The Fragmentation of expanding shells

Kazunari Iwasaki (Nagoya Univ.)

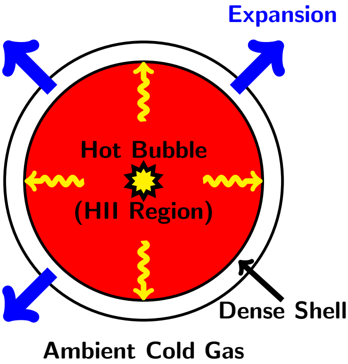
Collaborate with
S. Inutsuka (Nagoya Univ.)
T. Tsuribe (Osaka Univ.)

Outline

- Introduction
- Three Dimensional SPH Simulations
  - Expansion of shells
- Linear Analysis
  - to understand the results of 3-D simulations.
- Discussion
- Summary and Future Works

Radiative Feedback

- Massive stars emit ionizing (> 13.6 eV) and dissociating ($11 < h\nu < 13.6$ eV) photons
- can work as both positive and negative feadbacks for star formation.



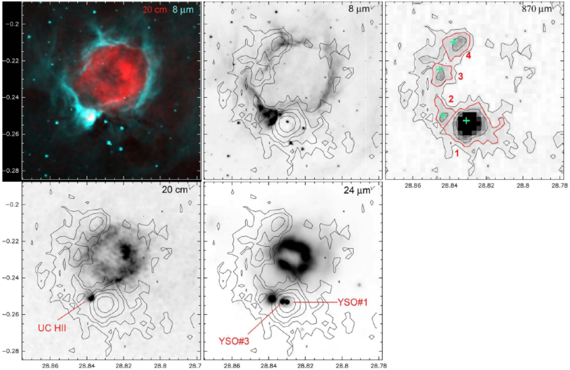
- **Positive Feedback**
  (Elmegreen & Lada '77)
  - over-pressured hot bubble
  - shock wave sweeps up molecular clouds into dense shells
    ⇒ Gravitational Instability (GI)
    ⇒ Star Formation

- **Negative Feedback** (Whitworth '79)
  - UV and FUV photons erode molecular clouds through dissociation and ionization, respectively
    ⇒ suppress star formation

Observations

- **Deharveng et al. (2010)**
  - **selected 102 bubbles.**
  - **show that 86% of these bubbles enclosed HII regions.**
  - **more than 20% of 64 bubbles (the angular resolution is sufficient) show massive star formation on their borders!**

An example, N49



1-D Numerical Simulation

- **Hosokawa & Inutsuka (2005, 2006)**
  - **One-dimensional Radiative Hydrodynamics.**
    - **Radiative Transfer of UV and FUV photons.**
    - **Solving Thermal and Chemical Processes.**

- **The PDR initially extends beyond the shell, but gradually trapped in the shell.**
- **Finally, most of the swept-up gas remains in the shell as the cold molecular gas.**
  - **reformation of molecular gas**
  - **self-shielding**
- **⇒ leading to star formation?**
- **But, gravitational fragmentation is multi-dimensional process.**

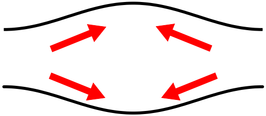
What about Multi-Dimensional Evolution ?

Linear Analysis

- isothermal gas layer confined by a hot rarefied gas on both sides.
  - Goldreich & Lynden-Bell ’65, Elmegreen & Elmegreen ’78,. . .
  - Behaviour of the GI depends on the column density.
    - In the early phase, the column density is low.

Low column density

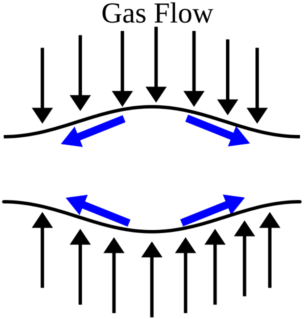
- thickness $L \ll c_s t_{\rm ff}$
- The sound wave travels the thickness many times during the development of the GI.
- ⇒ behaves like imcompressible fluid
- The gas tends to be round by the GI. But, density does not change.
- ⇒ The boundaries deform.



- However, the leading boundary of the shell is not contact discontinuity (CD) but shock front (SF).

The Effect of Shock Front

- the layer confined by shock fronts on both sides.
  - Vishniac ’83, Vishniac ’94, Whitworth et al.’94, KI & Tsuribe ’08.
- the shock fronts deform by the GI.
- tangential flow (blue arrow) is generated behind the shock front.
- tends to make the shock fronts flat.
- ⇒ stabilizes the shell



Dispersion Relation

$$\omega^2 = c_s^2 k^2 - 2\pi G k \Sigma$$

Suprisingly, the same as that of infinitly thin layer.

