

ISM

2008

Programme

- A** Introduction: Observations of the ISM
- B** Microscopic Processes (ref. Dyson & Williams + Spitzer + Shu).
- C** Astrophysics of Gaseous Nebulae (ref. Osterbrock + review de Williams).
- D** Interstellar Dust.
1. Extinction law + VSGs.
 2. Spectroscopy: mineralogy of the ISM.
 3. Polarimetry, alignment processes & reflection nebulae.
 4. Crystalline grains.
 5. Thermal Equilibrium.
 6. Origin & life-cycle of dust: processing in the ISM.

<http://www.das.uchile.cl/simon>

E Dynamics of the ISM

1. J shocks
2. C shocks
3. Supernova remnants
4. Ionisation fronts
5. Cloud equilibrium

E-1 J shocks

- References:

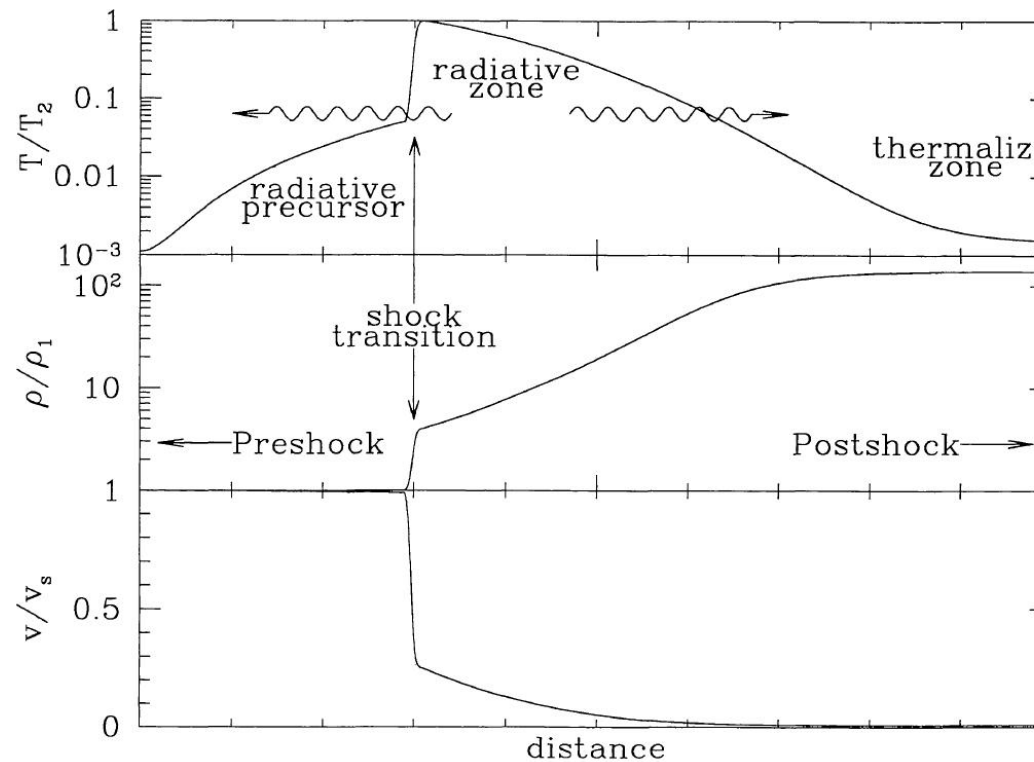
Tielens 2005

Draine & Mc Kee, 2003, ARA&A, 31, 373

- Shocks are irreversible processes: ordered kinetic energy from stellar winds, supernova shock waves, etc ..., is converted into heat and chemical processes, with a concomitant entropy increase.
- Shocks are at the origin of the large-scale structure of the ISM and of the hot-shocked plasma phase ($\sim 10^6$ K).
- There are two broad types of shocks: J (jump) shocks and C (continuous) shocks. J-types are strong shocks that occur in all phases of the ISM, while C shocks are found in (magnetised) molecular clouds. The main difference between C and J shocks is the shock velocity. The minimum velocity for J-shocks is $\sim 40 \text{ km s}^{-1}$.

E-1 J shocks

- In shocks the preferred reference system is that of the shock itself: the preshock gas flows towards the shock at the shock velocity v_s , while the postshock gas moves with the shock front, so has ~ 0 velocity relative to the shock.



E-1 Jump conditions

- J shocks are supersonic discontinuities. The speed of the shock can be expressed with the Mach number, $M = v_s/c_s$, where $c_s = \sqrt{\partial p/\partial \rho|_S}$ is the sound speed. For an adiabat $P \propto \rho^\gamma$ and the equation of state $P = \rho kT/\mu$, with $\gamma = 5/3$, $c_s = \sqrt{5/3 kT/\mu}$.
- The fluid equations of motions take on simple forms when integrated across sharp discontinuities. These are the Rankine-Hugoniot jump conditions, which express the conservation of mass, momentum and energy flux.
- The flux of any scalar quantity per unit mass ϕ is $\phi \rho v$. Examples:
 - ★ mass flux is ρv ,
 - ★ momentum flux is $(\rho v)v$ (v is the momentum per unit mass),
 - ★ kinetic energy flux is $(\rho v)(v^2/2)$,
 - ★ internal energy flux $(\rho v)(u/\rho)$, where $u = \sum_i (u_i + n_i I_i)$ is the internal energy per unit volume, and I_i is the binding energy of specie i , with number density n_i .

E-1 Rankine-Hugoniot conditions

$$\rho_0 v_0 = \rho_1 v_1, \quad \text{mass}, \quad (1)$$

$$\rho_0 v_0^2 + P_0 = \rho_1 v_1^2 + P_1, \quad \text{momentum}, \quad (2)$$

$$\frac{1}{2} v_0^2 + \frac{u_0}{\rho_0} + \frac{P_0}{\rho_0} = \frac{1}{2} v_1^2 + \frac{u_1}{\rho_1} + \frac{P_1}{\rho_1}, \quad \text{energy}. \quad (3)$$

Eq. 3 derives from equating $P_0 v_0 - P_1 v_1$, the work done by the shock per unit time, to the net energy flux through the shock: $E_1 - E_0$, where

$$E_i = \rho_i v_i \left(\frac{1}{2} v_i^2 + \frac{u_i}{\rho_i} \right).$$

Note Eq. 3 expresses energy conservation for an adiabatic shock - without radiative losses, which are important for the evolution of the shock.

