Effects of radiation on superbubbles in a dense medium

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Introduction

Energetic winds and radiation from massive star clusters push the surrounding gas and blow superbubbles in the interstellar medium.

Using 1-D hydrodynamic simulations, we study the role of radiation in the dynamics of superbubbles driven by a young star cluster of mass $\sim 10^6\,\mathrm{M}_\odot$. We have considered a realistic time evolution of the mechanical power as well as radiation power of the star cluster, detailed heating and cooling processes.

We compare the radiation pressure with the thermal pressure of the shocked wind region ($\sim 10^7\mathrm{K}$) and show that in dense media ($\gtrsim 10^2 m_\mathrm{H}\,\mathrm{cm}^{-3}$), the radiation pressure is dynamically important at early stages ($\lesssim 1\,\mathrm{Myr}$) of bubble evolution. At early times, the radiation pressure can play an important role in launching the shock into the ISM. We explore the parameter space of density and dust opacity of the ambient medium, and find that the size of the hot gas cavity is insensitive to the dust opacity $\sigma_d \approx (0.1-1.5)\times 10^{-21}\mathrm{cm}^2$ but the structure of the photoionized ($\sim 10^4\mathrm{K}$) gas depends on it. We calculate the effect of radiation in the total energy budget, and discuss the implications of ionization parameter and recombination-averaged density in understanding the dominant feedback mechanism. Finally, we compare our results with the observations of 30 Doradus.

The role of radiation pressure

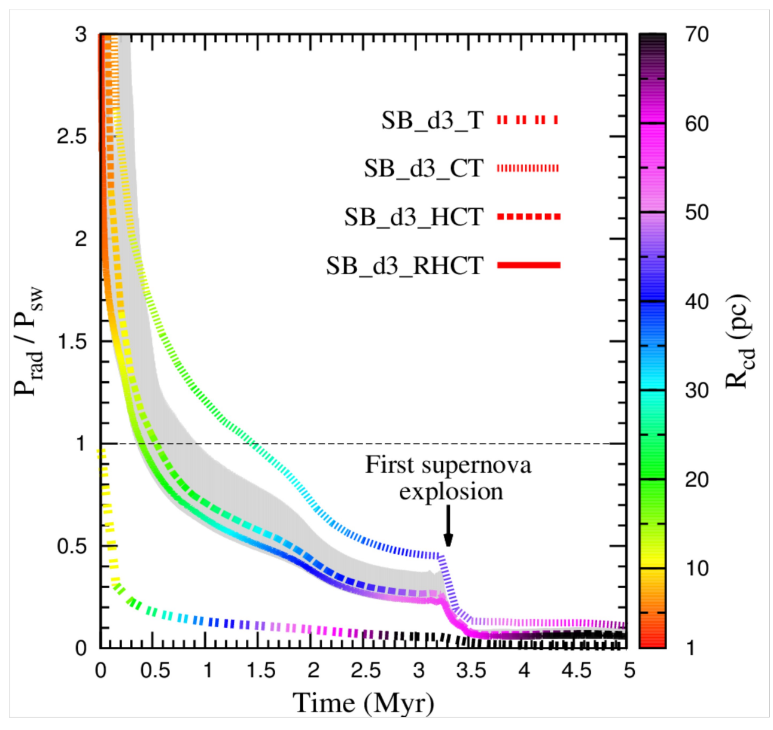

Figure 5 : The ratio of radiation pressure (P_{rad}) to the thermal pressure (P_{sw}). The shaded region shows this ratio for densities $1 \lesssim \rho_{amb} \lesssim 10^4 m_\mathrm{H}\,\mathrm{cm}^{-3}$.

