Triggered Star Formation: Radiative Feedback from Massive Stars

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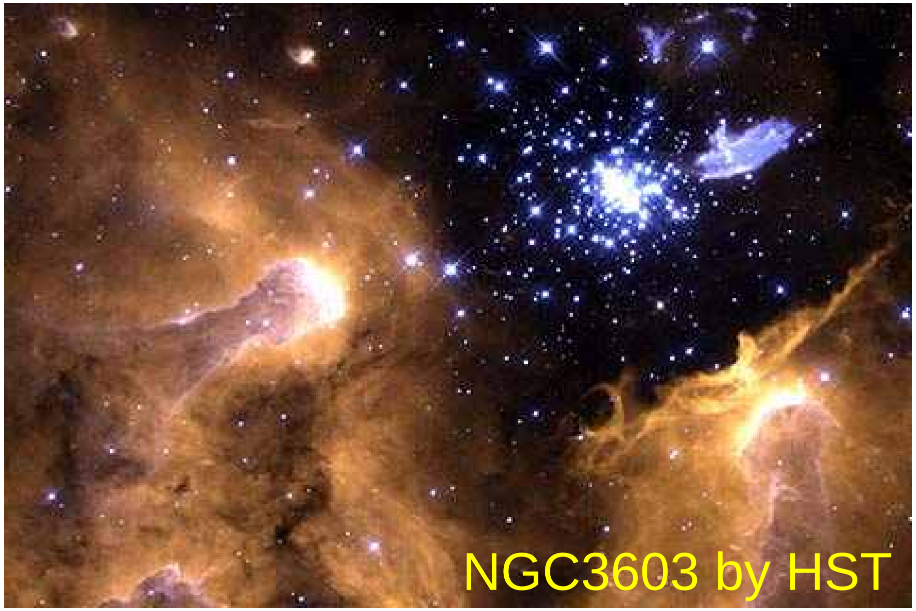
Takashi Hosokawa (NAOJ)

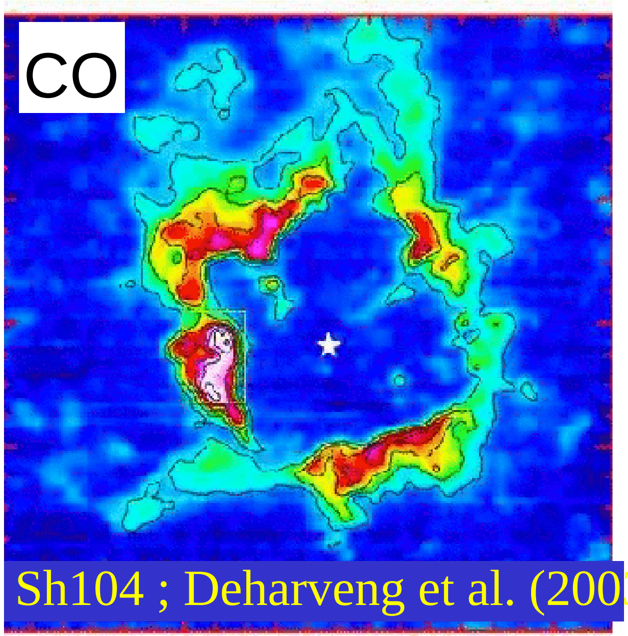
Ref. Hosokawa & SI (2005), ApJ **623**, 917
Hosokawa & SI (2006), ApJ **646**, 240
Hosokawa & SI (2006), ApJ **648**, L131
Hosokawa & SI (2007), ApJ **664**, 363

Outline

- Introduction
- Expanding HII region in Molecular Cloud
  - Radiation Hydro Calculation
  - Ionization Front & Dissociation Front
  - Comparison with Observation
- Expanding HII region in diffuse HI Cloud
  - Search for "Dark" Molecular Clouds
- Discussion
  - Thermal Instability & Gravitational Instability
- Future

Radiative Feedback for Molecular Cloud


NGC3603 by HST



Sh104 ; Deharveng et al. (2003)

- Ionizing photons ($h\nu > 13.6\mathrm{eV}$)
- Dissociating photons
  ($11.0\mathrm{eV} < h\nu < 13.6\mathrm{eV}$)

Negative Feedback

destroy molecular cloud and suppress star formation

($H2 \rightarrow HI \rightarrow HII$)

(e.g., Whitworth 1979)

V.S

Positive Feedback

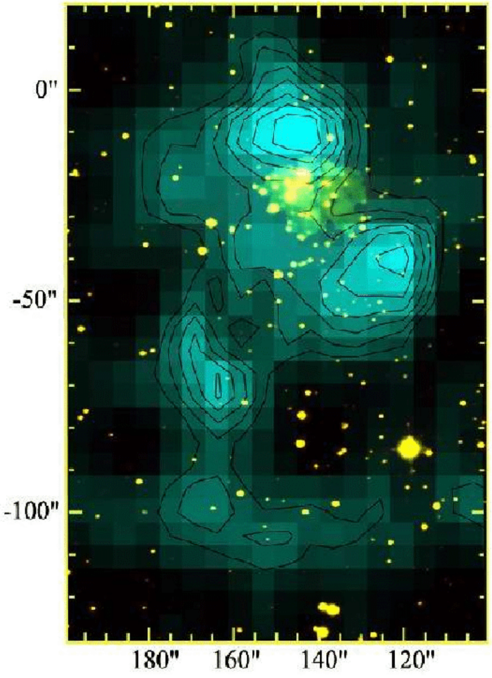
shock front sweeps up ISM to trigger star formation

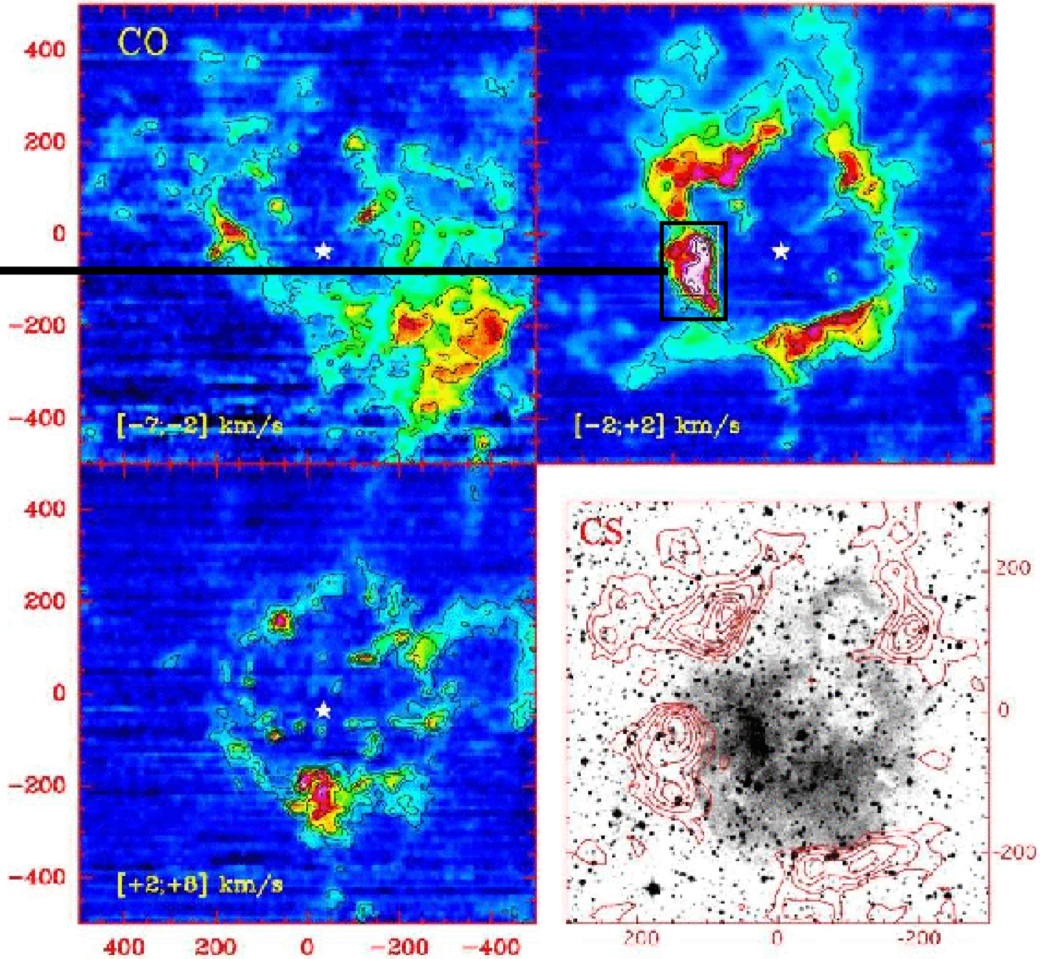
(compression of H2)

(e.g., Elmegreen & Lada 1977)

Expanding HII Region

Sh104 classical HII region, *R*≈4pc





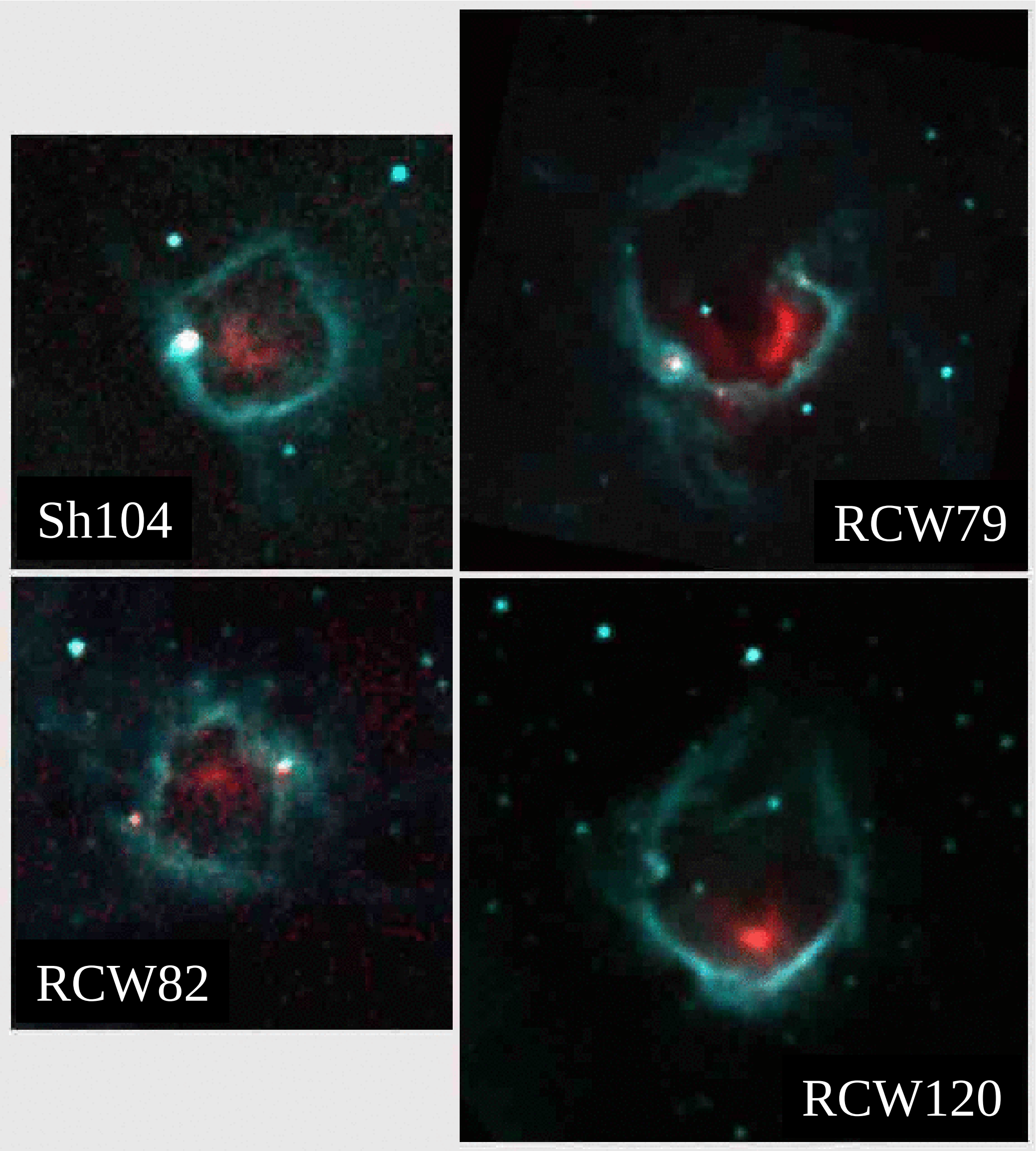
embedded young cluster in one clump

Deharveng et al. (2003) A&A, 408, L25

Direct Evidence of Collect and Collapse Scenario? Possible?

Other Similar Regions

Deharveng, Zavagno & Caplan (2005) , A&A, 433, 565



Dust emission

red : 21.3µm (grains)
green: 8.3µm (PAHs)

Many Similar Regions

Dust ring around HII regions
+ embedded point sources

Basic Equations

1D Radiation-Hydrodynamics Calculation

hydrodynamics : 2nd-order Godunov method

continuity▯ $$\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) - \frac{\partial(r^2 u)}{\partial m} = 0 \qquad (dm = \rho r^2 dr)$$

momentum eq. ▯ $$\frac{\partial u}{\partial t} + r^2 \frac{\partial p}{\partial m} = 0$$

Thermal Conduction

17 processes

energy eq. ▯ $$\rho\left(\frac{\partial E}{\partial t} + \frac{\partial(r^2 u p)}{\partial m} + \frac{\partial(r^2 q_{\mathrm{cond}})}{\partial m}\right) = n\boxed{(\Gamma - \Lambda)}$$

equation of state ▯ $$P = nkT\left(2x_{\mathrm{H+}} + x_{\mathrm{H}} + x_{\mathrm{H_2}}/2 + x_{\mathrm{He}}\right), \; \rho = 1.4 m_{\mathrm{H}} n$$

