ASTRONOMY 405, Spring 2013

Homework 11, due on April 22

1. Massive stars blow bubbles in the interstellar medium (ISM). Assume that a massive star with a wind mass loss rate $\dot{M}$ and velocity $V_{\rm w}$ is in a homogeneous ISM of density ρ_0. Assume further that the ambient medium is swept into a thin shell.

   (a) For a mass loss rate $\dot{M} = 10^{-5}$ $M_\odot$/yr and an ambient density is 1 H-atom cm^{-3}, show that the total wind mass lost in 10^5 years is negligible compared to the interstellar mass within a radius of 5 pc.

   (b) Show that $r(t) = (25\dot{M}V_{\rm w}^2/12\pi\rho_0)^{1/5}\ t^{3/5}$, if the kinetic energy of the stellar wind is conserved. *(i.e., the kinetic energy of the stellar wind has been totally deposited in the shell.)*

   (c) Show that the radius of the shell $r(t) = (3\dot{M}V_{\rm w}/2\pi\rho_0)^{1/4}\ t^{1/2}$, if the momentum of the fast wind is conserved. *(i.e., the momentum of the stellar wind has been totally deposited in the shell.)*

2. To distinguish between an adiabatic shock from an isothermal shock, we compare the cooling time scale and the dynamic time scale. The cooling time scale τ_t = (thermal energy) / (cooling rate) $\approx kT/\Lambda N_e$, where T is the kinetic temperature, Λ is the cooling function ($\sim 2\times10^{-23}$ erg cm^3 s^{-1} at $T > 10^6$ K, $\sim 5\times10^{-22}$ erg cm^3 s^{-1} at $T = 10^4 - 10^5$ K), and N_e is the electron density. The dynamic time scale τ_d = (width of the post-shock relaxation layer) / (shock velocity) $\approx L/V_s$. If $\tau_t > \tau_d$, the shock is adiabatic; if If $\tau_t < \tau_d$, the shock is isothermal.

   Let's consider a stellar wind blown bubble, for which the stellar wind velocity is 2500 km/s, the wind mass loss rate is 10^{-5} $M_\odot$/yr, the ambient density is 1 H-atom cm^{-3}, and the shell expansion velocity is 35 km/s. Two shocks are present in a bubble. The inner shock is where the stellar wind is shocked, while the outer shock is where the shell expands into the ambient ISM.

   (a) Assume an adiabatic shock and calculate the post-shock temperature for both the inner shock and the outer shock.

   (b) Calculate the cooling time scale for both the inner shock and the outer shock. *(Hint: For the stellar wind, you need to use $\dot{M}$ and $V_{\rm w}$ estimate the density of the wind. Assume that the wind is shocked at 1 pc from the central star.)*

   (c) Calculate the dynamic time scale for the inner shock, assuming the post-shock relaxation layer is 1 pc wide. Calculate also the dynamic time scale for the outer shock, assuming that the post-shock relaxation layer is 0.1 pc wide.

   (d) Are the inner and outer shocks adiabatic or isothermal?

   (e) What is the age of the bubble for a bubble radius of 5 pc?