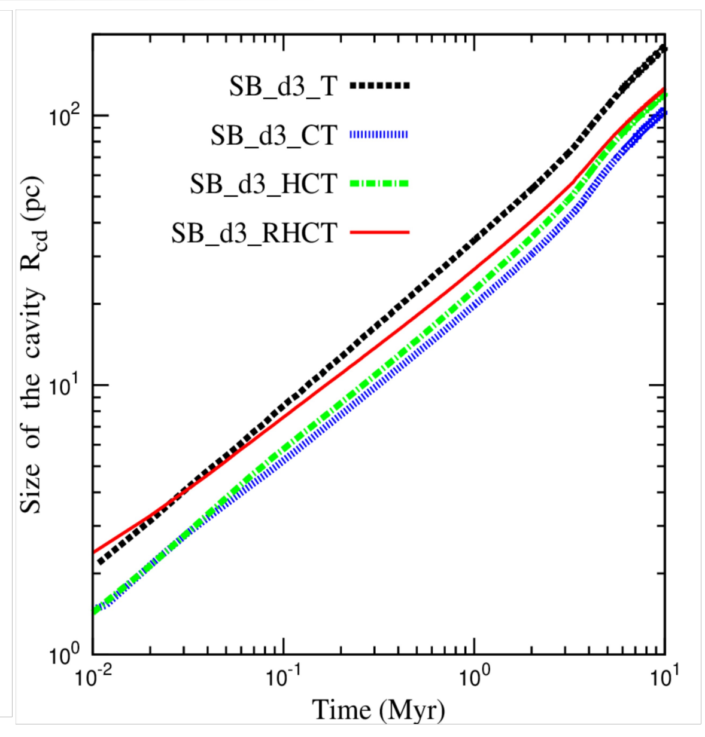

Figure 6 : The size of bubble in the absence/presence of different processes.

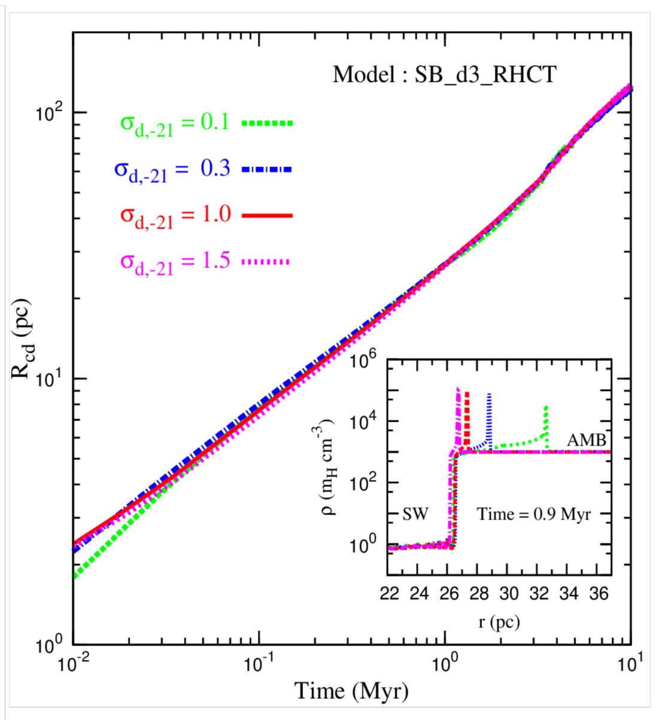

Figure 7 : The dependence of bubble size on dust opacity (σ_d) of the ambient medium. The inset shows the zoomed-in view of the shell for different dust opacities.

The ratio of radiation pressure (P_{rad}) to thermal pressure of the shocked wind region (P_{sw})

$$\frac{P_{rad}}{P_{sw}} = f_{trap}\frac{L_{bol}/(4\pi\, c\, R_{cd}^2)}{\rho_{amb}\, v_s^2},$$

v_s The shock velocity , ρ_{amb} the ambient density
R_{cd} Position of the contact discontinuity ,
L_{bol} Bolometric luminosity , f_{trap} trapping fraction