Expanding Shell

- **Elmegreen '94, Whitworth et al. '94**
    - **include expansion and accumulation effects of the ambient gas through SF.**
    - **neglect time evolution of the shell.**
    - **neglect the boundary effect of the CD.**
    - **thin-shell approx.**

$$i\omega = -\frac{3V}{R} + \sqrt{\left(\frac{V}{R}\right)^2 - \boxed{\left(c_s^2 k^2 - 2\pi G k \Sigma(t)\right)}}$$

V: **expansion velocity,** R: **radius of the shell.**

Criterion of the Gravitational Instability $i\omega > 0$

$$\boxed{\frac{\pi G \Sigma(t)}{c_s}} > \boxed{\sqrt{8}\frac{V(t)}{R(t)}}$$

- **Previous linear analyses are based on many assumptions.**
- **Multi-dimensional simulation is crucial**

Multi-dimensional simulation

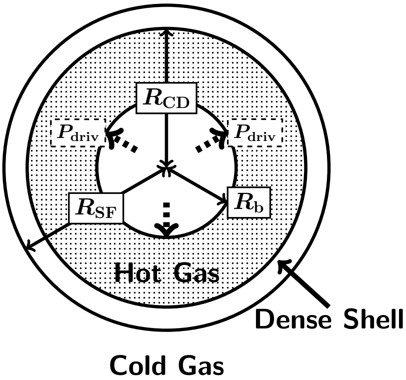
- To resolve propagating dense and thin shell all the time, AMR technique or SPH have been used.
- Since enormous meshes and SPH particles are required, researches are less advanced.

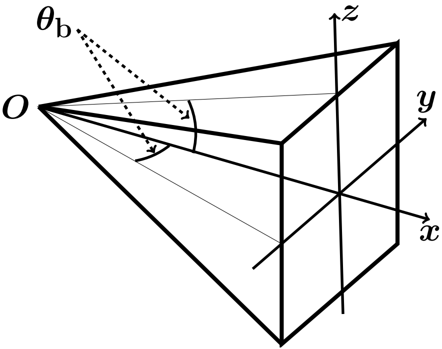
In this study

- We perform the high-resolution 3D simulation to investigate the fragmentation process of expanding shells.
- We compare the results of the 3D simulation with linear analysis.
- We present more accurate criterion of the GI.

Simulation Setup

- **do not calculate the radiative transfer of ionizing photon.**
- **but introduce cold and hot gases which evolve isothermally.**
- **Hot gas is pushed radially by a driving pressure $P_{\rm driv} \propto R_{\rm CD}^{3/2}$.**





- **To save SPH particles, we calculate not the whole but a part of the shell. $\theta_{\rm b} = 2\pi/26$ in this talk.**

Model Parameters

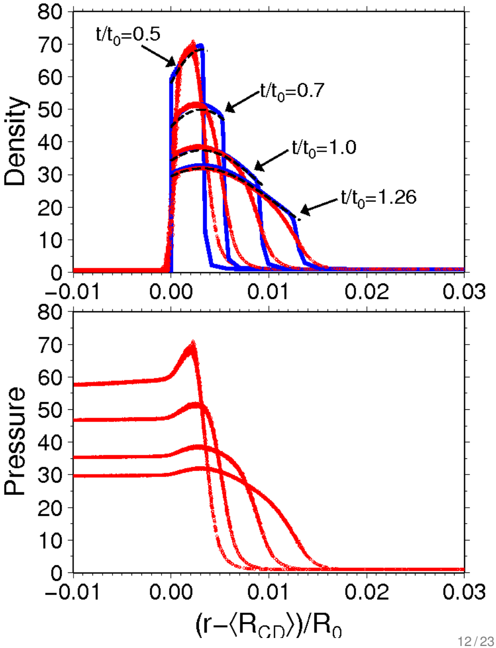
- The mass of the central star : $41 M_\odot$
  - corresponding UV photon luminosity, $Q_{\rm UV} = 10^{48.78}\ {\rm s}^{-1}$ (Diaz-Miller et al. ’98).
- the number density of ambient gas
  - the number density, $n_{\rm E} = 10^3\ {\rm cm}^{-3}$.
- Characteristic Scales (Simulation Units)

$$t_0 = \sqrt{\frac{3\pi}{32 G \rho_{\rm E}}} = 1.6\ {\rm Myr}\ \left(\frac{n_{\rm E}}{10^3\ {\rm cm}^{-3}}\right)^{-1/2},$$

$$R_0 = 5.9\ {\rm pc}\ \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{1/7} \left(\frac{n_{\rm E}}{10^3\ {\rm cm}^{-3}}\right)^{-4/7},$$

$$M_0 = \rho_{\rm E} R_0^3 = 5.0 \times 10^3\ M_\odot \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{3/7} \left(\frac{n_{\rm E}}{10^3\ {\rm cm}^{-3}}\right)^{-5/7}.$$

