Possible Lessons from Present-Day Star Formation

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agenda

- some phenomenology
- processes that influence present-day SF and their possible relevance for high-z SF:
  - turbulence
  - thermodynamics
  - magnetic fields
  - feedback
example: Orion

We see

• *Stars* (in visible light)

• Atomic hydrogen (in Hα -- red)

• Molecular hydrogen H₂ (radio emission -- color coded)

lets look at the Orion Nebula Cluster (ONC)
The Orion molecular cloud is the birthplace of several young embedded star clusters. The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.
example: Orion

Trapezium Cluster

- stars form in clusters!
- stars form in molecular clouds!
- (proto)stellar feedback is important!

(color composite J,H,K by M. McCaughrean)
NGC 602 in LMC

*end of formation phase*: star cluster with H II region
stellar mass function

Orion, NGC 3603, 30 Doradus (Zinnecker & Yorke 2007, ARAA, 45, 481)

(Kroupa 2002, Science, 295, 82)
nearby molecular clouds

- Orion
- Perseus
- Ophiuchus
- Taurus
- Pipe

scales to same scale

let's have a closer look

(from A. Goodman)
image from Alyssa Goodman: COMPLETE survey
agenda

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  - turbulence
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- some phenomenology

- processes that influence present-day SF and their possible relevance for high-z SF:
  - turbulence plus cluster environment
  - thermodynamics
  - magnetic fields
  - feedback
example: model of Orion

„model“ of Orion cloud:
15,000,000 SPH particles, 
$10^4 \, M_{\odot}$ in 10 pc, mass resolution $0,02 \, M_{\odot}$, forms
~2,500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)

(calculation by Ian Bonnell & Paul Clark)
explaination: model of Orion

„model“ of Orion cloud:
15.000.000 SPH particles,
$10^4 \, M_{\text{sun}}$ in 10 pc, mass
resolution $0.02 \, M_{\text{sun}}$, forms
$\sim 2.500 \, \text{„stars“} \, (\text{sink particles})$

MASSIVE STARS
- form early in high-density
  gas clumps (cluster center)
- high accretion rates,
  maintained for a long time

LOW-MASS STARS
- form later as gas falls into
  potential well
- high relative velocities
- little subsequent accretion

(calculation by Ian Bonnell & Paul Clark)
in dense clusters protostellar interaction may be come important!

Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
turbulence leads to fragmentation

this is true even for $Z=0$ (see talk by Paul Clark)
turbulence leads to fragmentation

this is true even for Z=0

(see talk by Paul Clark)
turbulence leads to fragmentation

- this is true even for Z=0 (see talk by Paul Clark)

- full stellar mass range from brown dwarf regime onwards?

- it could be that Pop III.2 stars are more massive than Pop III.1

- key questions: which processes could prevent or weaken fragmentation?
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EOS as function of metallicity

present-day star formation

\( \tau = 1 \)

\( Z = 0 \)

This kink in EOS is very insensitive to environmental conditions such as ambient radiation field --> reason for universal for of the IMF?


**IMF from simple piece-wise polytropic EOS**

\[ \gamma_1 = 0.7 \]

\[ \gamma_2 = 1.1 \]

\[ T \sim \rho^{\gamma - 1} \]

**EOS and Jeans Mass:**

\[ p \propto \rho^\gamma \Rightarrow \rho \propto p^{1/\gamma} \]

\[ M_{\text{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma - 4)/2} \]

IMF in nearby molecular clouds

$\rho_{\text{crit}} \approx 2.5 \times 10^5 \text{ cm}^{-3}$

at SFE $\approx 50$

need appropriate EOS in order to get low mass IMF right

IMF shape and universality

- combine scale free process $\rightarrow$ POWER LAW BEHAVIOR
  - gravity in dense clusters (Bonnell & Bate 2006, Klessen 2001)
  - universality: dust-induced EOS kink insensitive to radiation field (Elmegreen et al. 2008)

- with highly stochastic processes $\rightarrow$ central limit theorem
  $\rightarrow$ GAUSSIAN DISTRIBUTION
  - basically mean thermal Jeans length (or feedback)
  - universality: insensitive to metallicity (Clark et al. 2010, submitted)
transition Pop III to Pop II.5

what is more relevant? metal-line cooling or dust cooling?

dependence on $Z$ at low density

- at densities $n < 10^2 \text{ cm}^{-3}$ and metallicities $Z < 10^{-2}$
  - $H_2$ cooling dominates behavior.
  - (Jappsen et al. 2007)

- fragmentation depends on initial conditions
  - example 1: solid-body rotating top-hat initial conditions
    - with dark matter fluctuations (a la Bromm et al. 1999) fragment no matter what metallicity you take (in regime $n \leq 10^6 \text{ cm}^{-3}$) → because unstable disk builds up
    - (Jappsen et al. 2009a)

  - example 2: centrally concentrated halo does not fragment up to densities of $n \approx 10^6 \text{ cm}^{-3}$ up to metallicities $Z \approx -1$
    - (Jappsen et al. 2009b)
transition Pop III to Pop II.5

- Star formation will depend on the degree of turbulence in protogalactic halo (see talk by Paul Clark).

- Speculation: differences in stellar mass function?