Time evolution of mechanical and radiation power

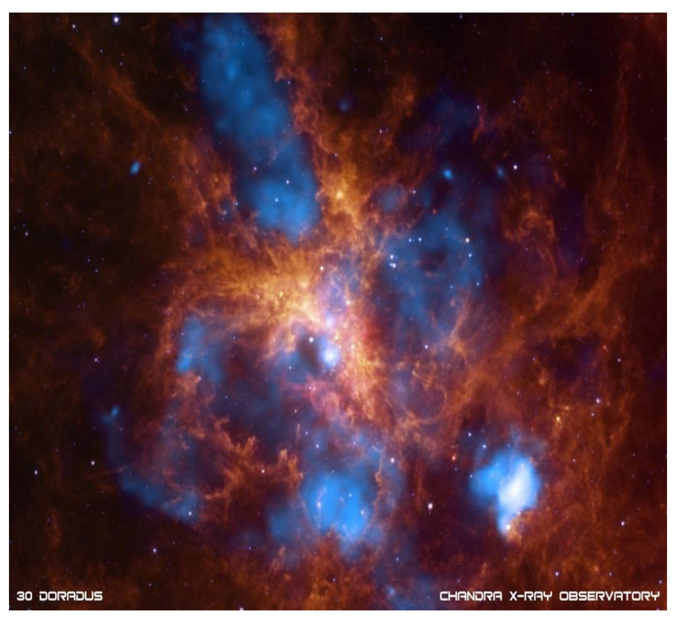

Figure 1: 30 Doradus is a young star cluster, located in the Large Magellanic Cloud.
Colour code : Orange - Infrared, Blue - X-rays.
Source : http://chandra.harvard.edu/photo/2011/30dor

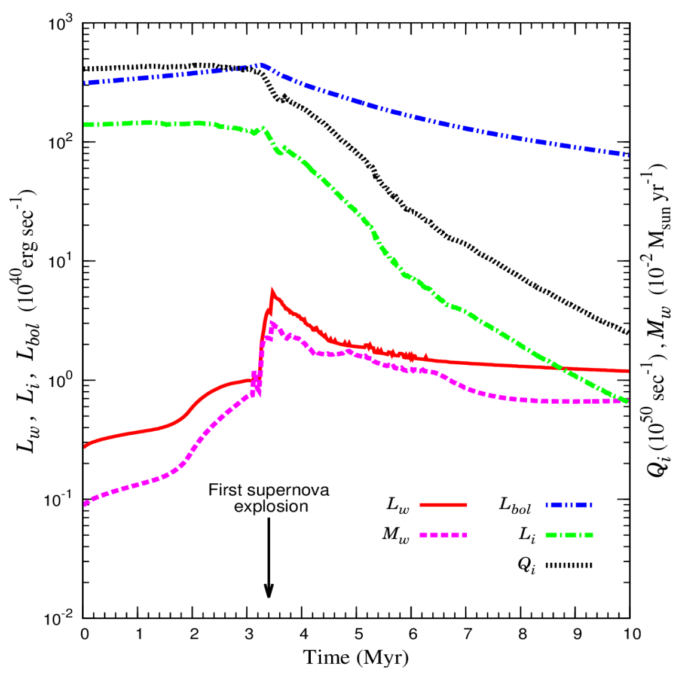

Figure 2: Star cluster output as a function of time.
L_w mechanical luminosity, M_w mass-loss rate,
L_{bol} bolometric luminosity, L_i ionizing luminosity,
Q_i ionizing photons flux
(Starburst99 -Leitherer et al. 1999)