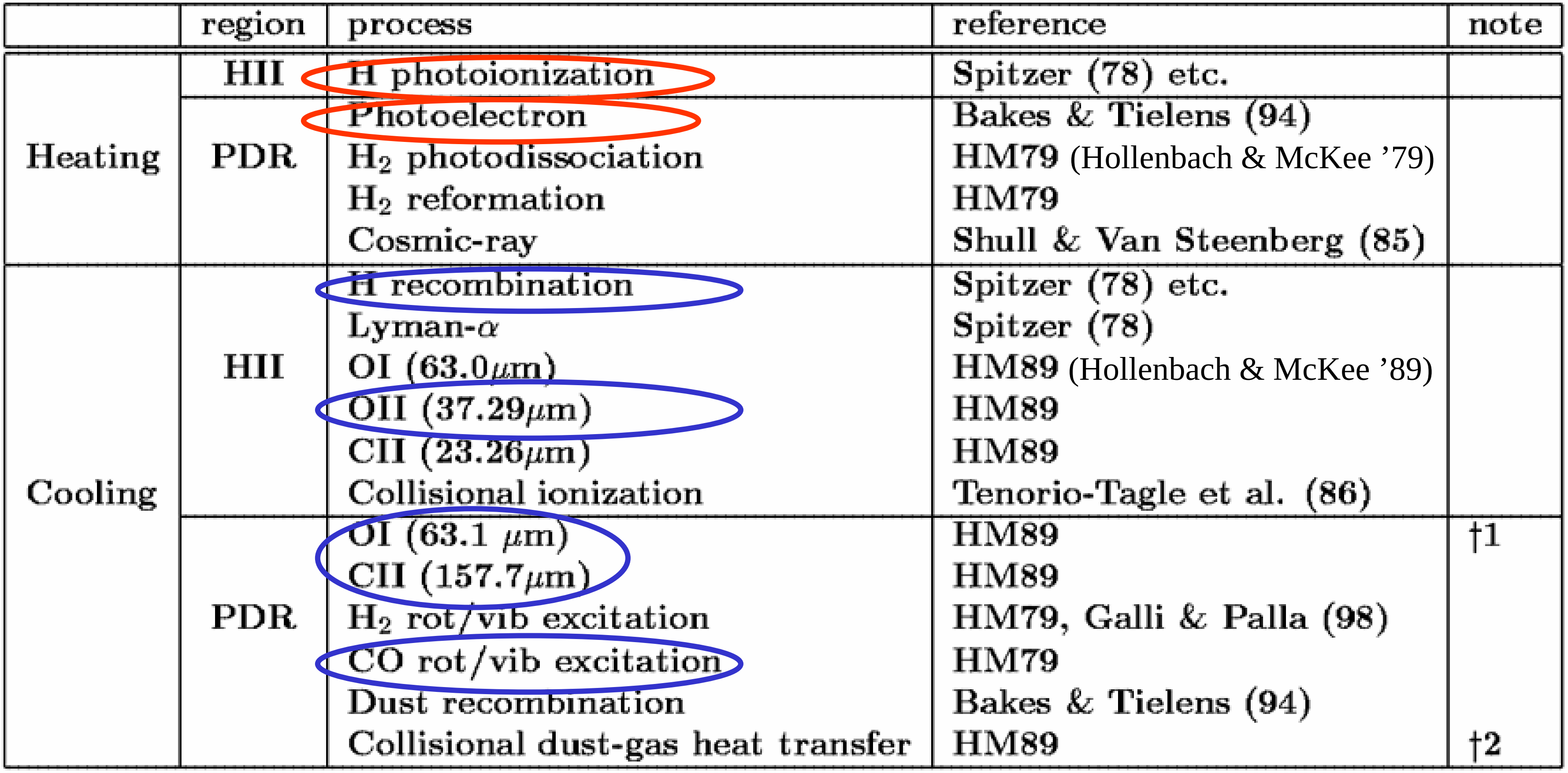
Radiative transfer ▯ UV photon ($h\nu > 13.6\mathrm{eV}$) FUV photon ($11.0\mathrm{eV} < h\nu < 13.6\mathrm{eV}$)

freq. dependent

chemistry▯ **H^+/H, O^+/O, H/H_2, C^+/CO** (Nelson & Langer 1998)

(photoinization) **(photodissociation)**

Heating / Cooling Processes



	region	process	reference	note
Heating	HII	H photoionization	Spitzer (78) etc.	
	PDR	Photoelectron	Bakes & Tielens (94)	
		H_2 photodissociation	HM79 (Hollenbach & McKee '79)	
		H_2 reformation	HM79	
		Cosmic-ray	Shull & Van Steenberg (85)	
Cooling	HII	H recombination	Spitzer (78) etc.	
		Lyman-α	Spitzer (78)	
		OI (63.0μm)	HM89 (Hollenbach & McKee '89)	
		OII (37.29μm)	HM89	
		CII (23.26μm)	HM89	
		Collisional ionization	Tenorio-Tagle et al. (86)	
	PDR	OI (63.1 μm)	HM89	†1
		CII (157.7μm)	HM89	
		H_2 rot/vib excitation	HM79, Galli & Palla (98)	
		CO rot/vib excitation	HM79	
		Dust recombination	Bakes & Tielens (94)	
		Collisional dust-gas heat transfer	HM89	†2

Main heating : energy gain from UV radiation

Main cooling : line-cooling

Radiative Transfer

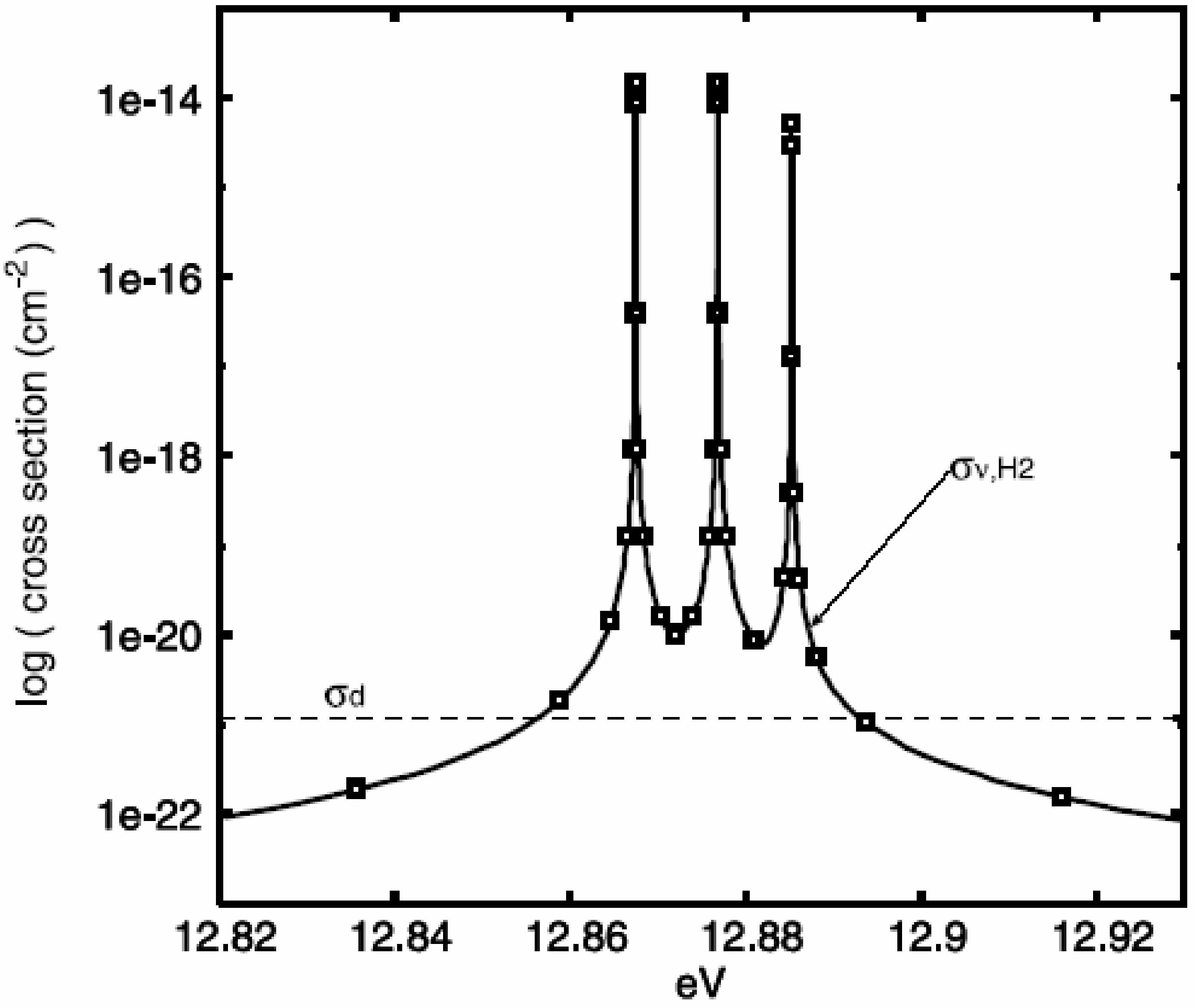
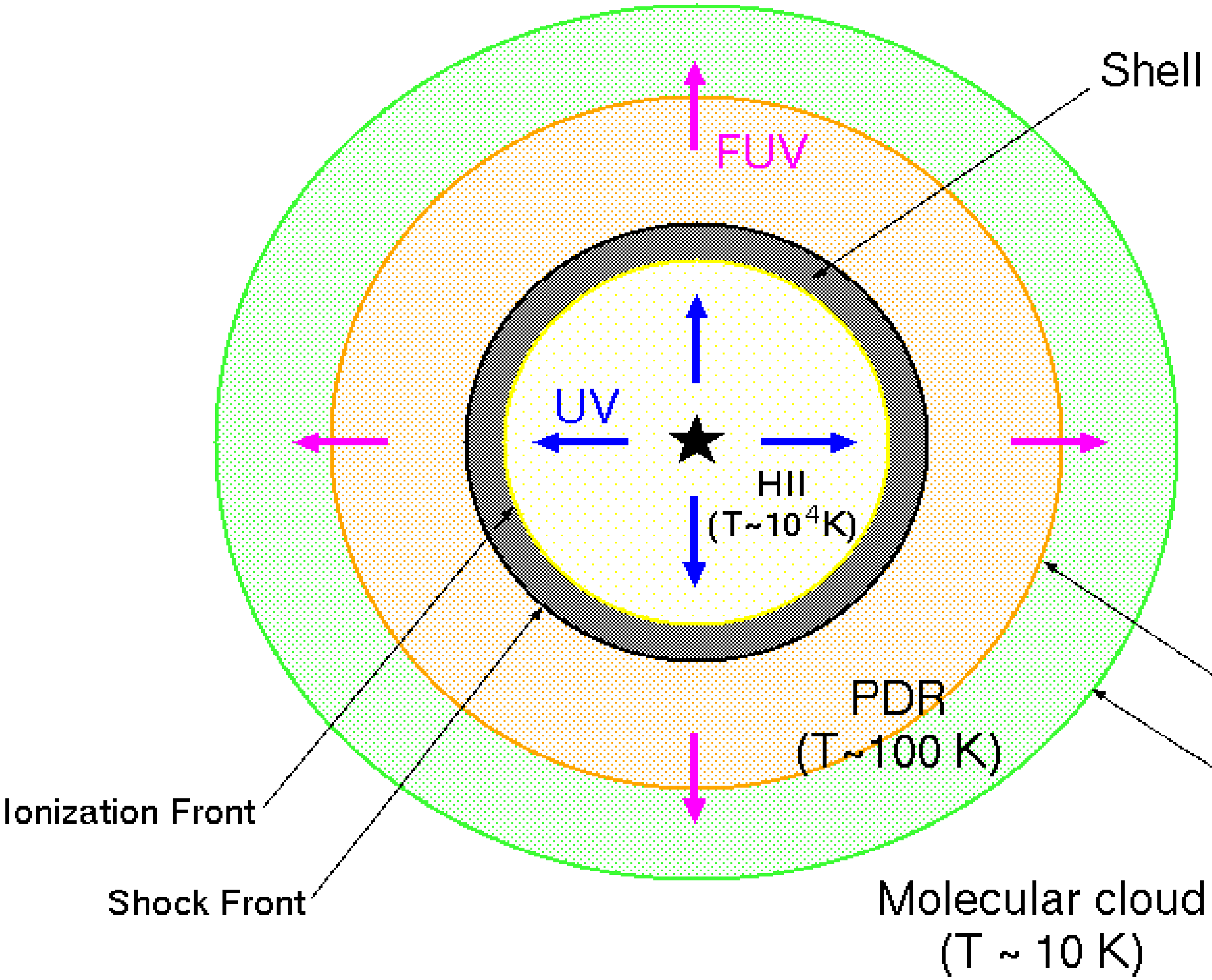
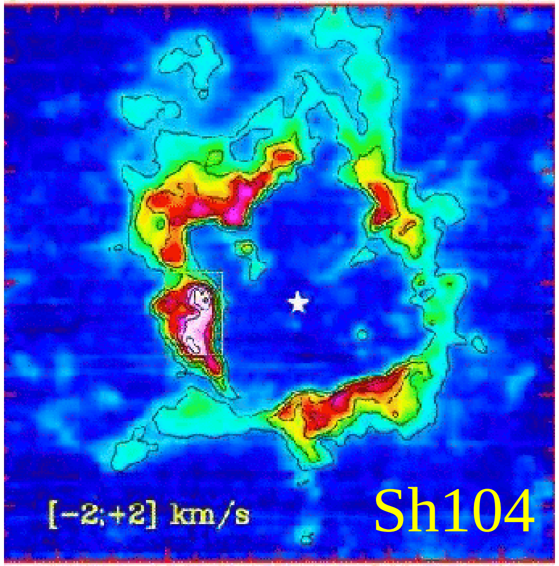


FIG. 1.—Our representative lines for Lyman bands, $\sigma_{\nu,\mathrm{H}_2}$. The points indicate the center of the grids. The dashed line means the dust absorption cross section for H_2 dissociating FUV photons, σ_d.

Expansion in Molecular Cloud





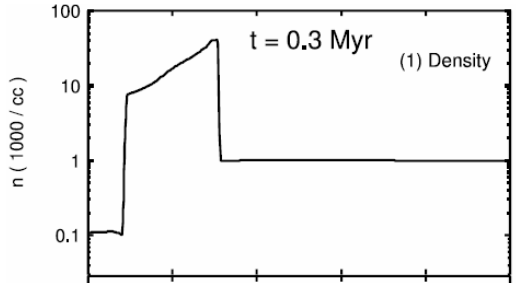
- study the physical/chemical structure of the shell
- Does molecular gas accumulates in the shell shielding FUV photons?

Gas Dynamics

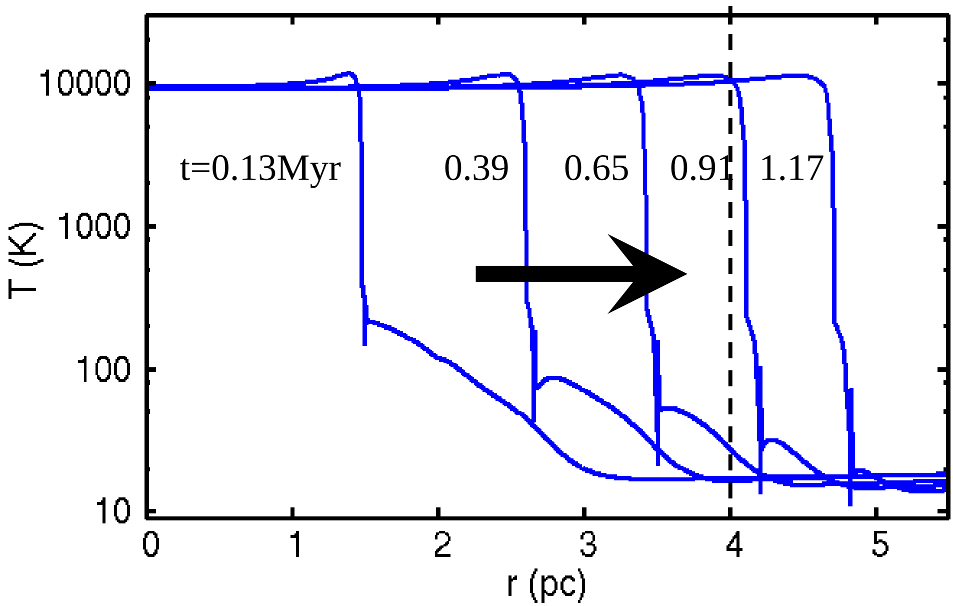
Central Star: $41M_{sun}$

Ambient Medium: homogeneous molecular gas

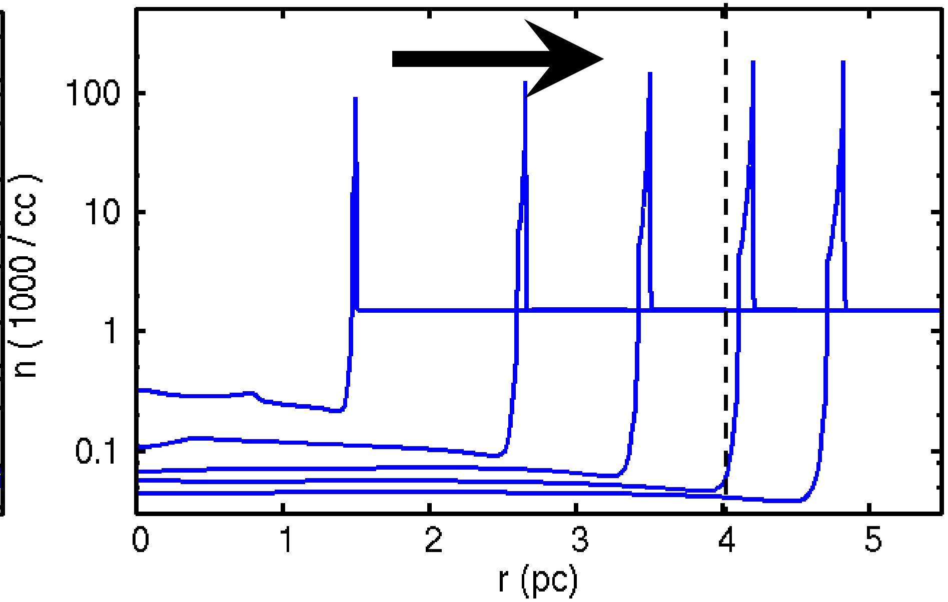
($n = 1.5\times10^3$ /cc)