- Speculation:
  - Low-mass halos $\rightarrow$ low level of turbulence $\rightarrow$ relatively massive stars?
  - High-mass halos (atomic cooling halos) $\rightarrow$ high degree of turbulence $\rightarrow$ wider mass spectrum, peak at lower-masses?

turbulence developing in an atomic cooling halo


see also talk by Thomas Greif
turbulence developing in an atomic cooling halo


see also talk
by Thomas Greif
transition: Pop III to Pop II.5

on the dust-induced cooling dip: see also poster by Gustavo Dopcke

dust induced fragmentation at $Z=10^{-5}$

$\Delta = t_{SF} - 67 \text{ yr}$

$\Delta = t_{SF} - 20 \text{ yr}$

$\Delta = t_{SF}$

$\Delta = t_{SF} + 53 \text{ yr}$

$\Delta = t_{SF} + 233 \text{ yr}$

$\Delta = t_{SF} + 420 \text{ yr}$

400 AU

dust induced fragmentation at $Z=10^{-5}$

dense cluster of low-mass protostars builds up:

- mass spectrum peaks below $1 \, M_{\text{sun}}$
- cluster VERY dense
  $n_{\text{stars}} = 2.5 \times 10^9 \, \text{pc}^{-3}$
- fragmentation at density
  $n_{\text{gas}} = 10^{12} - 10^{13} \, \text{cm}^{-3}$

binary fragmentation \((Z=10^{-4})\)

(Machida et al. 2009, 399,1255)
dust induced fragmentation at $Z=10^{-5}$

- mass spectrum peaks below $1 \, M_{\odot}$
- cluster VERY dense
  $n_{\text{stars}} = 2.5 \times 10^9 \, \text{pc}^{-3}$

- predictions:
  * low-mass stars with $[\text{Fe/H}] \sim 10^{-5}$
  * high binary fraction

Dust induced fragmentation at $Z=10^{-5}$

- Mass spectrum peaks below $1 \, M_{\odot}$
- Cluster very dense $n_{\text{stars}} = 2.5 \times 10^9 \, \text{pc}^{-3}$

- Predictions:
  * Low-mass stars with $[\text{Fe/H}] \sim 10^{-5}$
  * High binary fraction

(Plot from Salvadori et al. 2006, data from Frebel et al. 2005)

caveats / questions

how good is EOS approach?
- time to reach chemical + thermal equilibrium shorter than dynamical time?
- how does EOS depend on dynamics? (e.g. 1D collapse with large-gradient approx. versus complex 3D turbulent flows)

how important is heating from stars?
- accretion luminosity may heat gas and reduce degree of cloud fragmentation (cluster formation vs. high-mass SF)

how can we model that best?
- full radiation transfer vs. approximate schemes
effects of accretion heating

how important is heating from stars?

accretion luminosity may heat gas and reduce degree of cloud fragmentation (cluster formation vs. high-mass SF)

HOWEVER: the effect is NOT large (see poster by Rowan Smith)

fragmentation of Pop III disk (Z=0) without accretion heating
--> fragmentation radius 10.4 AU

fragmentation of Pop III disk (Z=0) with accretion heating
--> fragmentation radius 18.9 AU
Evolution of the protostellar disc

No stellar feedback

$t \sim t_{SF}$

$t \sim t_{SF} + 150\text{yr}$

With stellar feedback

$t \sim t_{SF}$

$t \sim t_{SF} + 230\text{yr}$

$66\text{ au}$
metall-free star formation

\( \tau = \) 

\( Z = -\infty \)

first disks are expected to fragment!

halos have large angular momentum \(\rightarrow\) disk forms around first protostar \(\rightarrow\) roughly isothermal disk are known to be unstable (see talk by Paul Clark)


also turbulence may lead to fragmentation!

(see talk by Paul Clark)

do first all first stars form in small clusters? what is the IMF?
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effects of magnetic fields

- magnetic fields can
  - suppress disk fragmentation
  - drive jets and outflows
  - induce additional turbulence (MRI / dynamo)
  - maybe present even in Z=0 gas
    - (either as primordial fields or generated by dynamo action)
  - see talk by Dominik Schleicher on Thursday

- need to be taken into account!!
effects of magnetic fields

- weak field: binary formation
- sufficient field strength: single star

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- feedback (focus on ionizing feedback)
single star: HII region and outflow

multiple protostars: dynamics of HII regions

• ionizing radiation cannot stop accretion
• however, fragmentation of disk can stop mass growth of the central star

feedback in Pop III star formation

- we expect *feedback* during PopIII protostellar collapse
  
  *NOT* to stop fragmentation (but possibly *reduce* number of fragments)

  *NOT* to prevent mass growth
  (if at all *fragmentation induced starvation* stops further mass growth)

- we expect the effects of *magnetic fields* to be potentially more important.
summary
just like in present-day SF, we expect
- turbulence
- thermodynamics
- magnetic fields
- feedback
to influence Pop III/II star formation.

masses of Pop III stars still uncertain (expect surprises from new generation of high-resolution calculations that go beyond first collapse)

disks unstable: Pop III stars should be binaries or part of small cluster

effects of feedback less important than in present-day SF
thanks!