Cooling losses and total energy budget

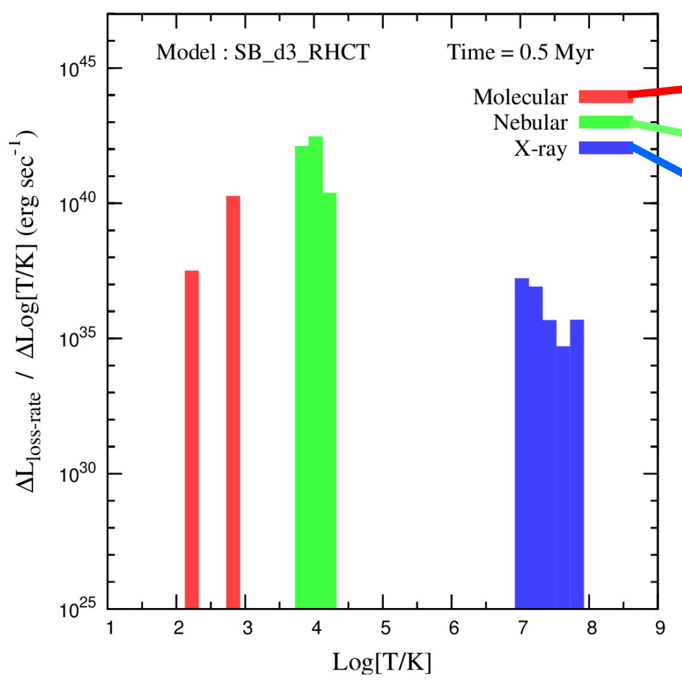

Figure 8: Temperature distribution of cooling losses at 0.5 Myr.

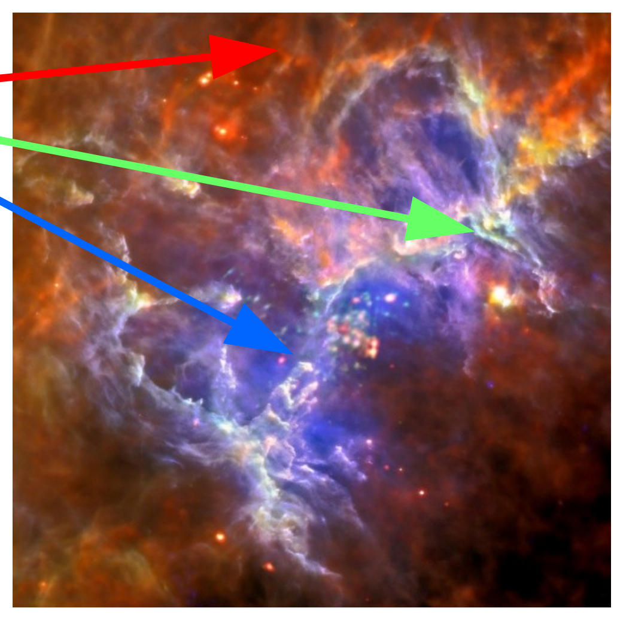

Figure 9: Multi wavelength image of the Eagle Nebula, which is located in the constellation Serpens.
Source:http://herschel.cf.ac.uk/results/eagle-nebula

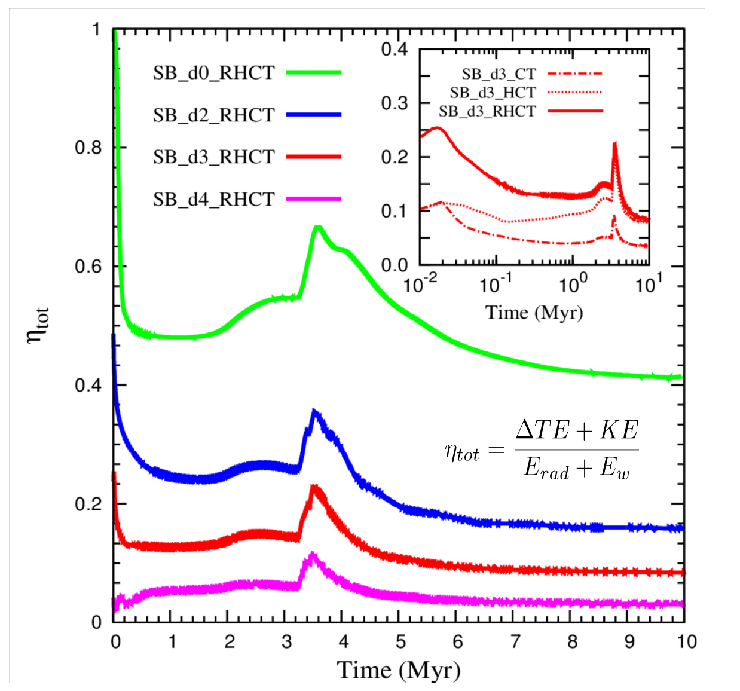

Figure 10 : Fraction of total input energy retention in our superbubbles as a function of time. The inset shows η_{tot} in the presence or/and absence of different physical processes.