E-1 Solution of the jump conditions

For an ideal gas in an adiabatic shock, manipulation of the jump conditions gives (tarea):

$$\frac{P_1}{P_0} = \frac{2\gamma M^2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1}, \quad (4)$$

$$\frac{\rho_0}{\rho_1} = \frac{\gamma - 1}{\gamma + 1} + \frac{2}{\gamma + 1} \frac{1}{M^2}, \quad (5)$$

$$v_i^2 = \frac{1}{\rho_i^2} (P_1 - P_0) \left(\frac{1}{\rho_0} - \frac{1}{\rho_1} \right)^{-1}. \quad (6)$$

For strong shocks, $M \gg 1$,

$$\frac{\rho_1}{\rho_0} = \frac{\gamma + 1}{\gamma - 1} \quad (= 4 \text{ for an ideal monatomic gas}), \quad (7)$$

$$P_1 = \frac{2}{\gamma + 1} \rho_0 v_0^2 \quad (= \frac{3}{4} \rho_0 v_0^2), \quad (8)$$

$$v_1 = v_0/4. \quad (9)$$

E-1 Temperature rise at the shock front

For an ideal gas, Eq. 8 gives

$$T_1 = \frac{2(\gamma - 1) \mu v_0^2}{\gamma + 1 k} = \frac{3 \mu}{16 k} v_0^2, \quad \text{for a monatomic gas.}$$

In a cosmic mix with a He abundance of -1 dex, $\mu/m_p = \sum n_i m_i / \sum n_i \approx 0.56$ for fully ionised gas, ≈ 1.3 for neutral gas, and ≈ 2.4 for molecular gas.

Thus, independently of the preshock phase,

$$T_1 \approx \frac{\mu}{m_p} 2.5 \cdot 10^5 \left(\frac{v_0}{100 \text{ km s}^{-1}} \right)^2 \text{ K}$$

E-1 Downstream conditions

Away from the (idealised) adiabatic shock front and into the postshock region, radiative losses decrease the temperature.

The flux of radiative energy F_{rad} varies as

$$\frac{d}{dz}F_{\text{rad}} = n^2\Lambda - n\Gamma - 4\pi\kappa J,$$

where z is a coordinate along the shock propagation, n is number density, Λ and Γ are the cooling and heating rates, respectively, and J is the average intensity from other regions in the shock.

At some distance from the shock front, in a region which we may label as “2”, the shocked gas will eventually relax to its preshock conditions, in region “0”. We may apply the jump conditions to the 0–2 discontinuity, with an isothermal gas ($\gamma = 1$), so that Eq. 5 gives

$$\rho_2/\rho_1 = M^2.$$

We see shock waves are very compressive!

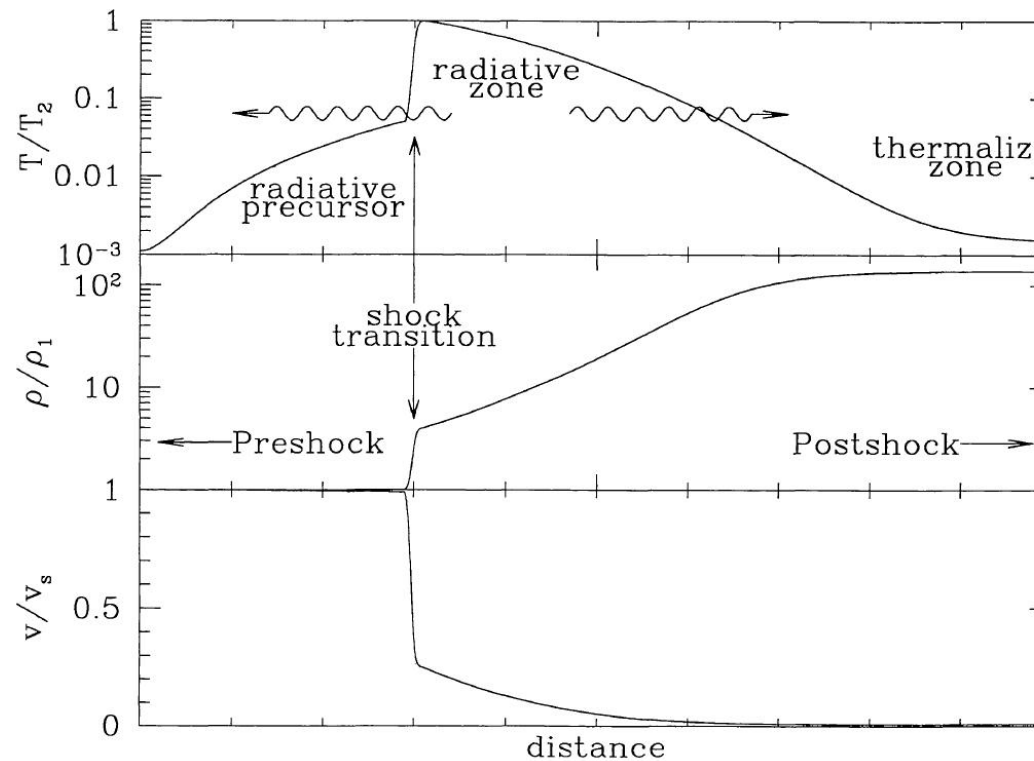
E-1 Downstream conditions

However, at very high temperatures the cooling rate is dominated by recombinations, with a rate $\Lambda \propto \sqrt{T}$, so that the cooling time scale, $\tau_{cool} = kT/(n\Lambda(T)) \propto \sqrt{T}$.

Hence, if the shock is very strong $M \gg 1$, the postshock temperature can be arbitrarily high, and τ_{cool} correspondingly long - and possibly even longer than the lifetime of the shock (or the dynamical time scale). If so then the postshock region never relaxes, as is the case of the ISM hot-shocked by SNRs.

E-1 Precursor ionisation

In fast shock, if the postshock temperature reaches $\sim 10^5$ K, then H I is collisionally ionised and radiates in the Lyman continuum. The correspond ionising radiation overtakes the shock front and ionises the preshock gas.