Without Perturbation (Test Calculation)



- **Time evolution of density and pressure profiles across the thickness.**
  - **The red circle: SPH simulation**
  - **The blue line: 1D simulation**
    1D spherically symmetric Lagrangian Godunov method.
- **The results of the 3D simulation agrees with that of 1D simulation very well although the shell is very thin.**

Perturbation

- **Corrugation-type perturbation are put into the shell.**
- **The displacement of the shell is assumed to be $\propto -\cos(l\phi)$ $\left(\phi = \tan^{-1}(y/x)\right)$. l: angular wavenumber.**
- **concentrate the evolution of a single mode in each calculation.**

Measures of Fluctuations

- **define radial unit vector $\vec{n}_i$.**
- **$\rho_{\mathrm{max}}\left(\vec{n}_i\right)$: angle-dependent maximum density along $\vec{n}_i$.**
- **$R_{\mathrm{cd}}\left(\vec{n}_i\right)$: the position of the CD along $\vec{n}_i$.**
- **average of $Q = (\rho_{\mathrm{max}}, R_{\mathrm{CD}})$ over $\vec{n}_i$ $(1 \le i \le N)$.**

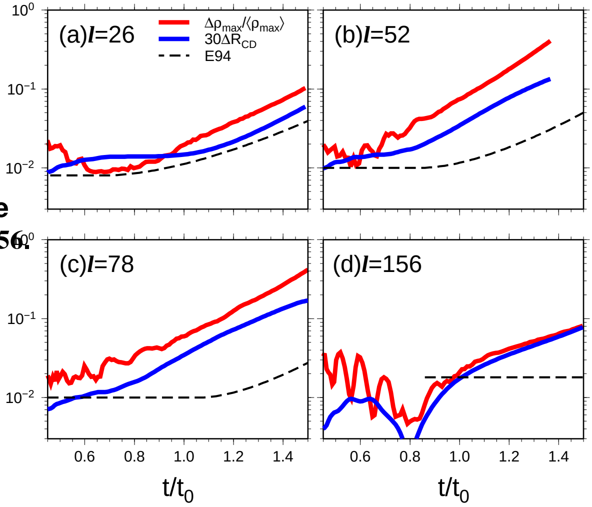
$$\langle Q\rangle = \frac{1}{N}\sum_i Q(\vec{n}_i).$$

- **dispersion**

$$\Delta Q = \sqrt{\frac{1}{N}\sum_i \left\{Q(\vec{n}_i) - \langle Q\rangle\right\}^2}.$$

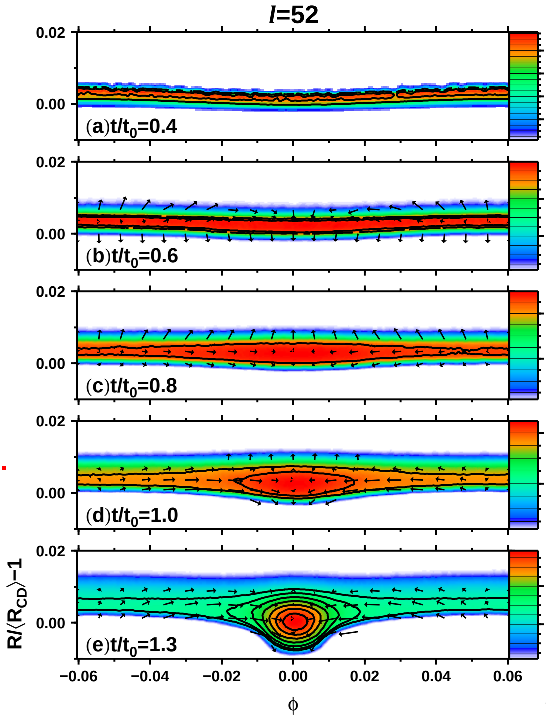
Result

- **Time evolution of the perturbation amplitude for $l = 26, 52, 78$, and 156.**
- $\Delta\rho_{\mathbf{max}}/\langle\rho_{\mathbf{max}}\rangle$
- $\Delta R_{\mathbf{CD}}$



- **Perturbations begin to grow earlier than the prediction based on Elmegreen ’94 (dashed lines).**
- **The behaviour of perturbations in the later phase roughly agrees the prediction of E94.**

- Cross sections through $z = 0$ plane of the shell.
  - color map: density.
  - arrows: velocity field.
- The CD highly deforms while the SF is almot flat.