Hydrodynamic equations coupled with radiation

1. Mass conservation equation :

$$\frac{\partial\rho}{\partial t} + \vec{\nabla}.(\rho\,\vec{v}) = \underbrace{S_\rho}_{\text{Mechanical mass-rate density}}$$

2. Momentum conservation equation :

$$\frac{\partial}{\partial t}(\rho\,\vec{v}) + \vec{\nabla}.(\rho\,\vec{v}\otimes\vec{v}) + \vec{\nabla}p = \underbrace{\rho\,\vec{a}_{rad}}_{\text{Radiation force density}}$$

Equations are solved in spherical 1-D geometry by using PLUTO (Mignone et al. 2007)

3. Energy conservation equation :

$$\frac{\partial}{\partial t}\left(\epsilon\rho + \frac{\rho v^2}{2}\right) + \vec{\nabla}.\left[\left(\epsilon\rho + \frac{\rho v^2}{2} + P\right)\vec{v}\right] = \underbrace{S_e}_{\text{Mechanical power density}} + \overbrace{(-\vec{\nabla}.\vec{F}_c)}^{\text{Thermal conduction}} + \underbrace{(-q^-)}_{\text{Cooling}} + \overbrace{(q^+)}^{\text{Heating}} + \underbrace{(\rho\,\vec{v}.\vec{a}_{rad})}_{\text{Radiation energy density}}$$

Observational parameters

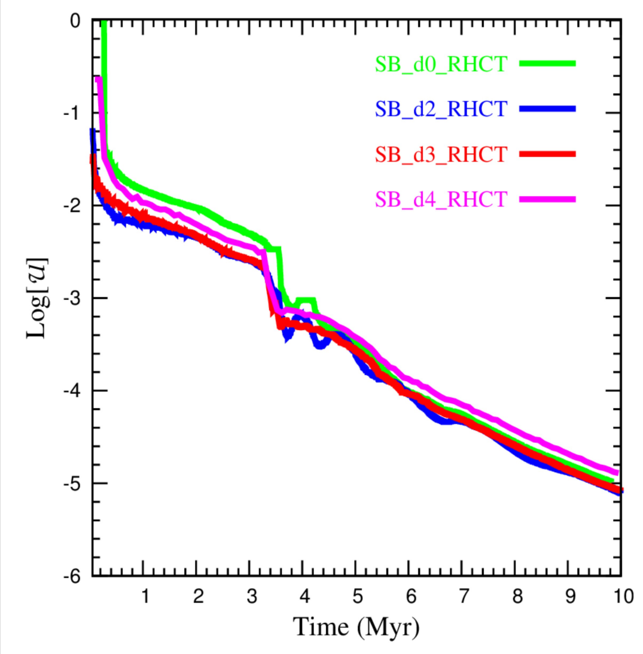

Figure 11 : Time evolution of ionization parameters for different ambient densities.

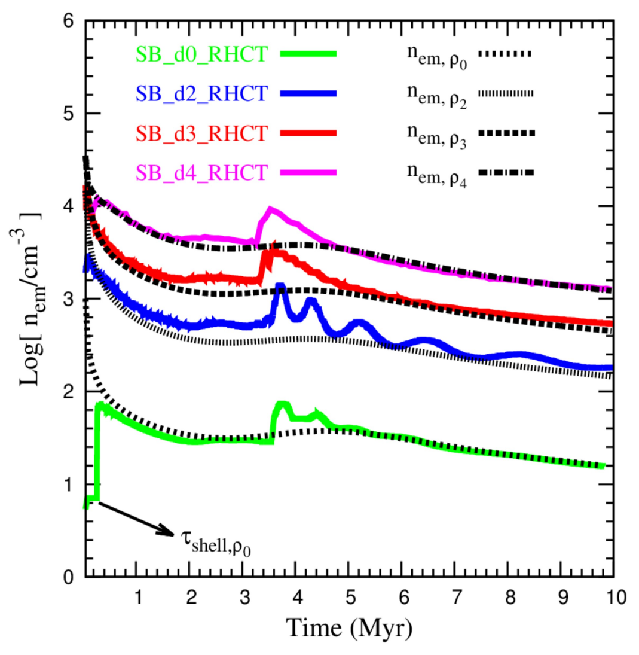

Figure 12 : Time evolution of recombination-averaged density for different ambient densities.