E-1 J shock chemistry

- Shocks lead to dissociation/ionisation and eventually to molecule formation in the relaxation zone behind the shock front.
- The shock chemistry is radically different from the ion-molecule chemistry that occurs in quiescent dark clouds.
- Collisional H_2 dissociation occurs for gas at $> 10^5$ K, or shock velocities higher than 50 km s^{-1} .
- In the postshock region, with elevated temperatures, the chemistry taps on the gas internal energy to generate molecules via endothermic reactions. The key players in this chemistry are H, H_2 and O (assuming a cosmic mix with $\text{O} > \text{C}$).
 - ★ If H_2 is not dissociated, then reactions with O leads to the formation of H_2O , so that the most abundant molecules are H_2 , H_2O , CO, and O_2 . Important trace molecules, characteristic of non-dissociating shocks, are CH^+ , SiO, H_2S .
 - ★ If H_2 is dissociated, loose H atoms collisionally dissociate molecules so that most of the gas is atomic (as expected from ~ 1000 K gas).

E-1 J shock spectra

- The spectra of non-ionising shocks reflect their chemistry.
- Ionising shocks lead to very hot, 10^6 K, gas and bright in X-rays. If the density is low, then the cooling timescale exceeds the shock lifetime, and columns are low, so that not much emission is found at UV-optical-IR wavelengths.
- If driven into dense media, ionising shocks may relax in the post-shock region, which is very compressed. The columns are then high enough for the detection of bright optical/IR collisionally excited fine structure lines.

- Since the relaxation zones dominate by mass the fully-ionised regions, the spectra of ionising shocks is dominated by low-excitation species, which are normally found in higher-ionisation stages in H II regions.
- Two (among many) popular diagnostics for shock excitation versus photionisation are:
 - ★ The ratio of [N II] $\lambda\lambda 6548, 6584$ to $H\alpha$ $\lambda 6565$ - [N II] is not as bright in H II regions than in shocks
 - ★ The ratio [Fe II] $1.644\mu\text{m}$ / $Br\gamma$ $2.166\mu\text{m}$ is high in shocks, because in H II regions Fe would be found in higher ionisation stages.

E-2 C shocks

- For interstellar conditions, the magnetic field is “frozen” to matter. The magnetic flux $\Phi = \int_S \vec{B} \cdot d\vec{S}$, where S is some surface tied to the fluid, is constant.
- When the gas is compressed perpendicular to \vec{B} , the field intensity increases so that $\Phi = SB$ is kept constant. As a result

$$B \approx \sqrt{n/1 \text{ cm}^{-3}} \mu\text{G}. \quad (10)$$

- Thus magnetic field intensities in dense molecular gas are high, and we must modify the shock equations to include the coupling of the magnetic field to the residual ionisation induced by cosmic ray ionizations.

E-2 C shocks

- Cosmic ray ionisation predicts an ionisation fraction of $x \approx 10^{-8} - 10^{-7}$, as observed (e.g. Wootten et al., 1979, ApJ, 234, 876).
- Most of the negative charge in molecular gas is found in PAH anions - they sweep out all the e^- ejected by the cosmic ray ionisation of H_2 .
- Magnetised shocks are thus 2 fluid shocks: the ions, which directly couple to the magnetic field, and the neutrals, which lag behind the ions and are coupled to the field by collision and frictional drag with the ions.

E-2 C shocks

- The linearisation of the hydromagnetic equations shows that magnetised media sustain a wide variety of magnetosonic waves (an extension of sound waves).
- The type of Alfvén waves that is most relevant to shocks are transversal oscillations of the magnetic field lines, as in vibrating strings. Their speed is $v_A = B(4\pi\rho_i)^{-1/2}$, where ρ_i is the mass density of the ion fluid.
- The Alfvén waves propagate the shock signal upstream, compressing the ions and dragging the neutrals. The wave energy is dissipated by ion-neutral friction, which raises the temperature.
- The shock front is merged with the relaxation layers. Thus magnetic shocks are continuous (C-shocks).

E-2 Structure of C shock: shock width

- The characteristic length over which the neutral fluid velocity changes is $L \approx v_d / (n_i k_L)$, where $v_d = v_i - v_n$ is the ion-neutral drift velocity (which can be of the order of the shock velocity since the ions are first set in motion, and subsequently drag the neutrals - v_d values can be as high as $\sim 30 \text{ km s}^{-1}$), and $k_L = \langle w \sigma_{in} \rangle \approx 10^{-7} \text{ cm}^3 \text{ s}^{-1}$ is the Langevin rate (the number of ion-neutral collisions per ion per unit time, where w is ion-neutral relative velocities in the frame of the neutrals).
- As for the calculation in J-shocks, the maximum compression of ions is $(n_i / n_{i,0}) \approx v_s / v_A$, where v_s / v_A is an extension of the Mach number and $n_{i,0}$ is the pre-shock ion density. A working number for the ion-neutral drift velocity is half the shock velocity. Thus

$$L \approx \frac{v_A}{2n_{i,0}k_L}.$$

- Assuming Eq. 10, we obtain $L \approx 1.1 \cdot 10^5 / (n_{i,0} k_L) \approx 10^{15} \text{ cm}$ if the pre-shock proton density is 10^5 and the ionisation fraction is $x \sim 10^{-8}$.

E-2 Structure of C shock: thermal balance

- Heating comes from the mechanical energy of the shock wave, hence

$$n\Gamma \approx \underbrace{\rho_0 v_s^2}_{\text{shock kinetic energy density}} \underbrace{\left(v_s / L \right)}_{\text{shock timescale}} .$$

- Shock cooling comes from H₂ rotational lines:

$$n^2 \Lambda(T) = 2.5 \cdot 10^{-33} n T^{3.82} \text{ erg cm}^{-3} \text{ s}^{-1} .$$

- Energy balance then gives the postshock temperature, $T \approx 1000 - 3000$ K for a 10 km s^{-1} shock with $L = 10^{15}$ cm and a factor of two density compression.