Temperature



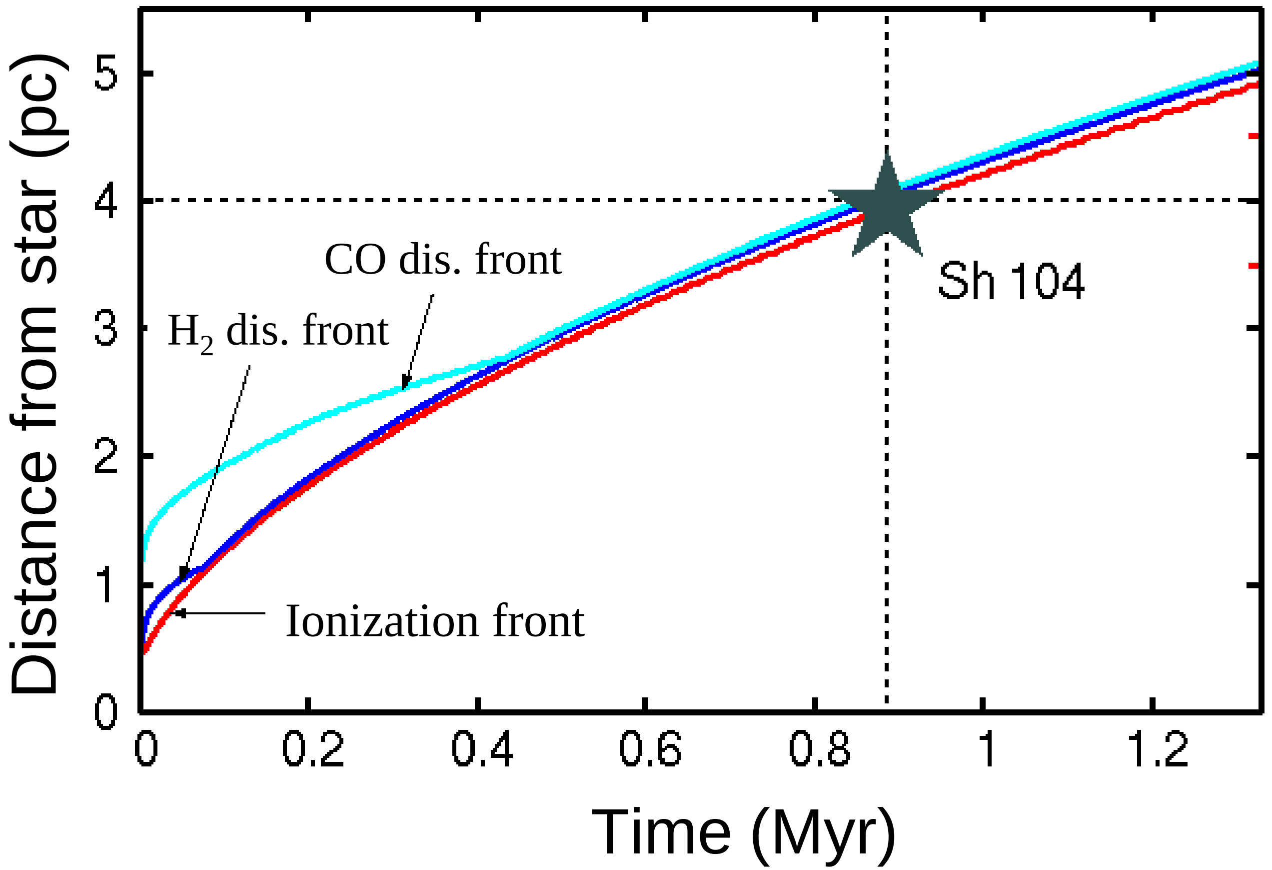
density



$T\sim10^4$K→HII region, T~100K→PDR, T~10K→molecular cloud

PDR is gradually trappeded in the shell

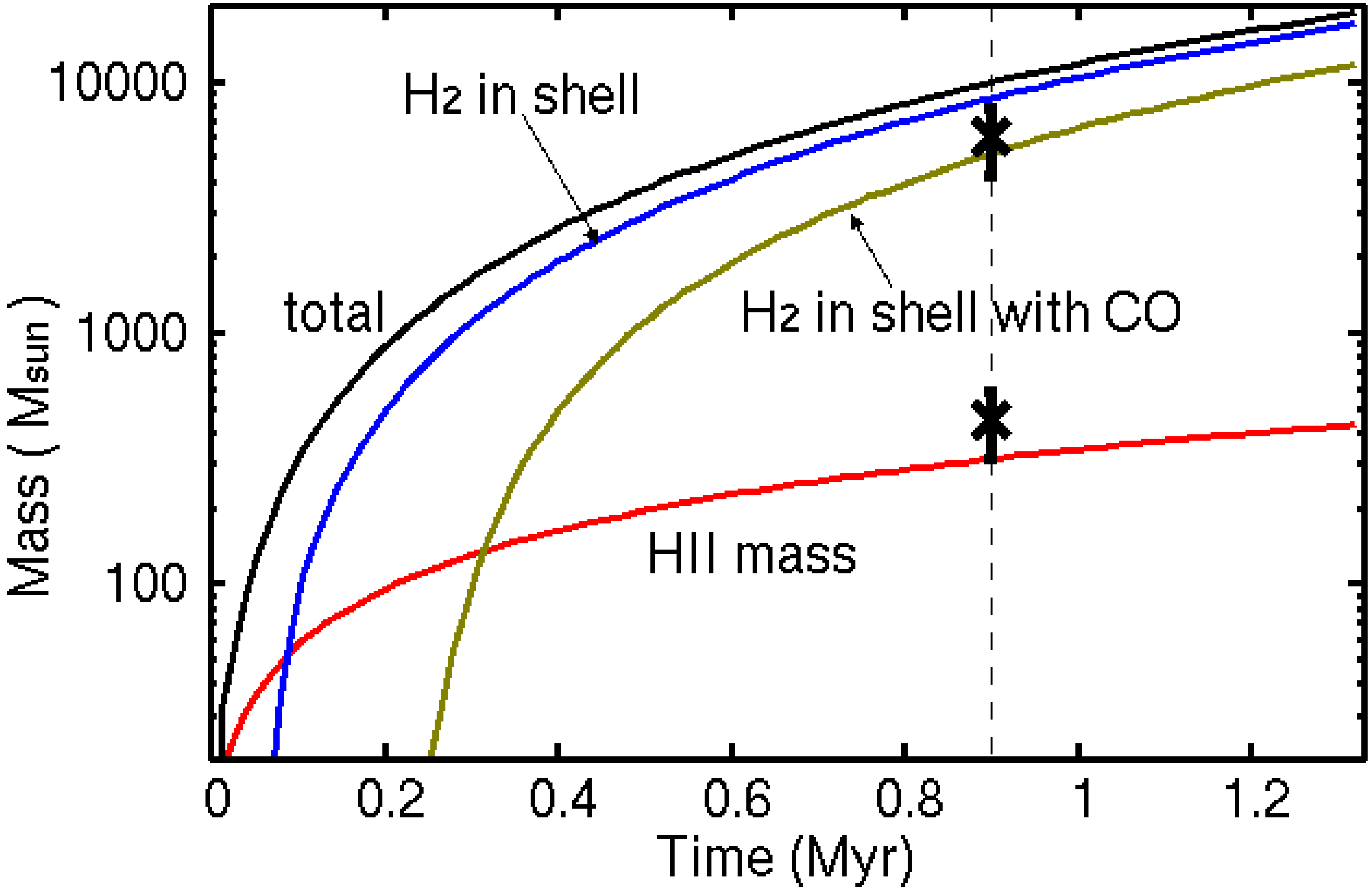
Front-Overtaking



Ionization front and shock front gradually overtake the preceding dissociation fronts.

The PDR is taken in the shell by the time when the HII region expands to the observed radius of Sh104.

Mass Evolution



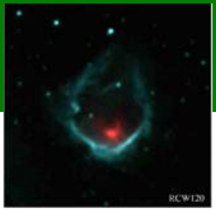
Sh104 obs.

Mass of HII region: ~ 450 $M_\odot$

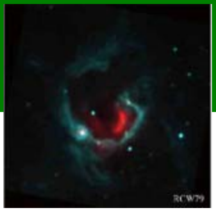
H_2 Mass of the shell : ~ 6000 $M_\odot$

Excellent agreement

Most of the swept-up gas remains in the shell as the molecular gas → ***Positive feedback***



Generality: Scaling relations



Quantitative change with different number density

up

Length scale: $R_{\mathrm{st}} \propto n^{-2/3}$

Time scale: $t_{\mathrm{dyn}} = R_{\mathrm{st}}/c_{\mathrm{HII}} \propto n^{-2/3}$

Shell mass: $M_{\mathrm{sh}} \propto n R_{\mathrm{st}}^3 \propto n^{-1}$

down

down

Shell column density: $\sigma_{\mathrm{sh}} \propto n R_{\mathrm{st}} \propto n^{1/3}$

Incident FUV flux from the star:

$$F_{\mathrm{FUV,i}} \propto S_{\mathrm{FUV}}/R_{\mathrm{st}}^2 \propto n^{4/3}$$

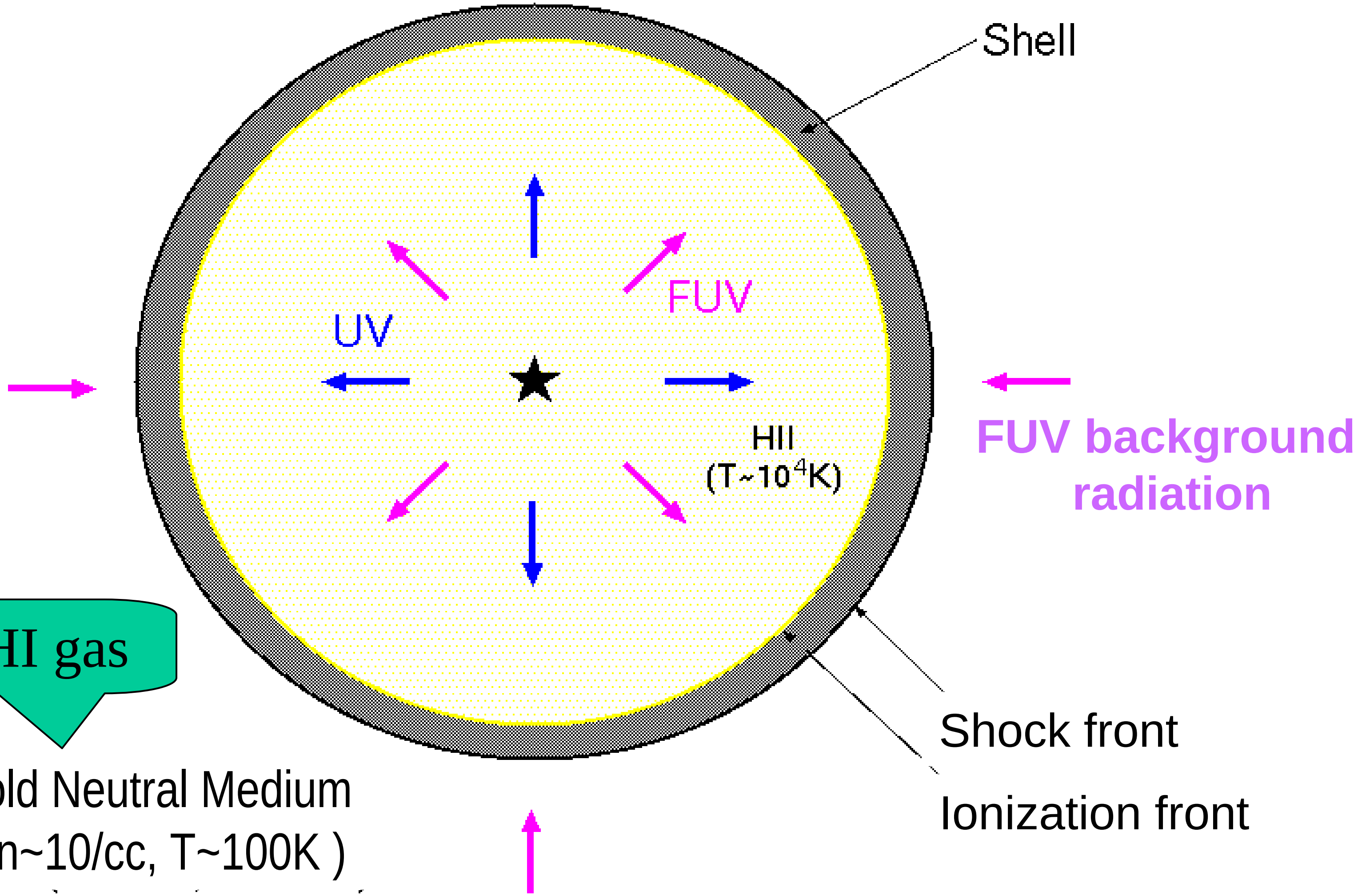
up

Low density → high density

Next Question:

What happens, if HII region expands into diffuse ISM (CNM)?