Ionization parameters (U) :

$$U = \frac{Q_i}{4\pi\, c\, R_{cd}^2\, n_{shell}} = \left(\frac{k_B T_i}{\langle h\nu\rangle_i}\right)\frac{P_{rad}}{P_\mathrm{HII}}$$

$\Rightarrow$ U depends on source parameters.

Recombination-averaged density :

$$n_{em} \approx \mathcal{M}^2 (T_{amb}/T_i) n_{amb}$$

$\Rightarrow$ Strength of the spectral lines ($\propto n_{em}$) depends on the upstream Mach number

Effects of the radiation on the structure of a bubble

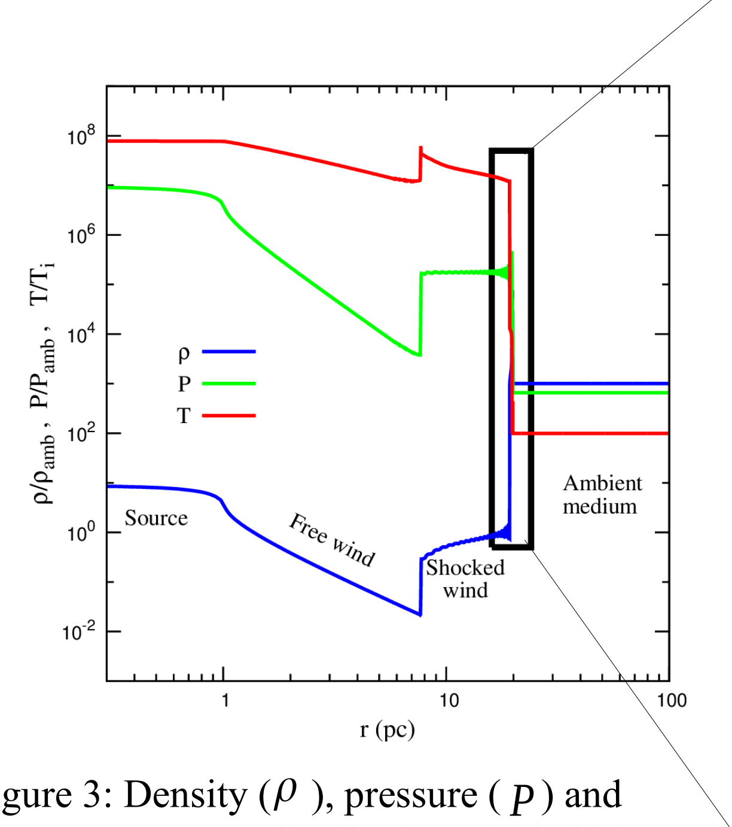

Figure 3: Density (ρ), pressure (p) and temperature (T) distribution of a bubble at 0.55 Myr.

SB_d3_RHCT : 'SB' - Starburst99, 'd3' – ambient density $10^3 m_\mathrm{H}\,\mathrm{cm}^{-3}$, 'T' - Thermal conduction, 'C' - cooling, 'H' – heating, 'R' – radiation pressure.