E-2 Structure of C shock: detailed calculations

From Kaufman & Neufeld, 1996, ApJ, 456, 611:

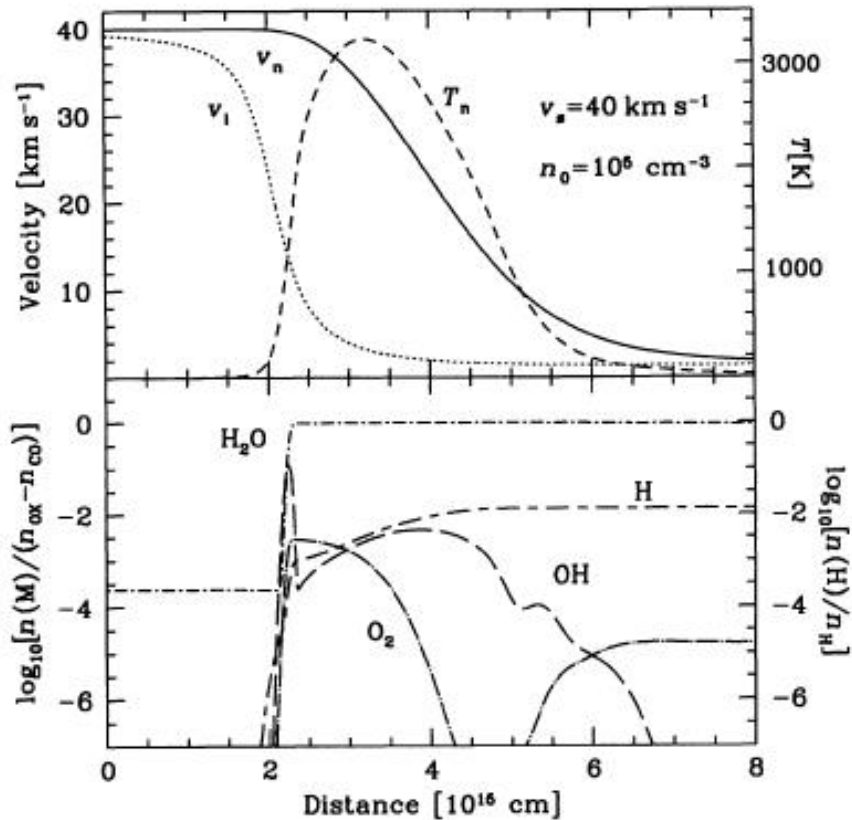


FIG. 1.—Shock profiles for a 40 km s^{-1} MHD shock propagating in gas of preshock H_2 density 10^5 cm^{-3} , and with a preshock magnetic field of $447 \mu\text{G}$. The upper panel shows the flow velocities of the neutral fluid (v_n) and the ionized fluid (v_i) and the temperature of the neutral fluid (T_n) as a function of distance through the shocked region. The lower panel shows the abundances of the species O_2 , OH , H_2O , and H [expressed relative to H nuclei in the case of H atoms (*right axis*) and relative to O nuclei not locked in CO in the case of O_2 , OH , and H_2O (*left axis*)].

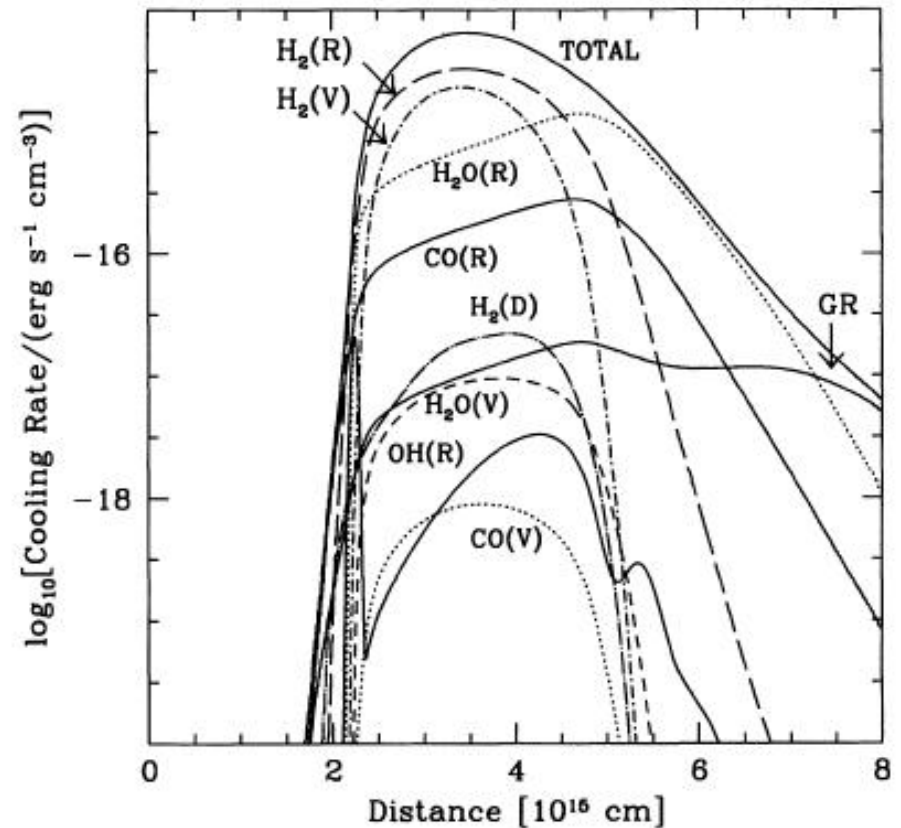


FIG. 2.—Cooling rate per unit volume attributable to vibrational (V) and rotational (R) emissions of CO , H_2 , OH , and H_2O ; from gas-grain collisions (GR); from H_2 dissociation [$\text{H}_2(\text{D})$]; and from all processes combined (TOTAL). Results apply to a shock with $v_s = 40 \text{ km s}^{-1}$ and $n_0 = 10^5 \text{ cm}^{-3}$ and a preshock magnetic field of $447 \mu\text{G}$.