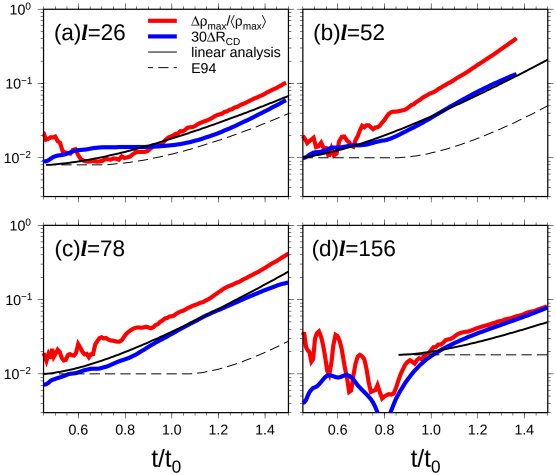


Linear analysis

- Previous linear analysis neglects the effect of the CD.
  - the same as that of the layer confined by shock fronts on both sides except for the expansion effect.
- We suggest the boundary effect of the CD destabilizes the expanding shell compared with the prediction from previous linear analysis.
- We perform a linear analysis of the expanding shell to understand the results of the SPH calculations under SF + CD boundary conditions.
  - consider the thickness
  - neglects unsteady effect
  - Unperturbed state:
    the instantaneous hydrostatic density profile at each instant of time.
  - Solve eigen- and boundary-values problem at each instant of time.
    $\Rightarrow \ \omega(k,t)$.
  - To include unsteady effects approximately,

$$i\omega = -\frac{3V}{R} + \sqrt{\left(\frac{V}{R}\right)^2 - \omega(k,t)^2}$$

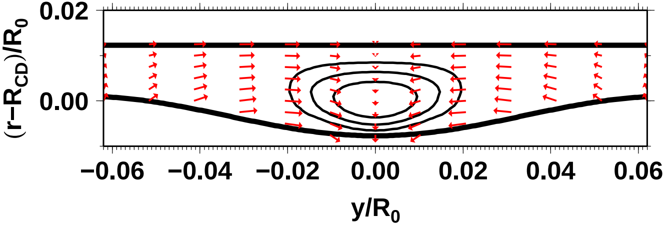
Growth Rate



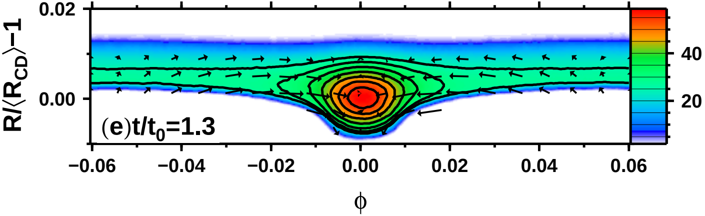
- **thin black solid line: the amplitude evaluated by our linear analysis.**
- **Our linear analysis accurately describes the results of the SPH calculations.**

Eigen-function

- **Eigen-funcitons**



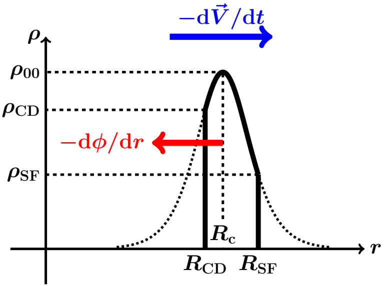
- **SPH calculation**



- **The cross seciton is similar to the results of the SPH calculations.**

Deformation of the CD

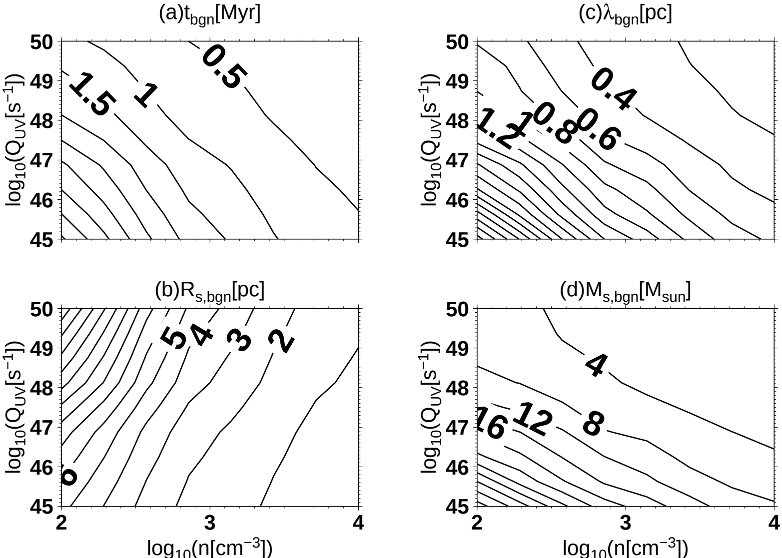
The density profile in later phase.



