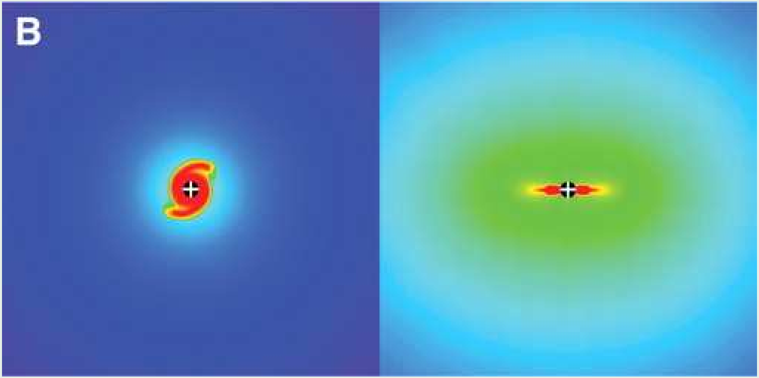
Simulation evolution and output



State-of-the-art simulations (cont.)

Krumholz et al. 2009

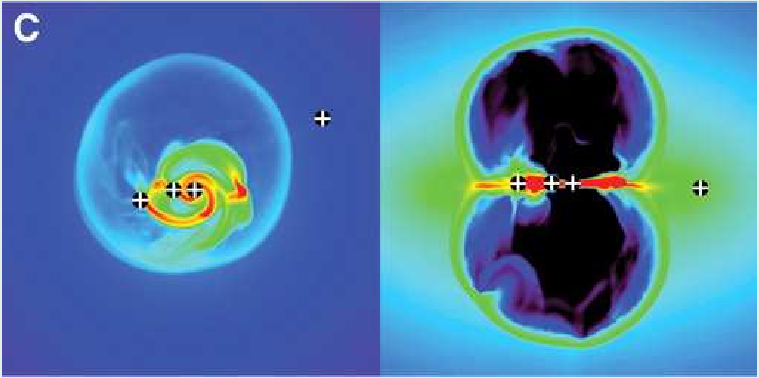
Simulation evolution and output



State-of-the-art simulations (cont.)

Krumholz et al. 2009

Simulation evolution and output



State-of-the-art simulations (cont.)

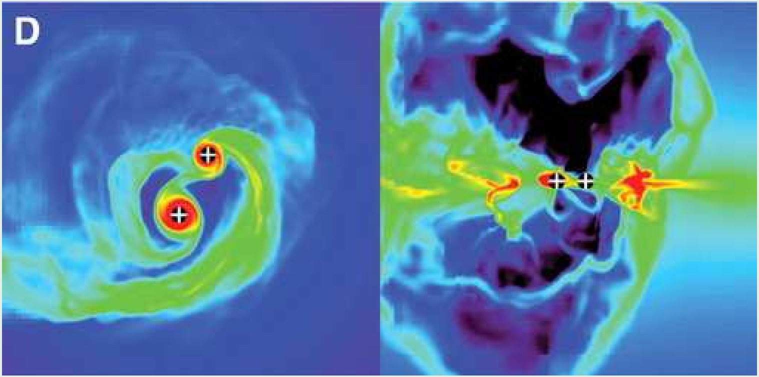
Krumholz et al. 2009

Simulation evolution and output

6. at 35 ky survivied stars in disk collide and form one object, which is able to survive in vicinity of the central star
7. this star creates its own disk and starts to accrete matter up to mass ratio over 0.5
8. mean total accretion rate onto both stars is roughly the same as before binary formation
9. the bubble exhibits instability, while it continues in slow expansion
10. At time of 57 ky (end of simulation) the qualitative state of system is conserved. Stars have masses $42\,M_\odot$ and $29\,M_\odot$ and the accretion via disk slowly continues. Semimajor axis is 1280 AU, excentricity 0.25 (typical for young O–type stars). The accretion continues to final masses approx. $47\,M_\odot$ and $32\,M_\odot$.

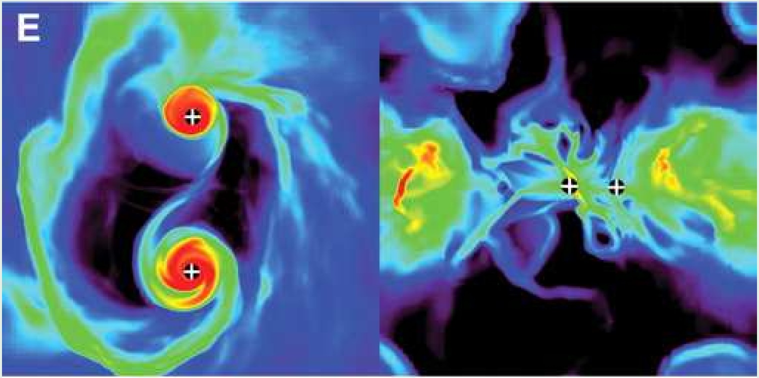
State-of-the-art simulations (cont.)
Krumholz et al. 2009

Simulation evolution and output



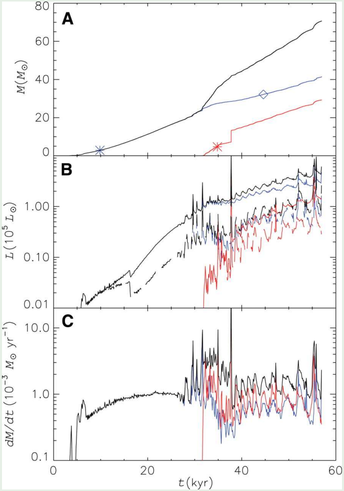
State-of-the-art simulations (cont.)
Krumholz et al. 2009

Simulation evolution and output



State-of-the-art simulations (cont.)
Krumholz et al. 2009

Simulation evolution and output



Summary and Conclusions

- formation of high mass stars have long been not fully understood
- every improvement in used physical model brought new findings
- proper simulations are still very computational expensive
  - full 3-D numerics employing AMR techniques
  - carefull treatment of dust properties
  - solving the radiation-transfer is still handled in rather approximative way and provides possibilities for improvements
- however, according to current results it seems, that radiation pressure exerting on dust particles around young forming massive stars does not necessarily stop the accretion and cut-off final mass of the star

Plans for Our Work

- Krtička & Kubát published in 2006 paper about winds of the first (zero-metallicity) stars. The environment around the first stars is pretty much different compared to further stellar generations. We want to study the interaction of radiation of first stars with accretion flow. The aim is to examine, whether the line-radiative force can modify the properties of the accretion flow onto the first hot stars.
- the first results shoud appear :) at IAU Symposium 270 – Computational Star Formation (Barcelona, May 31 – June 4 2010)

Thank you for your attention!