E-2 Structure of C shock: detailed calculations

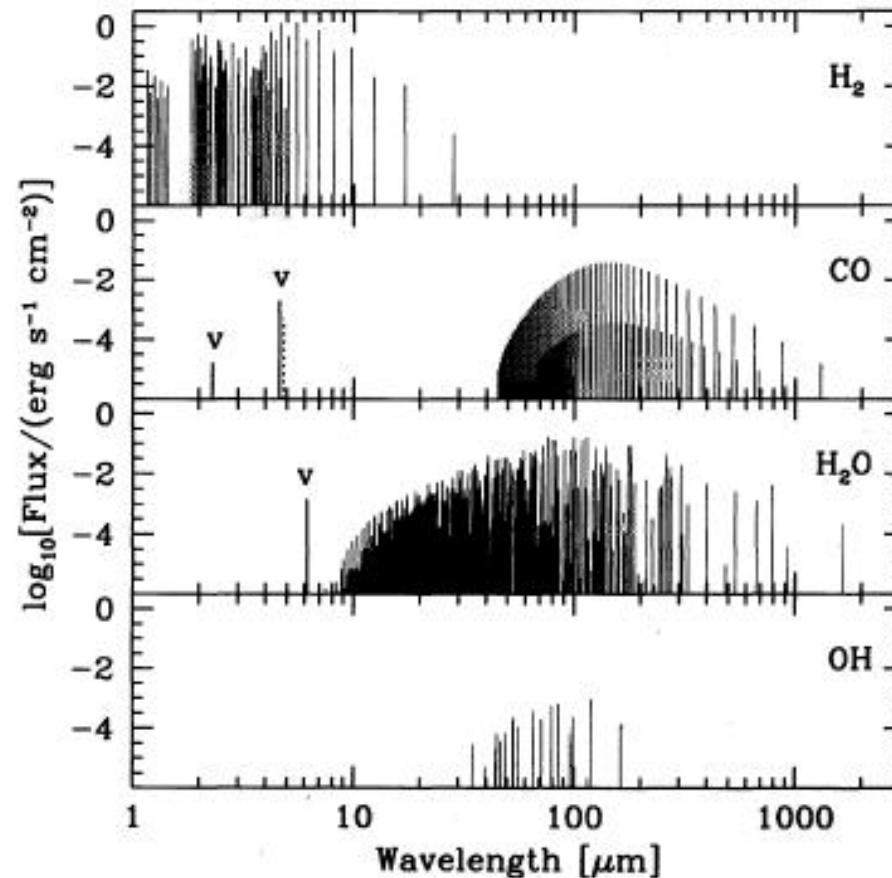


FIG. 4.—Line emission from a 40 km s^{-1} MHD shock wave propagating in gas with preshock density 10^5 cm^{-3} and with a preshock magnetic field of $447 \text{ } \mu\text{G}$. Results are shown for rotational and ro-vibrational transitions of H_2 (*top panel*), rotational transitions of ^{12}CO and ^{13}CO (*second panel*), rotational transitions of H_2O (*third panel*), and rotational transitions of OH (*bottom panel*). Also shown are the total fluxes in the ^{12}CO $v = 1-0$ and $v = 2-0$ vibrational bands near $4.6 \text{ } \mu\text{m}$ and $2.3 \text{ } \mu\text{m}$ (*solid lines*) and the $v = 2-1$ vibrational band near $4.6 \text{ } \mu\text{m}$ (*dotted line*) and in the v_2 H_2O vibrational band near $6.2 \text{ } \mu\text{m}$ (*solid line*).

E-3 Supernova Remnants

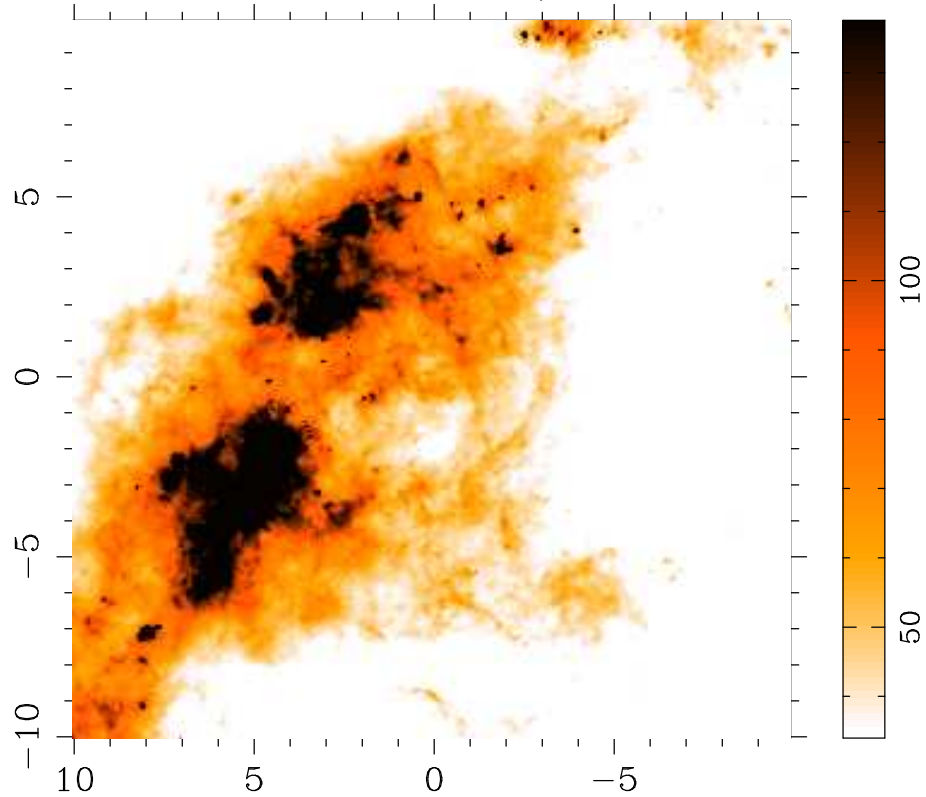
References:

- Lequeux, “The interstellar medium” (like Spitzer 1978).
- Rohlfs & Wilson “Tools of Radioastronomy” (emphasis on the synchrotron diagnostic).
- Tielens.