Expansion in Diffuse HI Gas



Diffuse HI gas

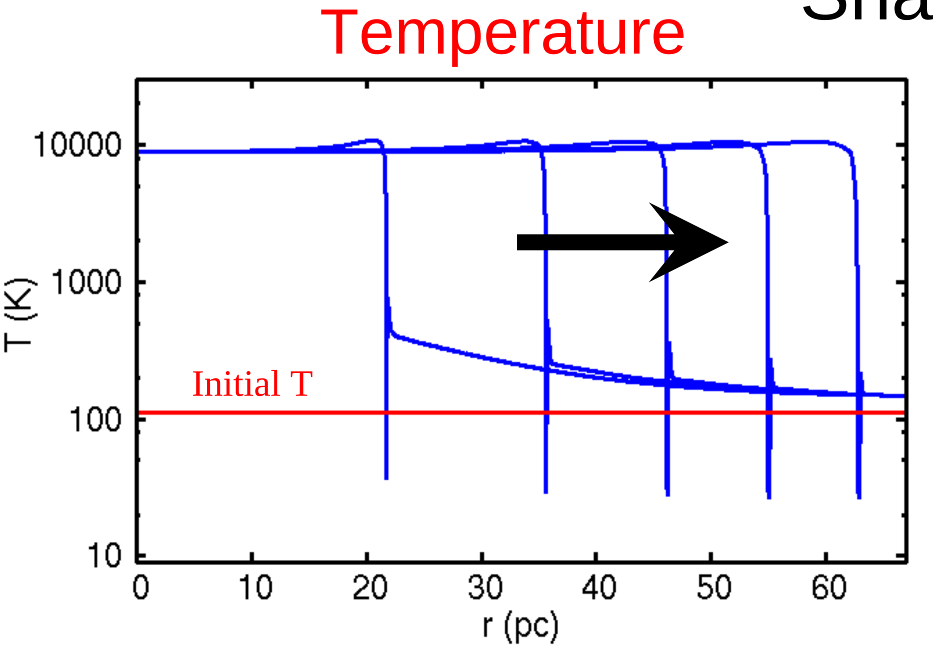
Cold Neutral Medium
(n~10/cc, T~100K)

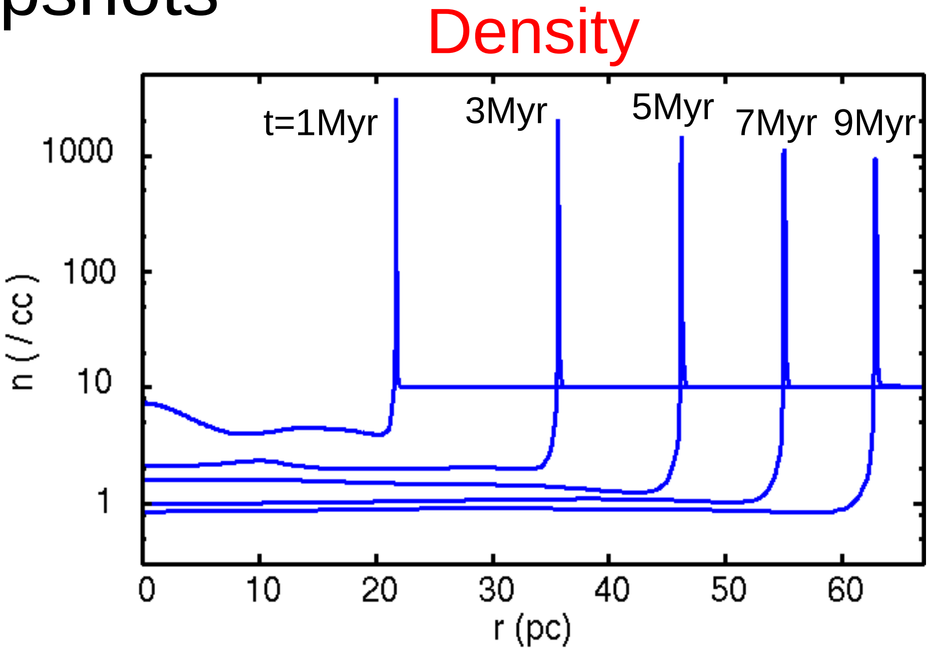
- Study the physical/chemical structure of the shell
- Does molecular gas form from ambient neutral medium?

Dynamical Evolution

Central star:41M_{sun} , ambient medium: CNM (n=10/cc)
(equilibrium state with typical FUV field)

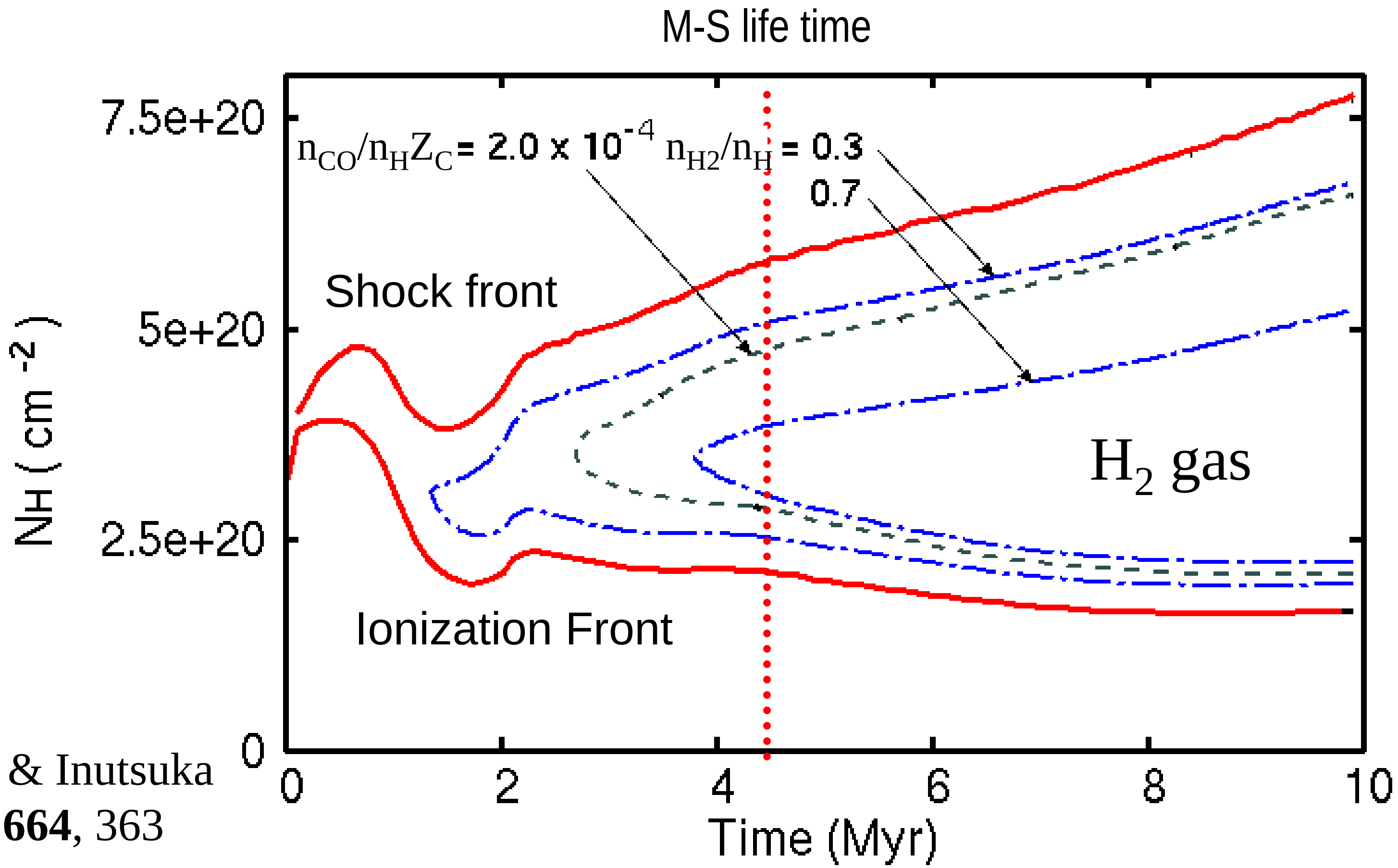
Snapshots





Dense and cold shell is formed around the HII region
density : n~1000/cc, temperature: T~30 K

Accumulation of Molecules



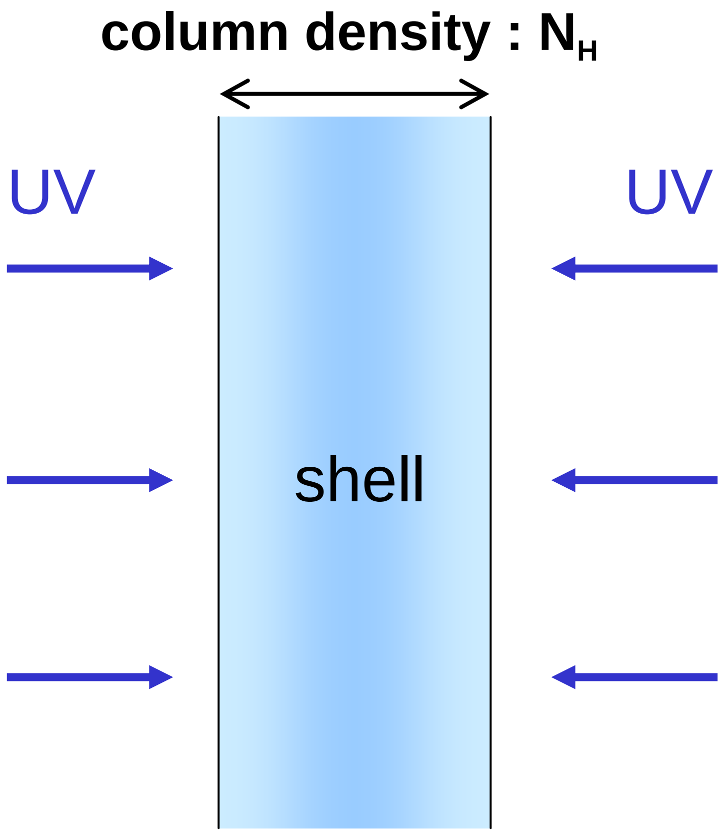
Hosokawa & Inutsuka 2007, ApJ **664**, 363

H_2 are formed in the shell, but CO are hardly formed : Dark H_2

⬇

Intermediate gas phase between neutral medium and molecular clouds

Why only H_2 molecules ?



Shell column density

: $N_H \sim$ a few $\times 10^{20}$ cm^{-2}

FUV shielding { dust ~~absorption~~

Self-absorption

Abundance of CO molecules is much smaller than that of H_2

➔ Self-shielding effect is efficient only for H_2.

➔ "Dark" Molecular Clouds

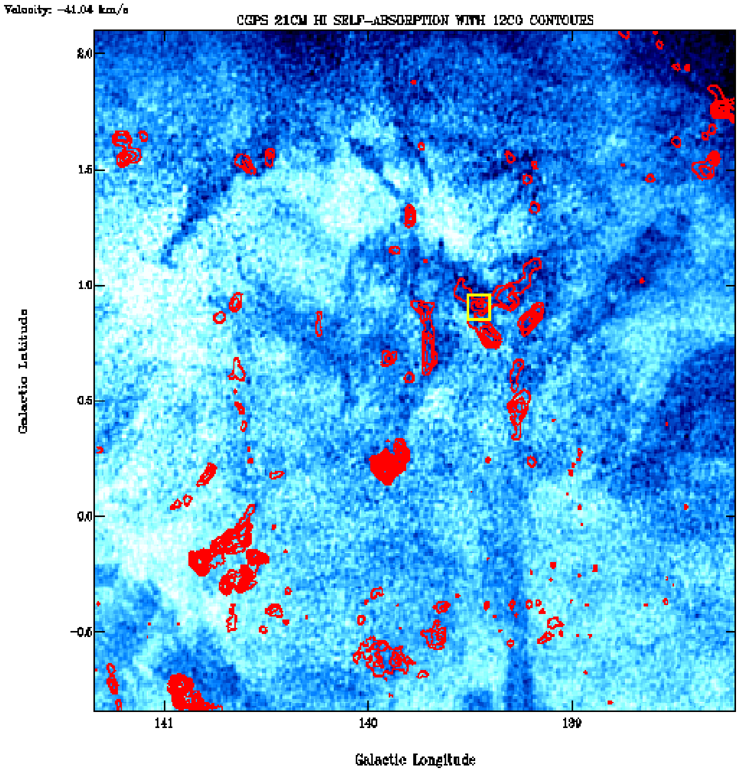
Hosokawa & SI 2007, ApJ **664**, 363

Search for "Dark" H_2 Clouds

Looking for cold (T~a few ×10 K) HI without CO

HI 21cm line emission

HI Self-Absorption (HISA) : absorption by colder HI against the emission by the warmer HI (T_b ~100 K)



Canadian Galactic Plane Survey

CGPS ; Taylor et al. (2003)

- galactic plane survey @ radio, IR
- angular resolution : about 1‘
- distribution of HI, HII, CO, dust

Channel Map

Blue image:21cm emission, Red contour:CO

CGPS data in W5 HII region

21cm continuum (HII gas)

T_b=5K (bright) → 12.5K (dark)

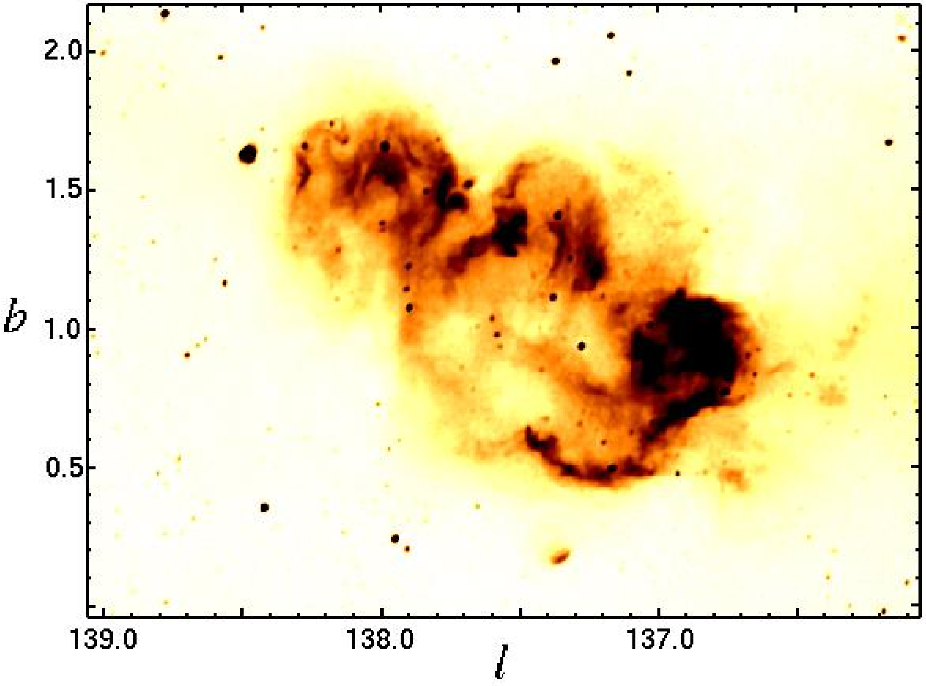
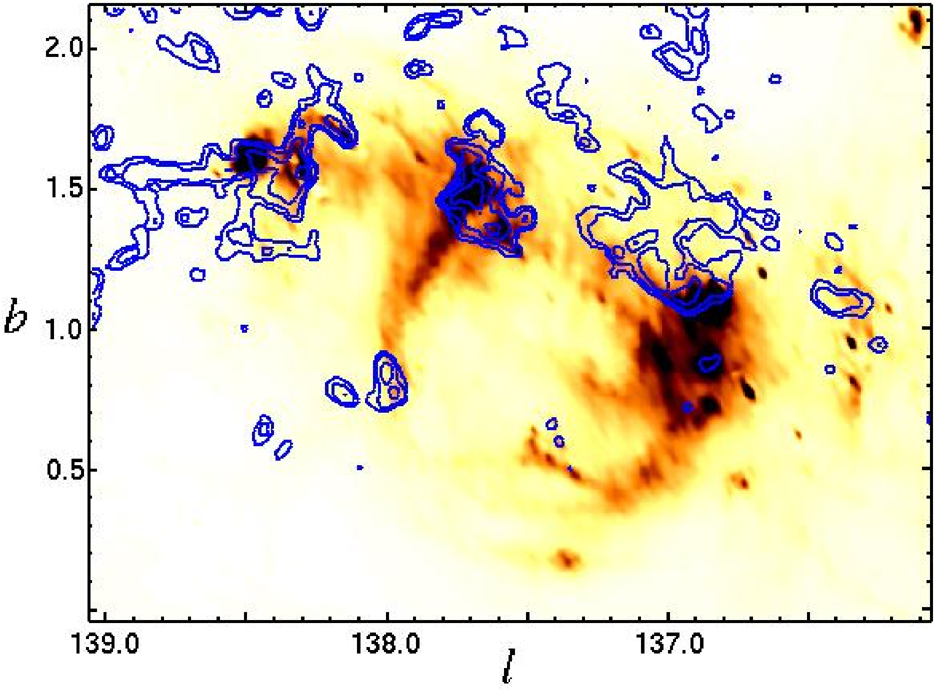