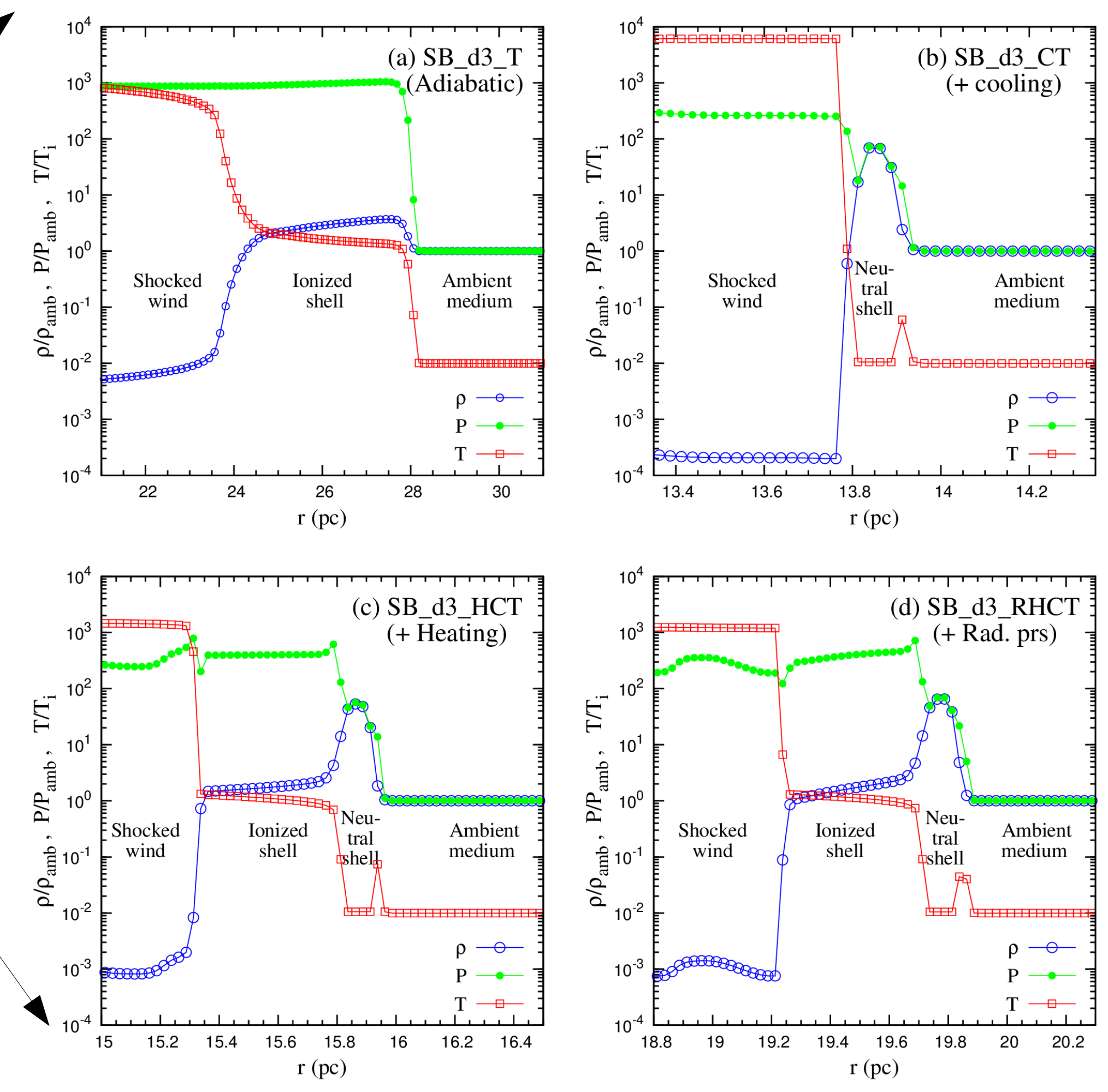

Figure 4 : The zoomed-in view of the shell at 0.55 Myr.

Summary

1. The effective dynamical force (Figure 5) :
The role of radiation pressure is important at early times ($\lesssim 1\,\mathrm{Myr}$). At later times, radiation heating and wind controls the dynamics of the bubble.

2. Dust opacity dependence (Figure 7) :
For a given ambient density and input source parameters, the size of the cavity depends weakly on the dust opacity ($\sigma_d \approx (0.1-1.5)\times 10^{-21}\mathrm{cm}^2$) of the ambient medium.

3. The effect of radiation in the total energy budget (Figure 10) :
A comparison of the total energy budget with and without radiation shows that radiation can increase the total energy efficiency by a factor of two.

4. Observational parameters (Figure 11, 12) :
The ionization parameter depends on the input source profile rather than the density of the ambient medium. Therefore, it can be used to model the luminosty of the input source. The strength of the spectral lines depends on the Mach number of the shock.

5. 30 Doradus :
At early times ($\lesssim 1\,\mathrm{Myr}$), the dynamics of 30 Doradus is controlled by radiation pressure.

References :

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