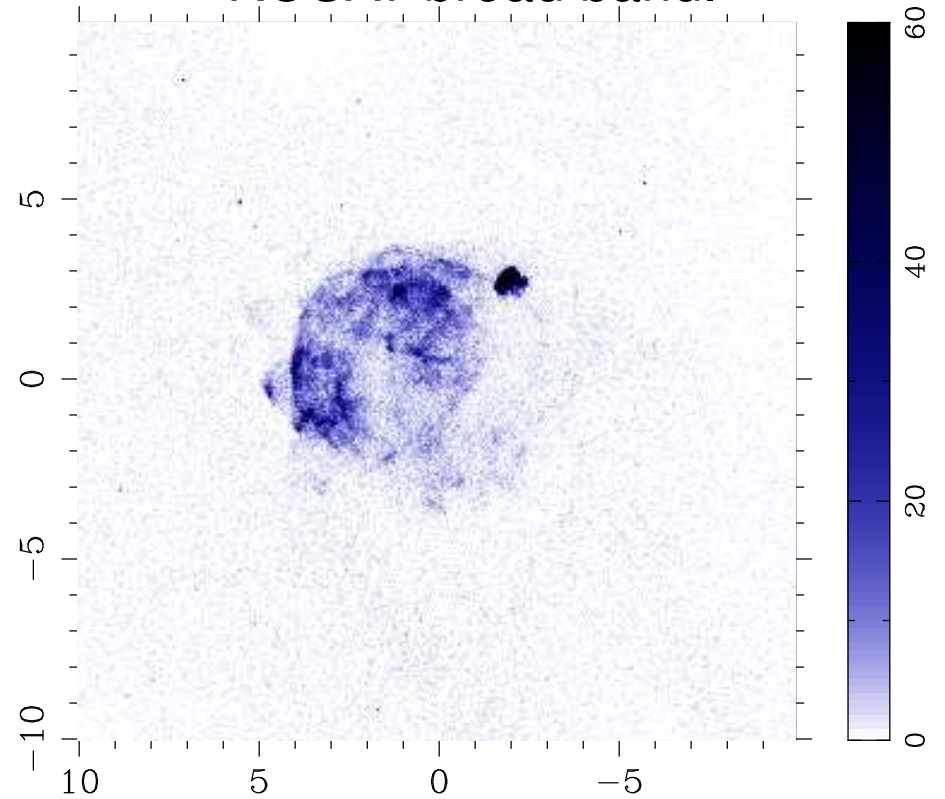
E-3 Supernova Remnants

- There are three broad phases in the expansion of a SN shock wave:
 1. a phase of free expansion, where the density of the ejected material is much larger than the density of the surrounding medium. This phase ends ~ 60 yr after the SN event. It has been studied extensively in extragalactic SNe.
 2. a phase of adiabatic expansion, where radiative losses are negligible, and where the temperature progressively cools through the work applied on the swept up ISM.
 3. an isothermal phase, where the remnant's energy is lost by radiation, and which ends when the SNR shell velocity is of order of the velocity dispersion in the ISM (\sim the sound speed, or 10 km s^{-1} in the diffuse ionised ISM at 10^4 K).
- SNRs of all types inject $\sim 10^{50}$ erg through a shocked shell driving into the ISM. SNe Ib/II may lead to *Plerions*: shell remnants filled with relativistic gas excited by a central pulsar.

E-3 SNRs examples: Vela¹

IRAS 100 μ m.

ROSAT broad band.



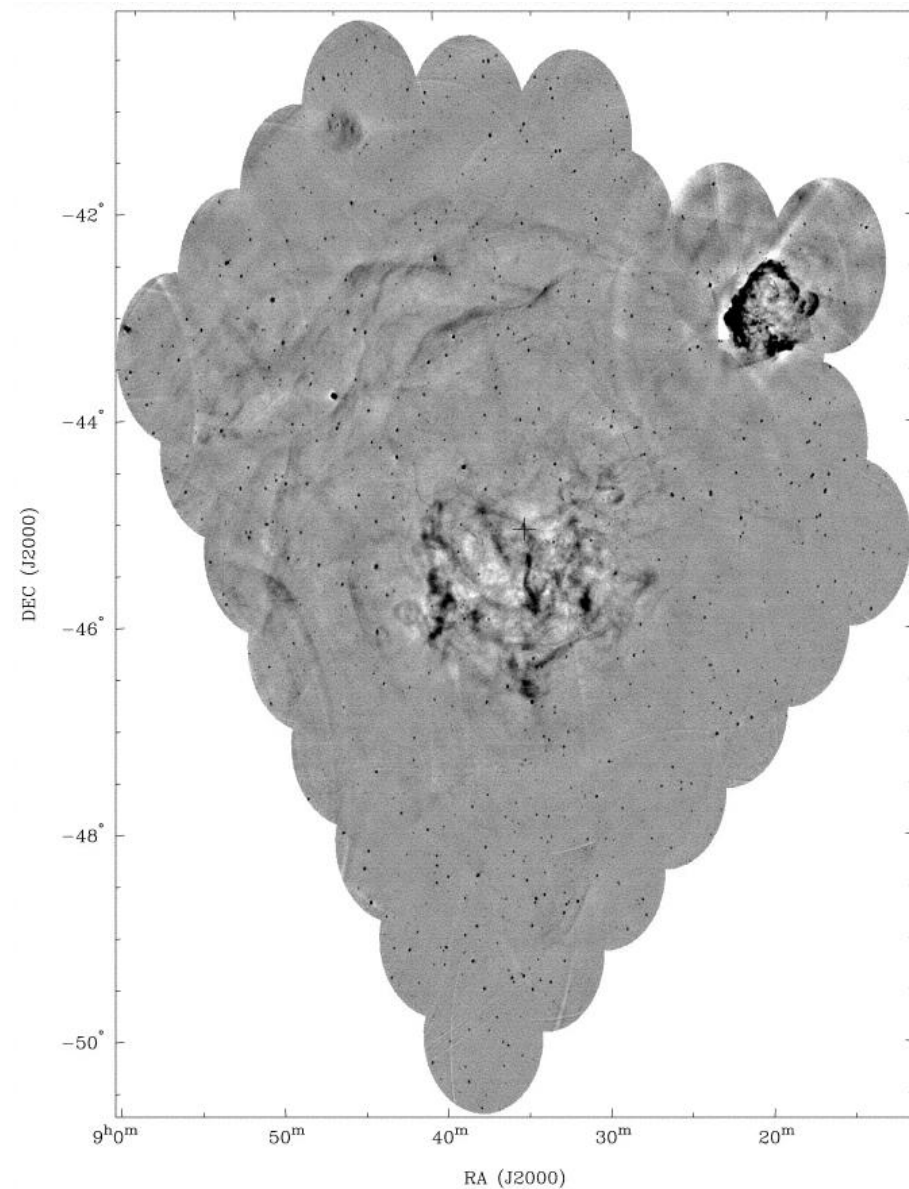
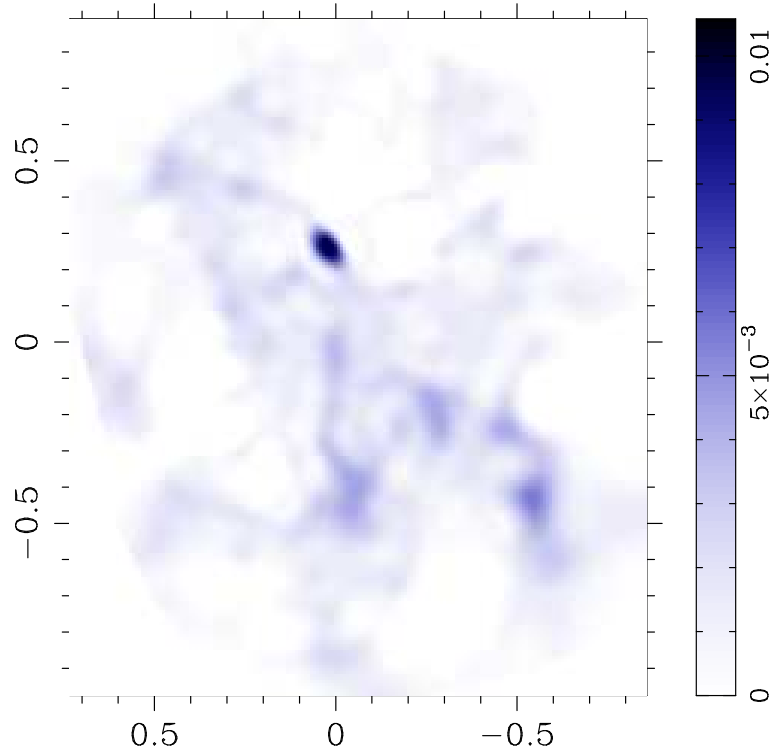
¹G263.806-03.371