Image : 60μm dust emission

Contour : ^{12}CO(1-0) @ v_{LSR}=-39.8 km/s

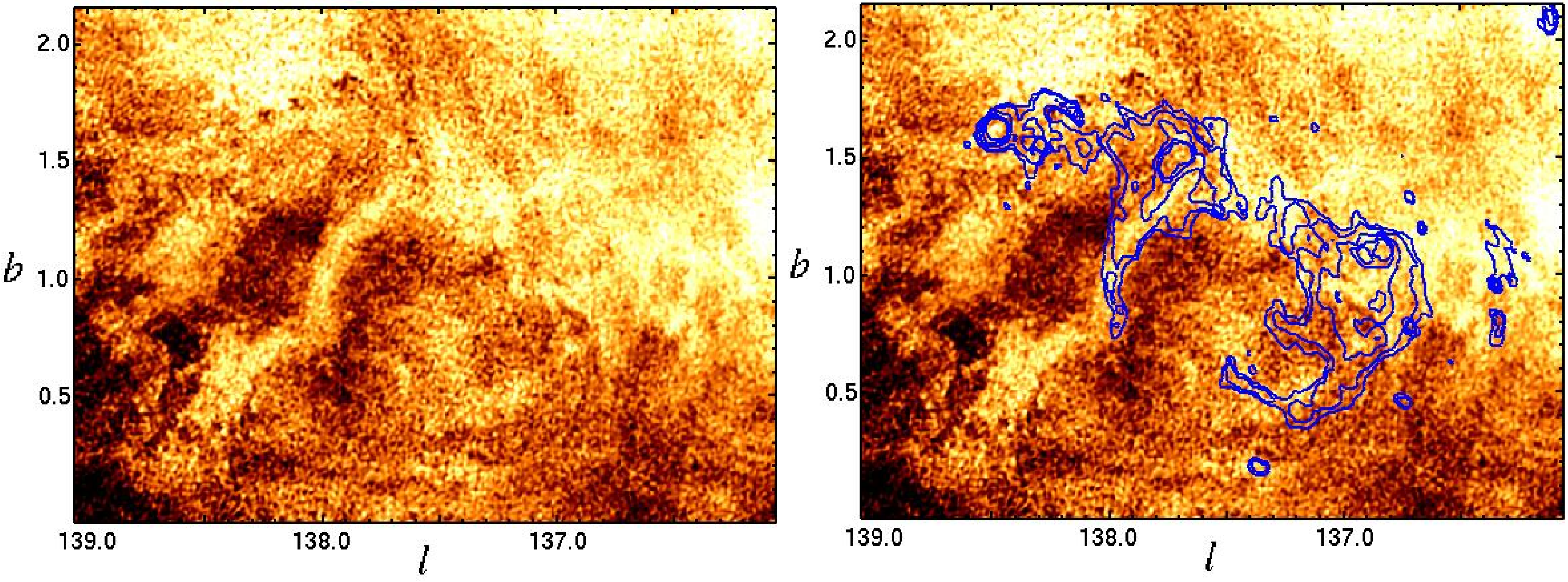


- Ionized gas is surrounded with the dust shell.
- Distribution of CO molecules show poor correlation with the dust shell.

CGPS data in W5 HII region

HI 21cm emission @ v_{LSR}=-39.8 km/s

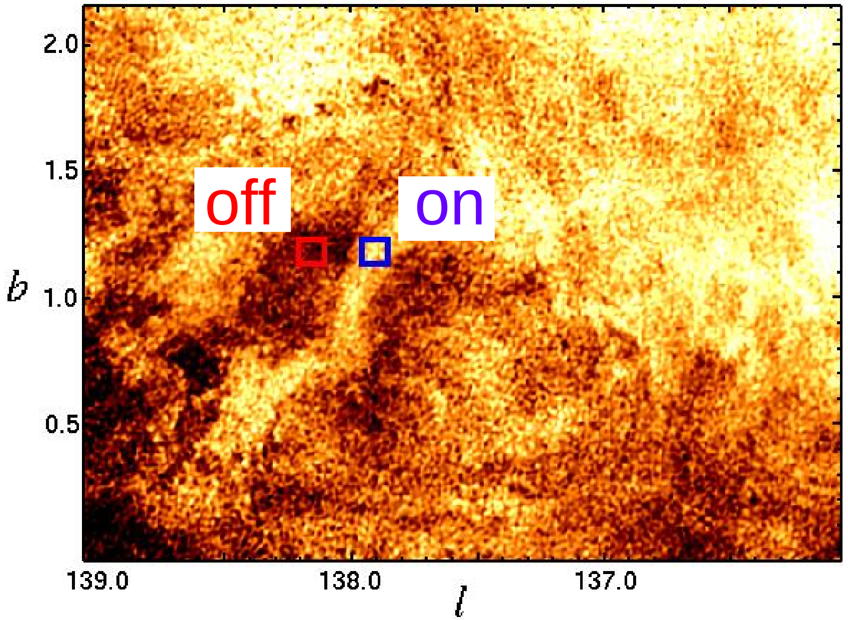
: T_b=45K (bright) → 110K (dark)

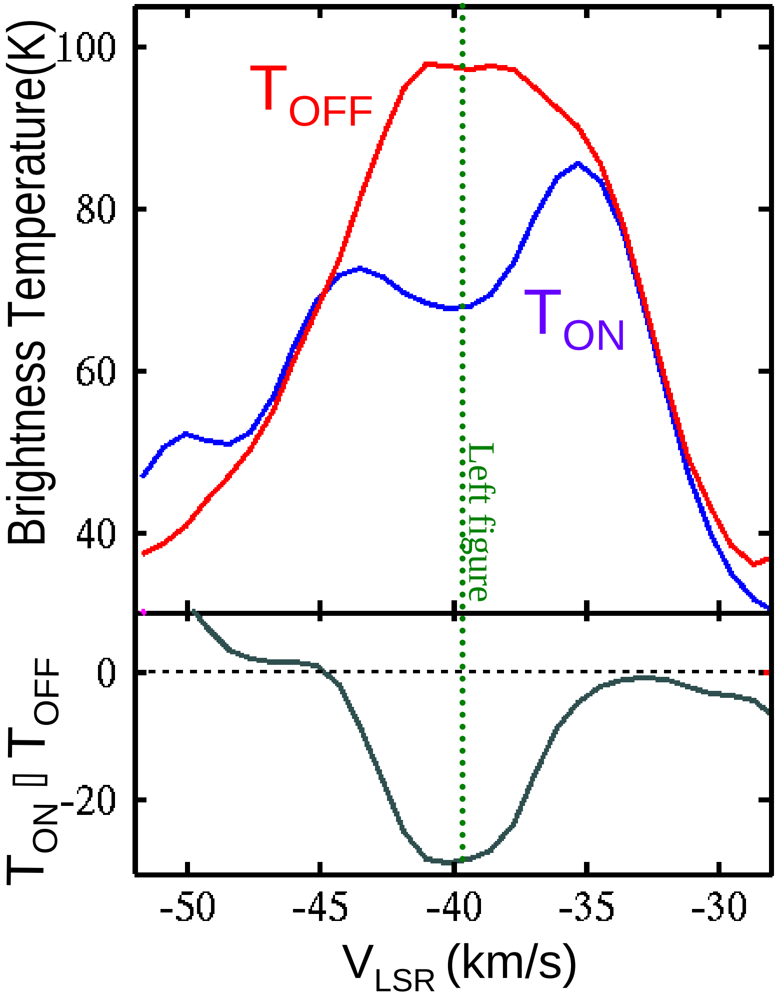


contour : 60μm dust emission

- ➢ Shell-like HISA feature is found around W5 HII region.
- ➢ HISA feature overlaps with the dust shell.

Absorption Line Profile





line depth : ΔT ~ 30K,

line width : Δv ~ 5 km/s

$$p \equiv \frac{\tau_{\mathrm{bg}} T_{\mathrm{bg}}}{T_{\mathrm{off}}}$$

The HISA temperature is less than T~80K.

If $p < 0.75$, HISA is fairly cold ($T < 50$K).

Summary

We have studied the feedback of the stellar UV/FUV radiation in the molecular clouds and diffuse neutral medium.

(I) In the molecular cloud

- Cold (T~30K) and dense (n~10^5 /cc) shell is formed around HII region.
- 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**, which agrees with some observations ***; positive feedback***

(II) In the diffuse interstellar medium (HI)

- Cold (T~30K) and dense (n~1000/cc) shell is formed around HII region.
- H2 is formed from ambient HI in the shell, but CO is hardly formed. **intermediate gas phase between the diffuse neutral medium and molecular clouds**
- Recent observational data shows the signs of this predicted gas phase.

Discussion: What about 2D/3D Dynamics?

- Propagation of Shock Wave into CNM
  - Generic Process in ISM

    Koyama & Inutsuka 2002, ApJL **564**, L97

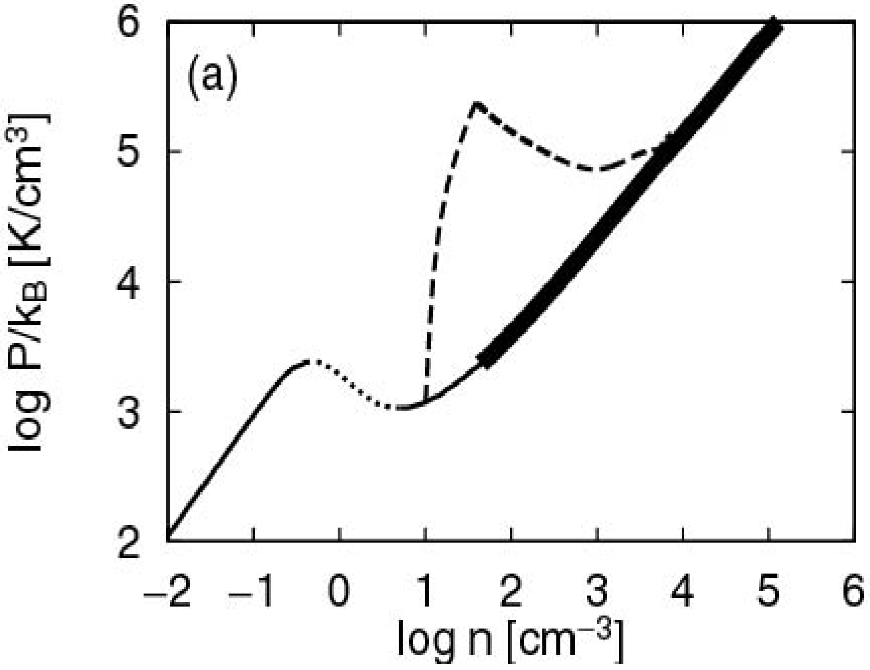
    Audit & Hennebelle 2005

    Heitsch et al. 2005

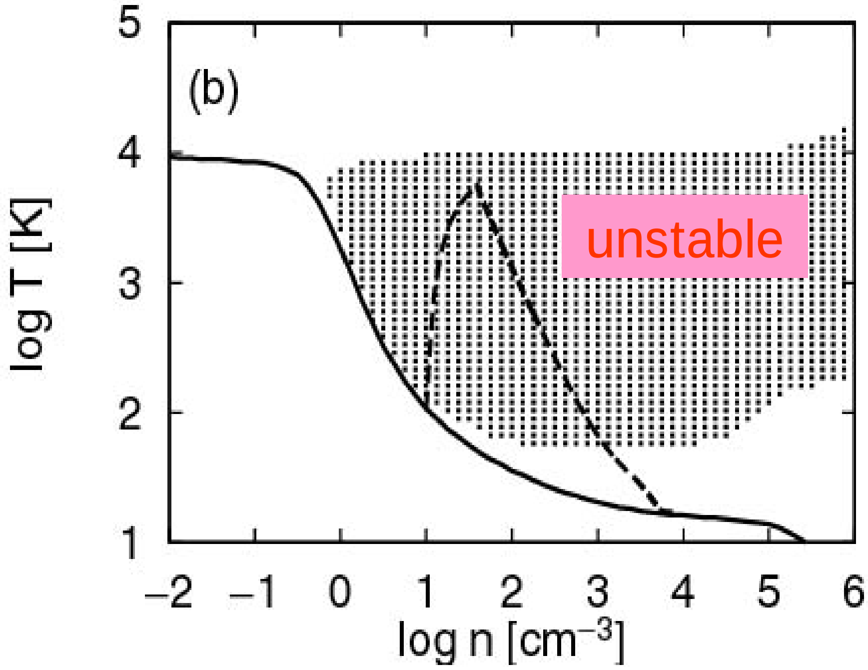
    Vazquez-Semadeni et al. 2006, etc.

1D Shock Propagation into CNM

Density-Pressure Diagram



Density-Temperature Diagram

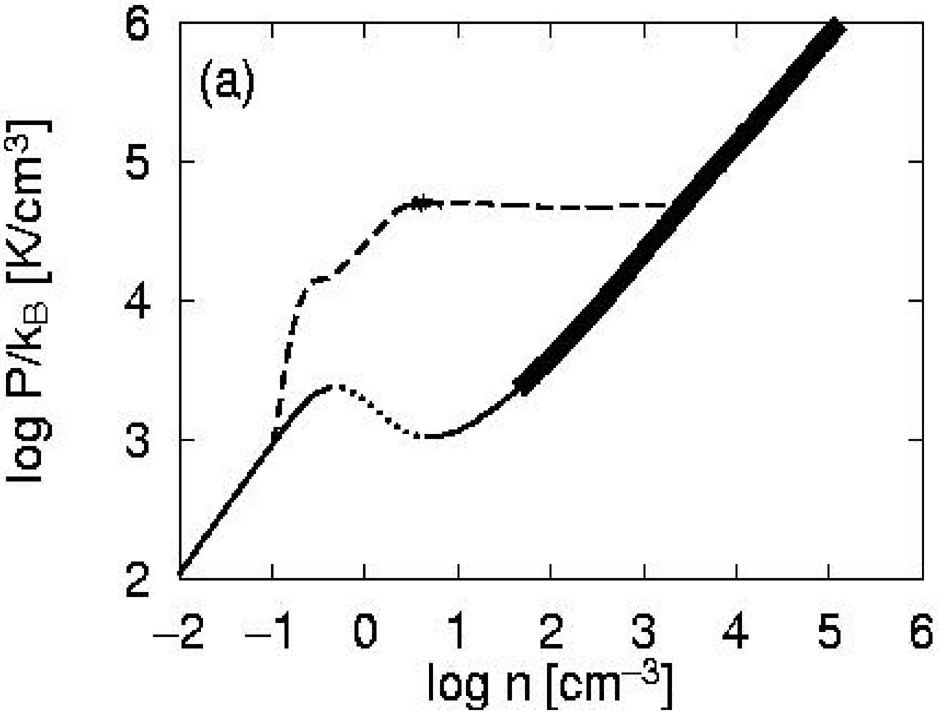


CNM becomes thermally unstable with shock.