- **The gas tends to accumulate toward the density peak because ϕ_0 has minimum value there.**
- $R_{\mathrm{SF}} - R_{\mathrm{c}} > c_{\mathrm{s}} t_{\mathrm{ff}}$ **(compressible mode)**
  - **The gas at $> R_{\mathrm{SF}}$ can collapse to the peak leaving behind the gas around boundary.**
- $R_{\mathrm{c}} - R_{\mathrm{CD}} < c_{\mathrm{s}} t_{\mathrm{ff}}$ **(incompressible mode)**
  - **the pressure gradient prevent from collapsing. Instead, the GI grows through the deformation of the CD.**

Time When the GI Starts

- **evaluate time when the GI begins to grow by using the linear analysis.**



Fitting Formulae

- derive fitting formulae which well approximate the dependence of physical variables on $Q_{\rm UV}$, $T_{\rm c}$, and $n_{\rm E}$.

$$t_{\rm bgn} = 0.6\ {\rm Myr} \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{-3/28} \left(\frac{T_{\rm c}}{10\ {\rm K}}\right)^{3/8} \left(\frac{n_{\rm E}}{10^{3}\ {\rm cm}^{-3}}\right)^{-25/56}$$

$$R_{\rm s,bgn} = 3.4\ {\rm pc} \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{5/56} \left(\frac{T_{\rm c}}{10\ {\rm K}}\right)^{3/16} \left(\frac{n_{\rm E}}{10^{3}\ {\rm cm}^{-3}}\right)^{-61/112}$$

$$l_{\rm bgn} = 54 \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{3/14} \left(\frac{T_{\rm c}}{10\ {\rm K}}\right)^{-3/4} \left(\frac{n_{\rm E}}{10^{3}\ {\rm cm}^{-3}}\right)^{-3/28}$$

$$\lambda_{\rm bgn} = 0.4\ {\rm pc} \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{-1/8} \left(\frac{T_{\rm c}}{10\ {\rm K}}\right)^{15/16} \left(\frac{n_{\rm E}}{10^{3}\ {\rm cm}^{-3}}\right)^{-7/16}$$

$$M_{\rm bgn} = 3.5\ {\rm M}_{\odot} \left(\frac{Q_{\rm UV}}{10^{49}\ {\rm s}^{-1}}\right)^{-9/56} \left(\frac{T_{\rm c}}{10\ {\rm K}}\right)^{33/16} \left(\frac{n_{\rm E}}{10^{3}\ {\rm cm}^{-3}}\right)^{-47/112}$$

Fitting Formulae

- The dependence of physical quantities at $t = t_{\rm bgn}$ on $Q_{\rm UV}$, $T_{\rm c}$, and $n_{\rm E}$ gives close agreement with Whitworth et al. '94 (W94).
- But, $t_{\rm bgn}$, $R_{\rm s,bgn}$, and $\lambda_{\rm s,bgn}$ are roughly half those in W94.
- $M_{\rm bgn}$ is roughly $1/8$ those in W94.
- Our results predict the shell splits into many fragments ($\sim l^2_{\rm bgn}$) which mass is less than $10\ M_\odot$.
- But, observed core mass is several dozen $\sim$ several hundreds $M_\odot$. There are not so many cores under star formation.

Future Works

- Effect of supersonic turbulence in ambient molecular gas.
- Effect of thermal instability of shocked gas which can produce turbulence.
  - Supersonic velocity dispersion can suppress collapse of perturbations.
  - Coalescence between cold clouds.

Summary

Summary

- We perform three-dimensional SPH simulations of expanding shells driven by HII region.
- The gravitatioal instability begins to grow earlier than the prediction from the linear analysis under the thin-shell approximation.
- During the development of the gravitational instability, the CD highly deforms while the shock front is almost flat.
- We perform new linear analysis taking into account the thickness of the shell. It describes the results of the SPH simulations well in growth rate and eigen-functions.
- We derive useful fitting formulae of the epoch when the GI begins to grow and the fragment scale.