E-3 SNRs examples: Vela²

Hales et al. 2004, ApJ, 613, 977.

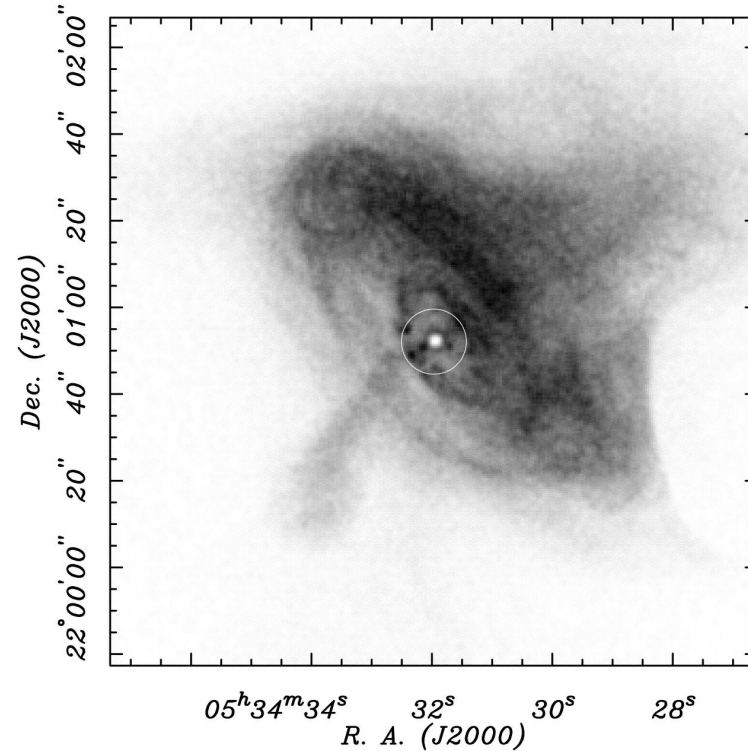
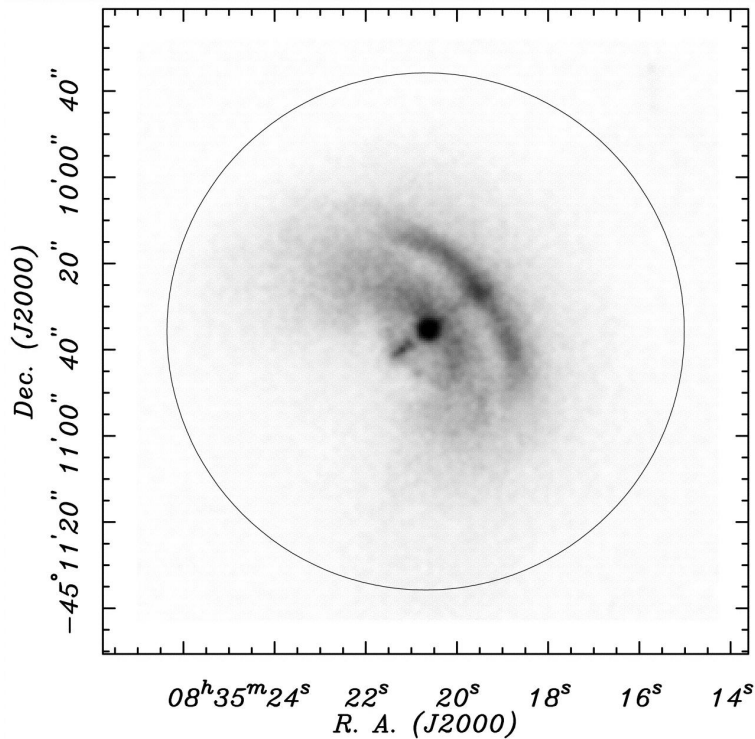
Bock et al., 1998, ApJ, 116, 1886.

Blondin et al. 2001, ApJ, 563, 806.



²Distance to Vela is ~ 250 pc \rightarrow 1 deg \sim 5 pc

E-3 SNRs examples: PWNe



Helfand et al. 2001, ApJ, 556, 380. Note the age of both PWNe is very different (Vela X is $\sim 10^4$ yr, see Blondin et al.). The circles have equal radii of ~ 0.05 pc. The Vela X PSR radiates as a $1.7 \cdot 10^6$ K blackbody 10 km in radius, and the diffuse emission is synchrotron. That the arcs are not complete rings may be due to the head-light effect in the outflowing relativistic expansion.

E-3 SNR free-expansion phase

- The SN event ejects the stellar envelope at $\sim 10^4 \text{ km s}^{-1}$.
- For fully ionised gas the mean free path involves the Coulomb cross section of protons:

$$l = m^2 v^4 / (Z^2 n e^4 \ln \Lambda), \text{ with } \Lambda = 1.3 \cdot 10^4 T^{3/2} / n_e^{1/2}. \quad (11)$$

- At $v \sim 10^4 \text{ km s}^{-1}$, the Coulomb cross section is so low that $l \sim 400 \text{ pc}$ for protons, so that they would escape the envelope.
- But a small magnetic field of only $\sim 1 \mu \text{ G}$ confines the protons to Larmor radii of only $\sim 10^{-8} \text{ pc}$. Thus the freely-expanding SNRs are MHD shocks.
- The free-expansion phase ends when the SNR expansion has swept up enough mass to slow down due to momentum conservation.