Koyama & Inutsuka,2000,ApJ **532**,980

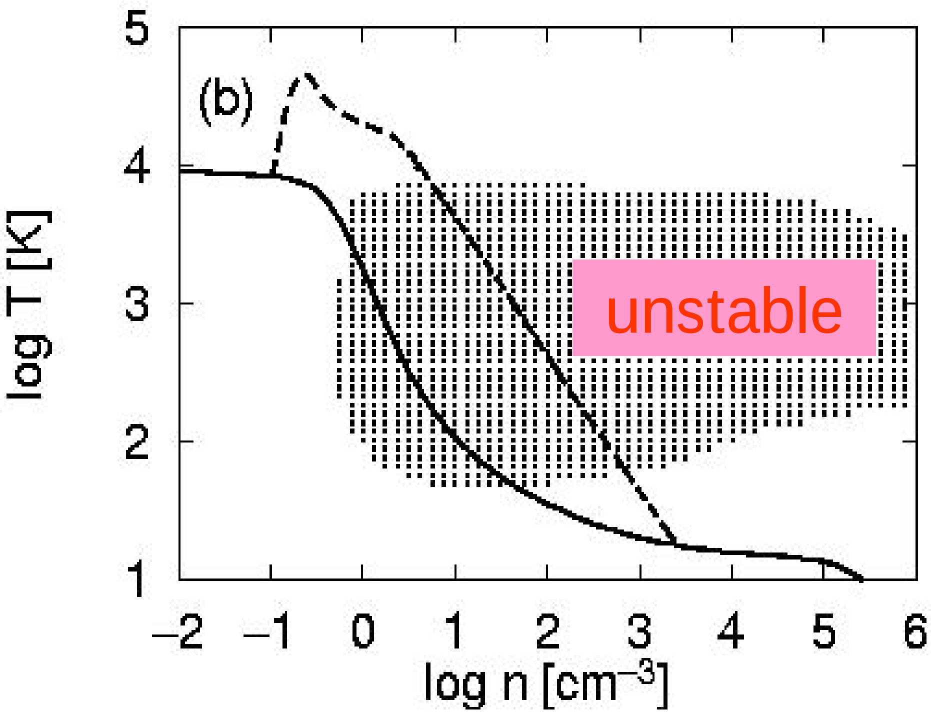
1D Shock Propagation into WNM

Density-Pressure Diagram



Density-Temperature Diagram

– through unstable region

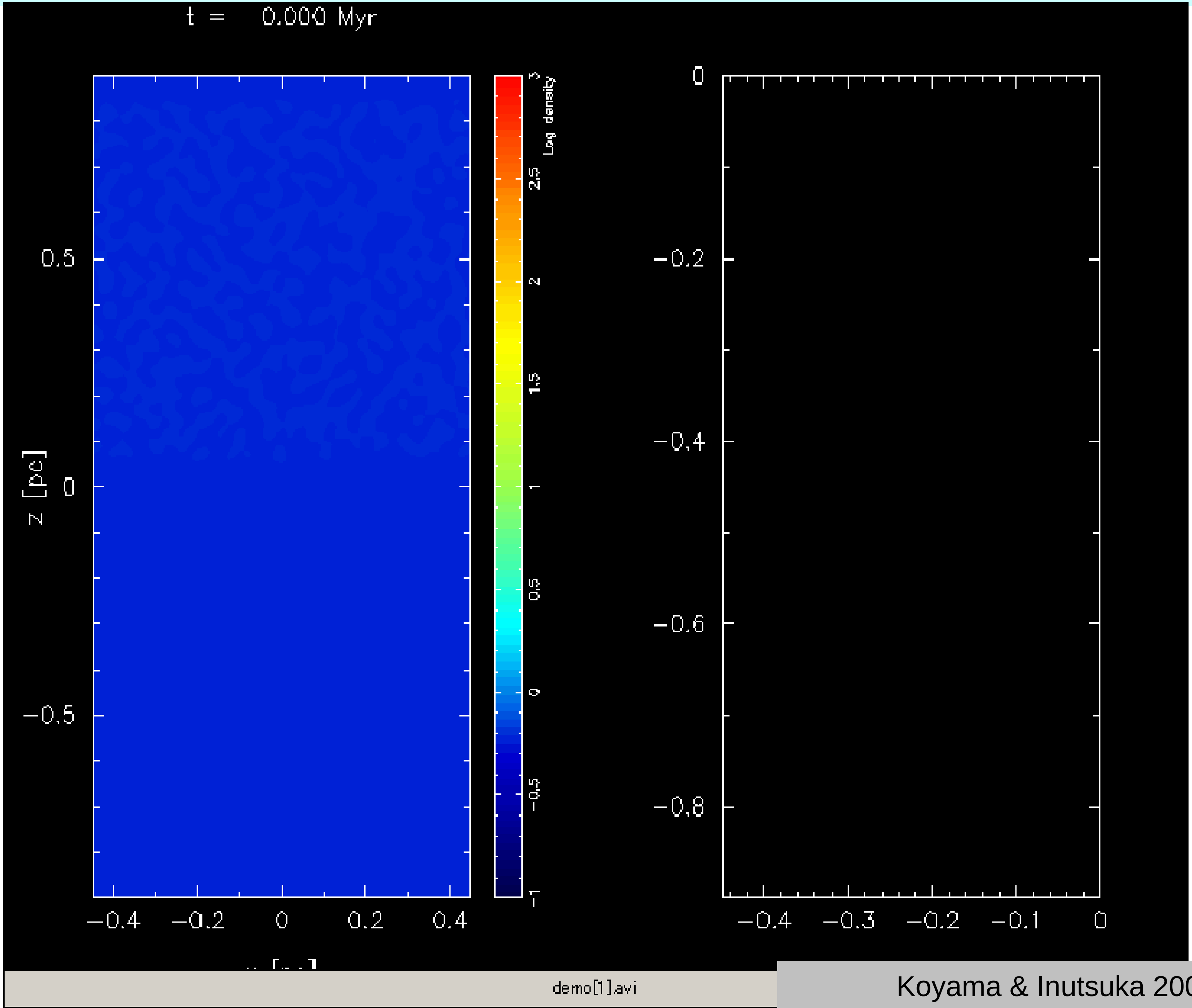


Koyama & Inutsuka 2000, ApJ **532**, 980

See also Hennebelle & Pérault 1999

Shock Propagation into WNM

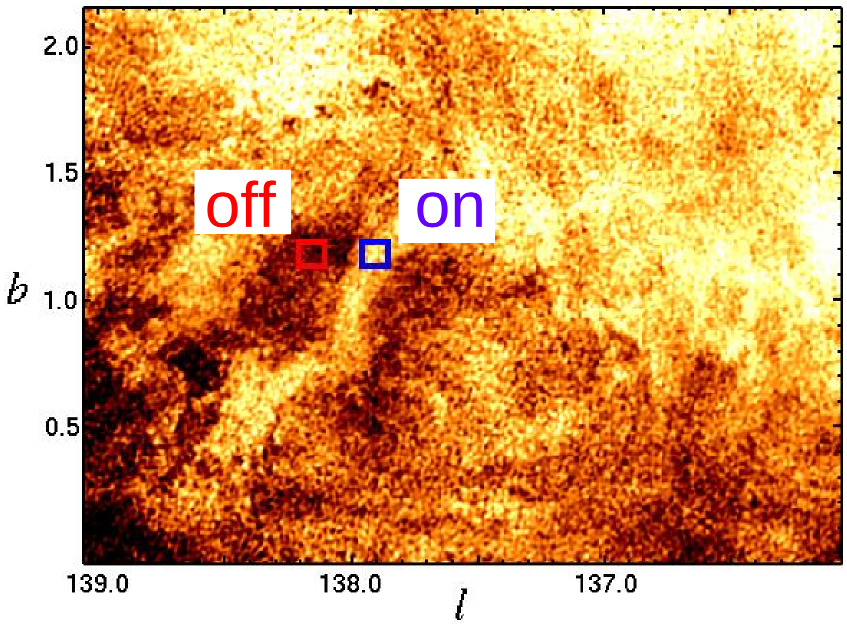
↑ direction of propagation

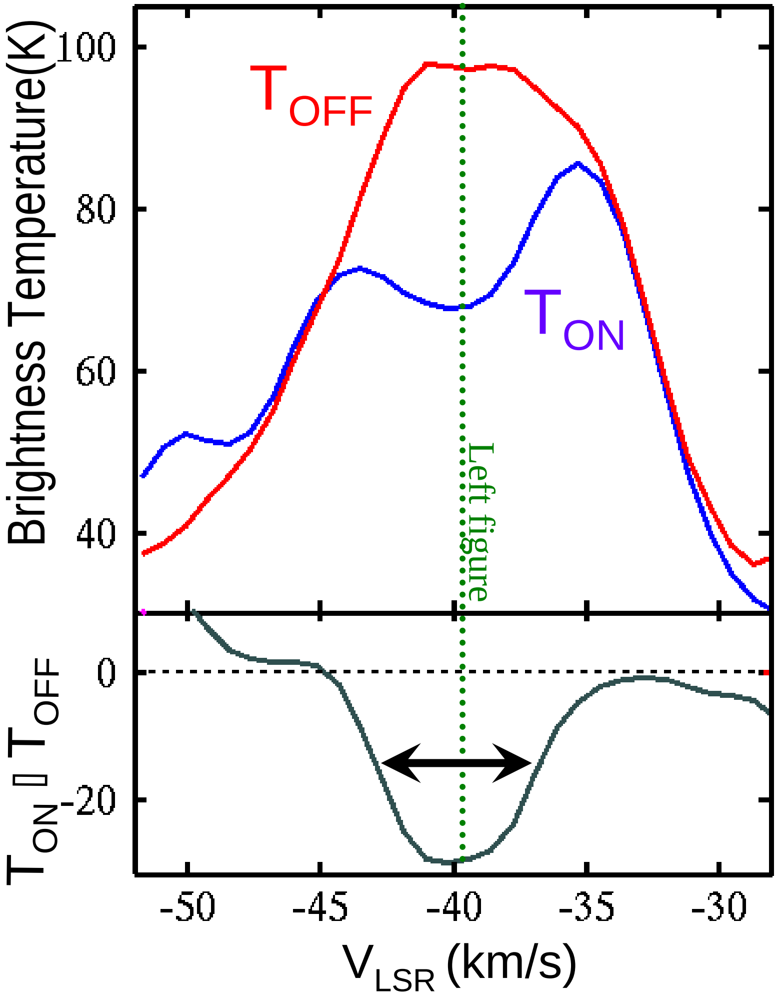


watching from moving frame

Koyama & Inutsuka 2002

Generation of Turbulent Dense Shell?





line depth: $\Delta T \sim 30$K,
line width: $\Delta v \sim 5$ km/s

Dense shells are turbulent!
Due to thermal instability?

Generality of Triggered SF

- M_{av}: average mass of formed stars
- $f\,(>20\mathrm{M}_{\mathrm{o}})$: number fraction of massive stars
- M_{sh}: mass of dense shell
- ε : SF efficiency

$$\frac{\text{\# of star formed in shell}}{\text{\# of original stars}} = \frac{f(>20M_{\odot})}{M_{\mathrm{av}}} M_{\mathrm{sh}}\varepsilon$$

$$= \left(\frac{0.6M_{\odot}}{M_{\mathrm{av}}}\right)\left(\frac{f(>20M_{\odot})}{0.0006}\right)\left(\frac{M_{\mathrm{sh}}}{10^4 M_{\odot}}\right)\left(\frac{\varepsilon}{0.1}\right)$$

Hosokawa & SI (2005), ApJ **623**, 917

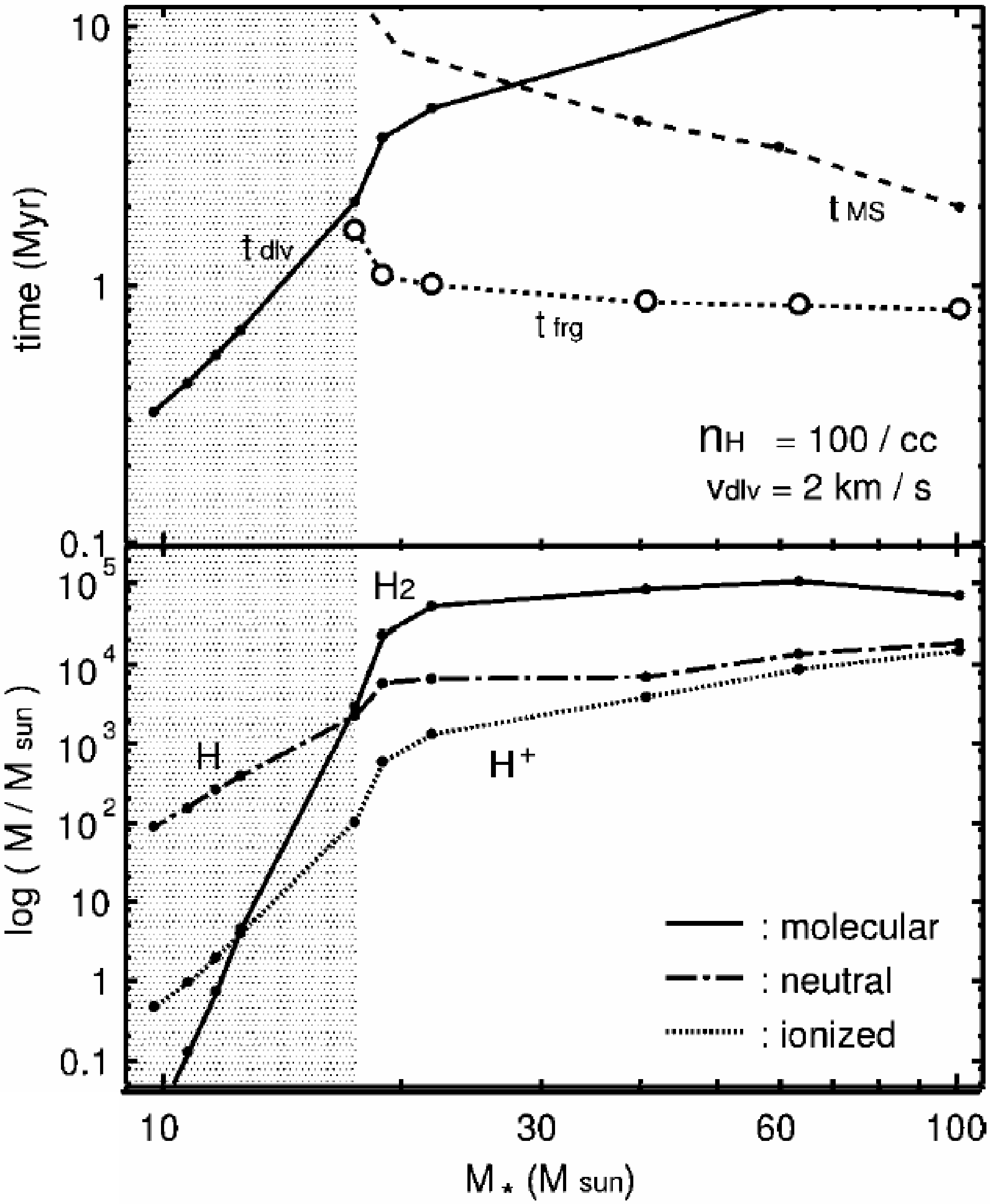
Condition for Star Burst

If $M_* > 20\mathrm{M_o}$,

then number of massive stars increases exponetially.

Hosokawa & SI (2006)

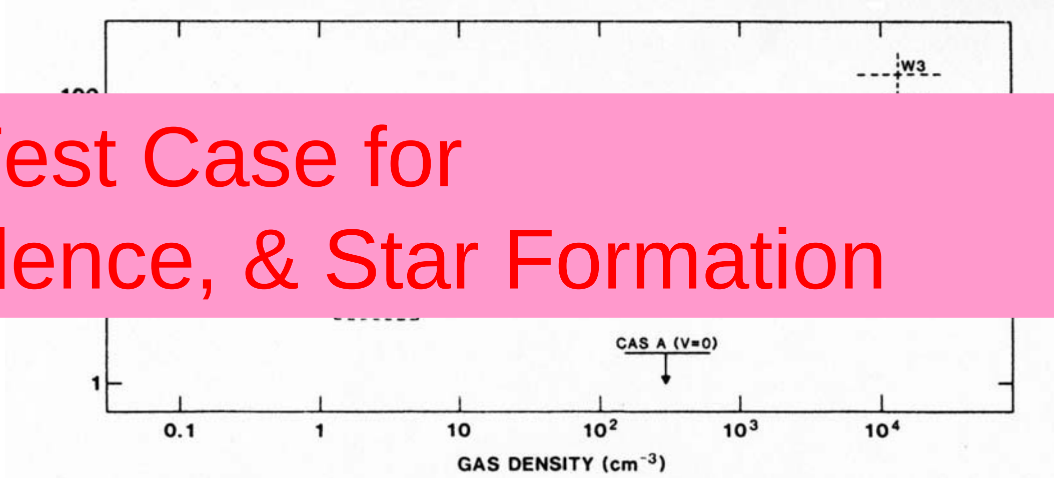
ApJ **648**, L131



Future

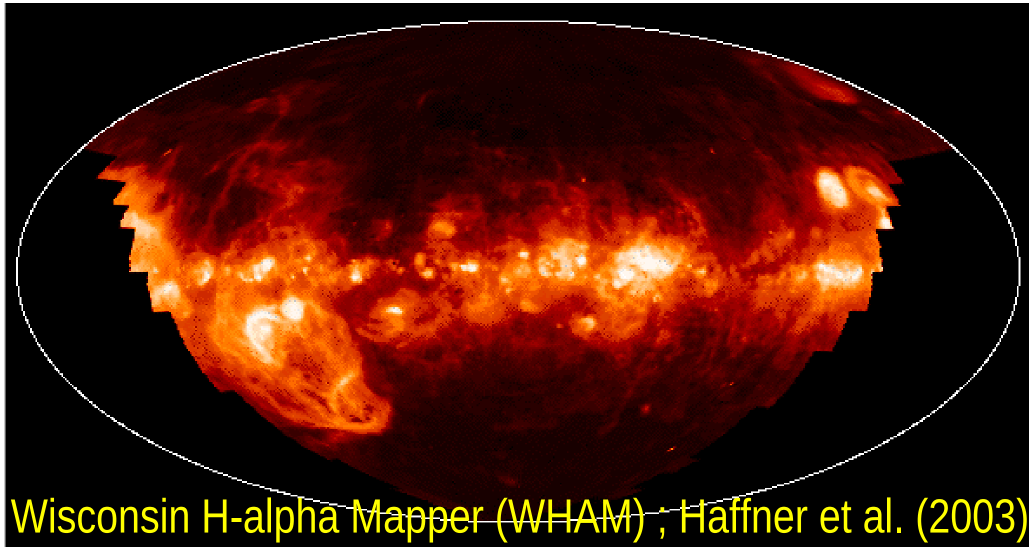
- Multi-Dimensional Simulations
  - – Thermal Instability (*Field Length* ~ AU Scale!)
  - – Gravitational Instability (*Jeans Length*)
- Effect of Magnetic Field
  - – Non-Ideal MHD (ambipolar diffusion, etc.)
    - 2-fluid MHD simulations always result in a few μG.

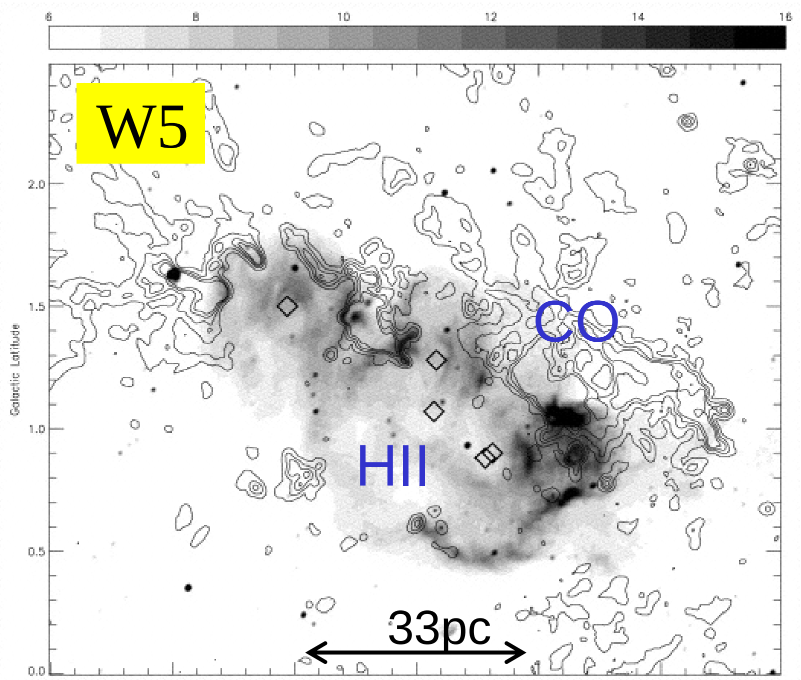
Inoue et al. 2007, ApJ 658, L99



Ideal Self-Contained Test Case for
Feedback, Turbulence, & Star Formation

Radiative Feedback for Diffuse ISM


Wisconsin H-alpha Mapper (WHAM) ; Haffner et al. (2003)



Karr & Martin (2003)

Negative Feedback

Photoionization of the neutral medium
: promising process to supply
the diffuse warm ionized medium.

(HI → HII)

(e.g., Miller & Cox 1993)

V.S

Positive Feedback

Shock front sweeps up the ambient neutral medium. Reformation of molecule is triggered in the compressed layer.

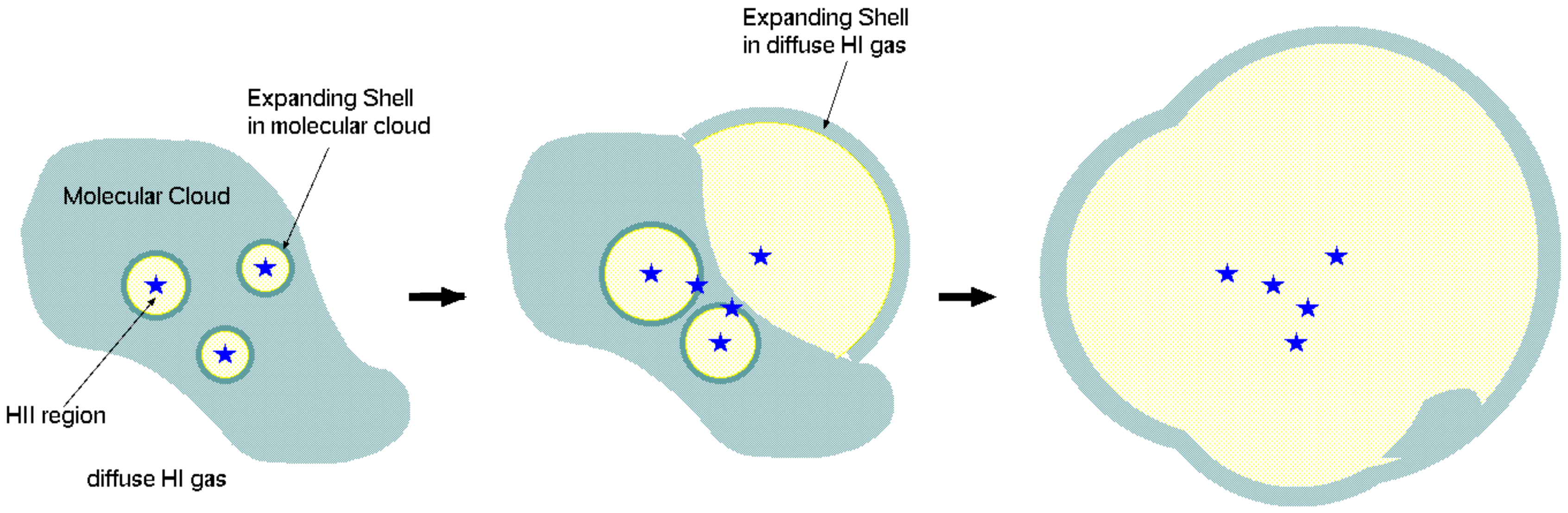
(HI → H2)

(e.g., Koyama & Inutsuka 2000)

Motivation

Phase. I

Phase. II



(1) HII regions expand in the molecular clouds

(2) Expanding HII regions trigger the star formation and/or destroy the molecular cloud

(3) HII region expands in the diffuse neutral medium

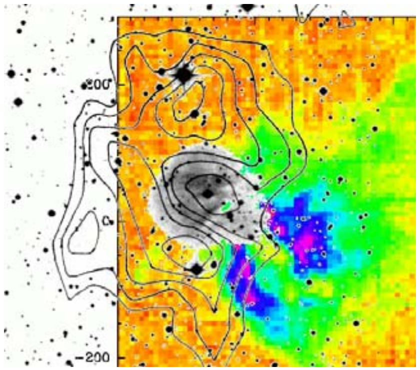
Negative feedback ***Positive feedback***

Phase I : dissociation + ionization *v.s.* Compression of molecular gas

(H2 → HI → HII)

Phase II : ionization (HI→HII) *v.s.* Reformation of molecular gas (HI → H2)

Modeling of Sh219 requires ρ gradient



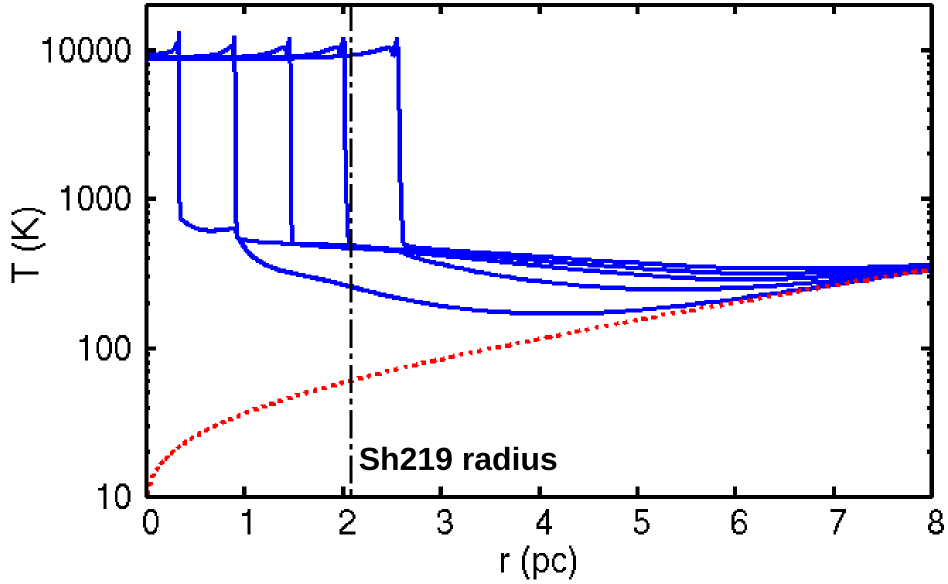
Central star 19 M_{sun} ← **obs.**

Density profile $$n(r) = \begin{cases} n_C & \text{for } r < R_C \\ n_C \left(\frac{r}{r_{core}}\right)^{-w} & \text{for } r > R_C \end{cases}$$

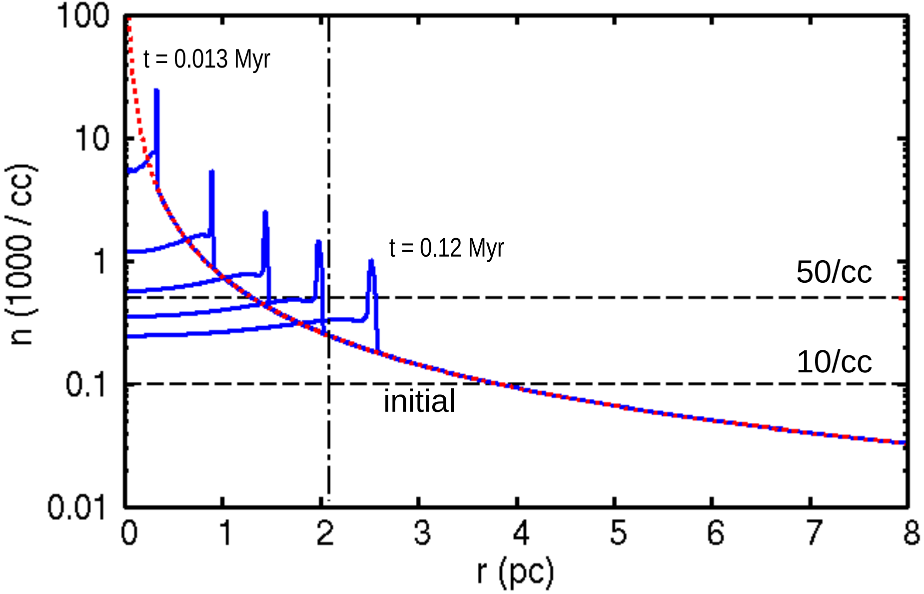
w=1.5

Snapshots

temperature

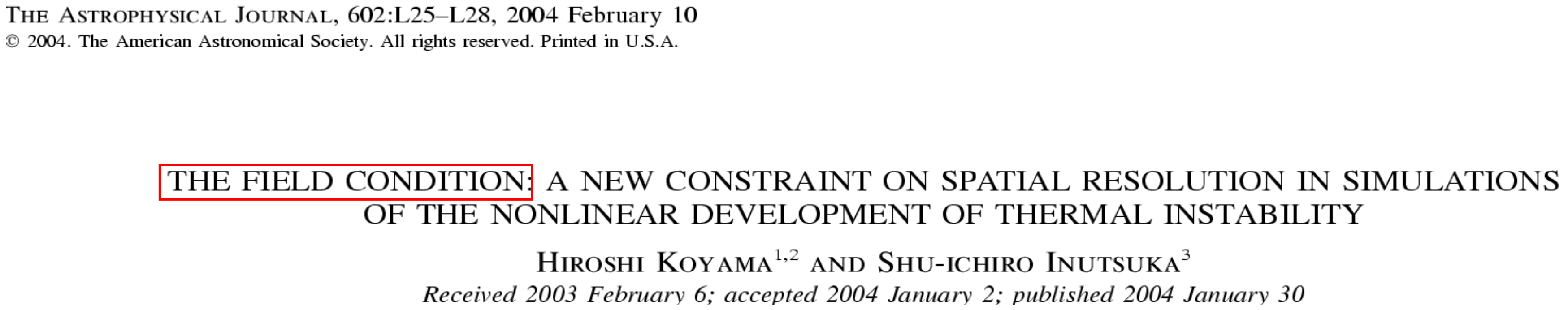


density



- at ~ 0.1Myr, the HII region expands to the observed radius of Sh219
- The HII, HI densities agree with the observed values.