This occurs when when the mass swept by the envelope, $\frac{4}{3}\pi r_s^3 \rho_0$, where ρ_0 is the surrounding density, is similar to the mass of the ejecta, M_{ej} . For $n_0 \approx 1 \text{ cm}^{-3}$ and $M_{\text{ej}} = 0.25 M_{\odot}$ (type Ia) we have $r_s = 1.3 \text{ pc}$, which is reached only 60 yr after the explosion if the expansion velocity is 20000 yr.

E-3 SNR adiabatic (Sedov) expansion phase

- *Adiabatic* expansion means that the postshock temperature is so high that radiative losses are negligible. The mechanical SN energy E is constant.
- Sedov (1959) showed that adiabatic expansion is self-similar: its macroscopic parameters are related by power-laws (see Chap. A). In the Sedov phase,
 - ★ the fraction of E that is thermal is $K_1 E$, with $K_1 = 0.72$,
 - ★ the ratio $K_2 = P_1 / \langle P \rangle = 2.13$, where P_1 is the pressure immediately behind the shock, and $\langle P \rangle$ is the average pressure inside the spherical remnant.

E-3 SNR adiabatic (Sedov) expansion phase

Once the expansion slows down to, say, 1000 km s^{-1} , the magnetic energy density is negligible compared to the thermal energy density and we can use the J-shock results.

- With the above results from Sedov, and since for an ideal gas $\langle P \rangle = \frac{2}{3} K_1 E \frac{3}{4\pi r_s^3}$, we have $P_1 = KE / (2\pi r_s^3)$, where $K = K_1 K_2$.
- In the limit of a strong shock, $M \gg 1$, the Rankine-Hugoniot relations give $v_0 = \sqrt{\frac{4P_1}{3\rho_0}}$, and since the shock velocity $v_s \approx v_0$, we obtain

$$v_s = \sqrt{\frac{2KE}{3\pi r_s^3}}. \quad (12)$$

E-3 SNR adiabatic (Sedov) expansion phase

- Integrating Eq 12,

$$\begin{aligned}
 r_s &= \left(\frac{5}{2}\right)^{2/5} \left(\frac{2KE}{3\pi\rho_0}\right)^{1/5} t^{2/5}, \\
 &= 0.26 \left(\frac{n_H}{\text{cm}^{-3}}\right)^{1/5} \left(\frac{t}{\text{yr}}\right)^{2/5} \left(\frac{E}{4 \cdot 10^{50} \text{ erg}}\right)^{1/5} \text{ pc.}
 \end{aligned}$$

- again, with the strong shock conditions Eq. 7 to 9,

$$T_1 = \frac{3}{16k} \mu m_H v_s^2 = 1.5 \cdot 10^{11} \left(\frac{n_H}{\text{cm}^{-3}}\right)^{-2/5} \left(\frac{t}{\text{yr}}\right)^{-6/5} \left(\frac{E}{4 \cdot 10^{50} \text{ erg}}\right)^{1/5} \text{ K.}$$

- we see that the T increases towards the centre, which reflects the neglect of radiative losses, and the fact that v_s was higher when the central layers were overtaken by the shock.

E-3 adiabatic expansion: thermal conductivity

- However, in the absence of strong magnetic fields, the Coulomb mean free path l (Eq. 11) is so high that diffusion is important, with thermal conductivity

$$\kappa = \frac{5}{3} \frac{kT}{\langle v_T \rangle} l n \frac{3k}{m}, \quad \text{with } \langle v_T \rangle = (3kT/m)^{1/2}. \quad (13)$$

- Solving for the thermal balance including the heat flux $Q = -\kappa \nabla T$ leads to uniform temperatures in the SNR interior (Chevalier 1975, ApJ, 198, 355):

$$T \approx 1.4 \cdot 10^{10} \left(\frac{n_0}{\text{cm}^{-3}} \right)^{-1} \left(\frac{r_s}{\text{pc}} \right)^{-3} \frac{E}{10^{51} \text{ erg}} \text{ K}. \quad (14)$$

- However, a finite magnetic field exists inside the remnant, so that the mean free path and the conductivity κ are reduced. The real temperature inside the remnant thus lies in between Eq. and Eq. 14.

E-3 adiabatic expansion: reverse shock

- An more accurate (numerical) treatment shows that the transition between free and adiabatic expansion generates a reverse shock.
- The reverse shock propagates inwards, towards the centre of the ejected matter.
- Qualitatively, the reverse shock stems from the pressure increment behind the shock front. The finite radiative losses lower the temperature inwards and away from the shock front. Thus the sound speed decreases inwards, and the pressure perturbation right behind the (outer) shock turns into an inner, or reverse, shock.
- After the passage of the reverse shock the SNR expansion becomes truly adiabatic.

E-3 Isothermal expansion

- When the postshock temperature falls below $T_1 \approx 10^6$ K, metals start recombining, and radiative cooling is strongly enhanced through line emission from ions of C, N and O.
- Energy is no longer conserved - rather, the expansion of the remnant is controlled by momentum conservation.
- The transition into the isothermal phase occurs at an age of $\sim 10^4$ yr, for an ambient density $n_0 \sim 1 \text{ cm}^{-3}$, a shell radius ~ 15 pc, and an expansion velocity of 85 km s^{-1} .

E-3 Isothermal expansion

- Momentum conservation requires that Mv_s is constant, where M is the ISM mass swept-up by the remnant:

$$\frac{4}{3}\pi r_s^3 \rho_1 v_s = \text{constant}.$$

- Integration then gives

$$r_s = r_{\text{rad}} \left(\frac{8t}{5t_{\text{rad}}} - \frac{3}{5} \right)^{1/4},$$

where r_{rad} and t_{rad} are the radius and age of the remnant at the start of the isothermal phase.

E-3 Final mixing with the ISM

- When the age of the remnant is of order 10^6 yr, its radius will be ~ 40 pc, and $v_s \sim 10 \text{ km s}^{-1}$ - comparable to the sound speed of 10^4 K 'warm-ionised' ISM with $n_0 = 1 \text{ cm}^{-3}$. Thus the remnant will no longer be supersonic, and will mix with the ISM.
- The efficiency η for the input of mechanical SN energy E into the ISM is

$$\eta = \frac{1}{2} M_f v_f^2 / E$$

, where M_f and v_f are the final mass and velocity of the remnant. Lequeux (2005) shows that $\eta \approx 0.03$.