Warning to Numerical Simulation



THE ASTROPHYSICAL JOURNAL, 602:L25–L28, 2004 February 10

THE FIELD CONDITION: A NEW CONSTRAINT ON SPATIAL RESOLUTION IN SIMULATIONS OF THE NONLINEAR DEVELOPMENT OF THERMAL INSTABILITY

HIROSHI KOYAMA[1,2] AND SHU-ICHIRO INUTSUKA[3]

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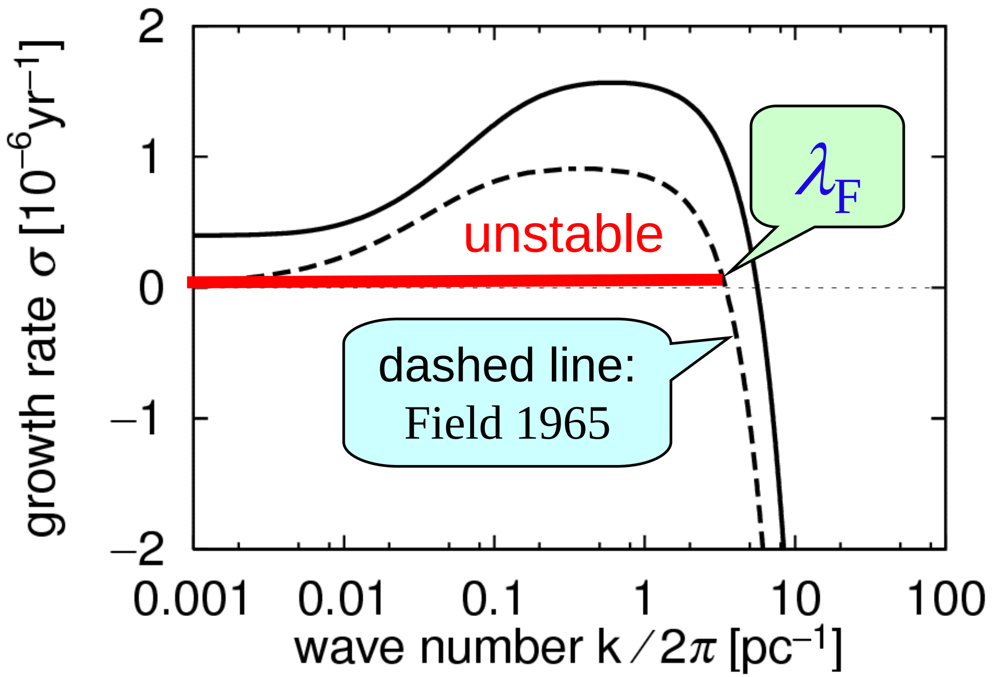
Requirement for
Spatial Resolution
"Field Condition"

We should resolve the structure of transition layer: λ_F



$$\text{"Field length"}: \lambda_F \equiv \sqrt{\frac{KT}{\rho^2 \Lambda}} \approx 10^{-2}\,\text{pc}$$

No convergence for $\Delta x > \lambda_F / 3$

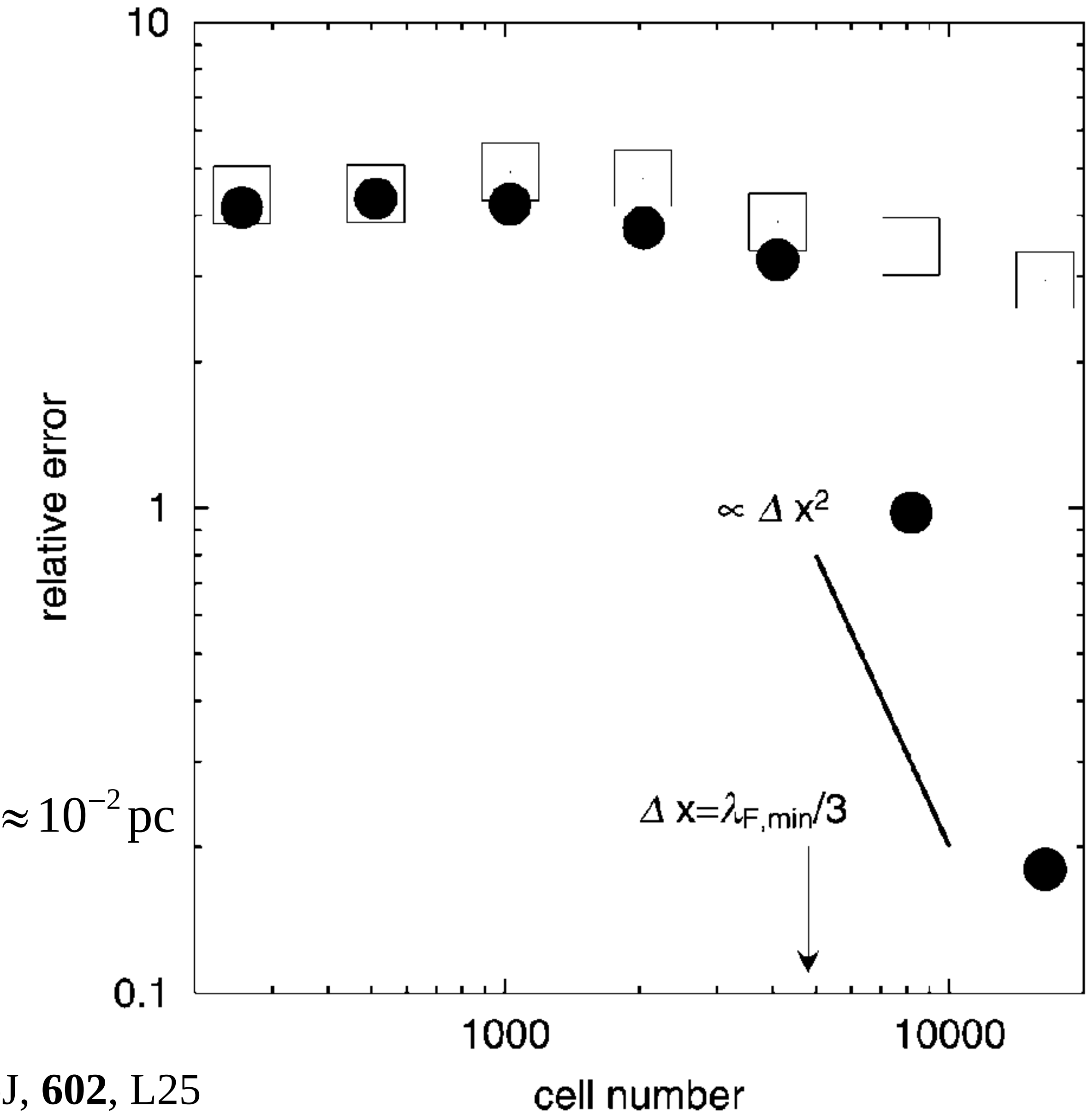
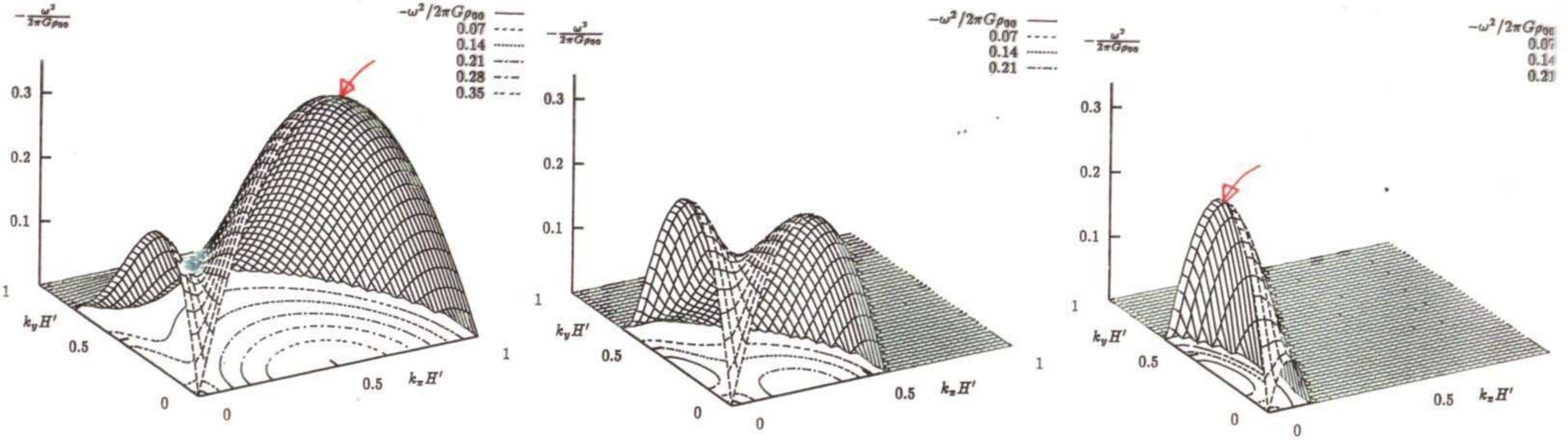


FIG. 3.—Convergence test for density distribution at $t = 8$ Myr. The error function is defined by eq. (6). Model CV (*open squares*) and model CCV (*filled circles*) are presented.

$$\text{“Field length”}: \lambda_F \equiv \sqrt{\frac{KT}{\rho^2 \Lambda}} \approx 10^{-2}\,\text{pc}$$

Koyama & Inutsuka (2004) ApJ, **602**, L25

Linear Stability Analysis of Magnetized Sheet-like Clouds



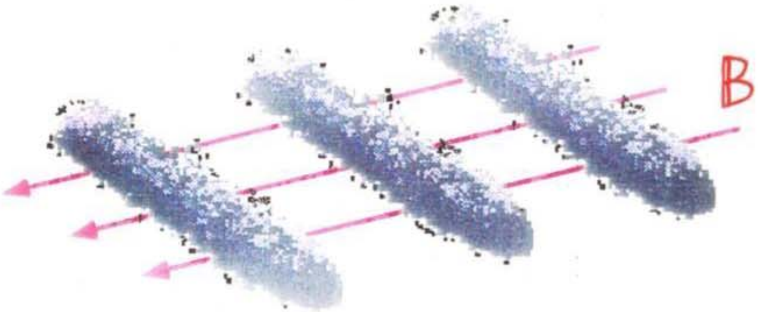
$\frac{Z_B}{H}$ = 5.0 $\quad$ $1/\sqrt{2}$ $\quad$ 0.1

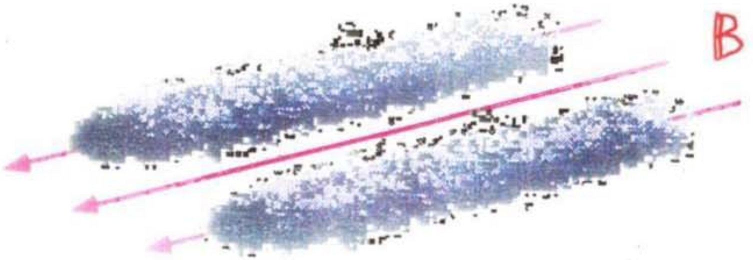
→ Large External Pressure

self-gravitating $\quad$ pressure-bound

$(k_x, k_y) = (k_{x\,max}, 0)$ most unstable

$(0, k_{y\,max})$ most unstable





Nagai, SI, & Miyama 1998, ApJ **506**, 306

Gravitational Fragmentation of Magnetized Sheet-like Clouds

Linear Analysis: Nagai, SI, & Miyama 1998, ApJ **506**, 306

Non-linear: Umekawa, Matsumoto, Miyaji, & Yoshida 1999, PASJ **51**, 625

Smaller $P_{\rm ext}$

Filament $\perp$ B

$M_{\rm Line} > M_{\rm Line,Crit} \equiv 2C_S^2/G$

Radial Collapse toward the Axis

Isothermal to Adiabatic □

minimum mass scale of fragment

$M \geq 0.1 M_{\odot}$

SI & Miyama 1997, ApJ **480**, 681

Masunaga & SI 1999, ApJ **510**, 822

Larger $P_{\rm ext}$

Filament $\parallel$ B

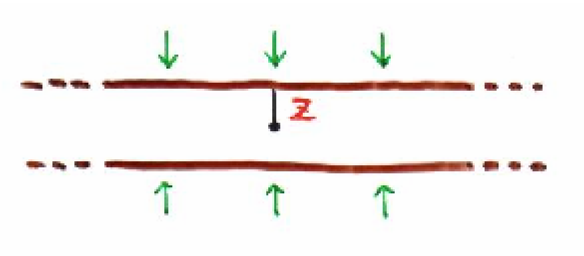
$M_{\rm Line} < M_{\rm Line,Crit}$

less-unstable filaments

no star formation▯

Character of Gravity

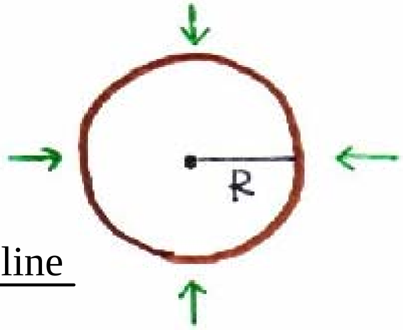
Sheet-Like Cloud



$$-\frac{\partial \Phi}{\partial z} \propto G\sigma$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial z} \propto \frac{C_S^2}{z}$$

Filamentary Cloud



$$-\frac{\partial \Phi}{\partial R} \propto \frac{2GM_{\mathrm{line}}}{R}$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial R} \propto \frac{C_S^2}{R}$$

Collapse cannot be halted by pressure.

SI & Miyama 1997, ApJ **480**, 681

Character of Gravity

Filamentary Cloud

$$-\frac{\partial \Phi}{\partial R} \propto \frac{2GM_{\text{line}}}{R}$$

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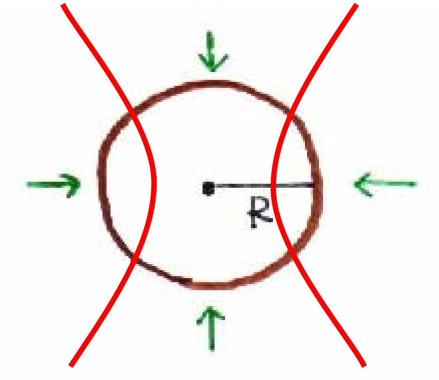

$$-\frac{1}{\rho}\frac{\partial B^2}{\partial R} \propto \frac{1}{R}$$

Collapse cannot be halted by pressure and magnetic field.

Isothermal EoS of Gas

In dense region, **gas** and **dust grains** are thermally well coupled.

Heating rate ($\Gamma_{\mathbf{g}}$) and Cooling rate ($\Lambda_{\mathbf{g}}$) of **Dust Grains**

initially negligible

$$4\pi\kappa\rho\langle I\rangle \quad \text{[redacted]} \quad = \quad 4\pi\kappa\rho\sigma_{\mathrm{SB}}T^4 \equiv \Lambda_{\mathrm{thin}}$$

radiative heating collisional heating by gas radiative cooling

Grains stay almost isothermal unless the gas is heated up by rapid contraction, shock, etc.

(Gaustad 1963, ApJ 138, 1050; Hayashi 1966, ARAA 4, 171)

Transition from Isothermal to Adiabatic Evolution

SI & Miyama 1997, ApJ **480**, 681; Masunaga & SI 1999, ApJ **510**, 822