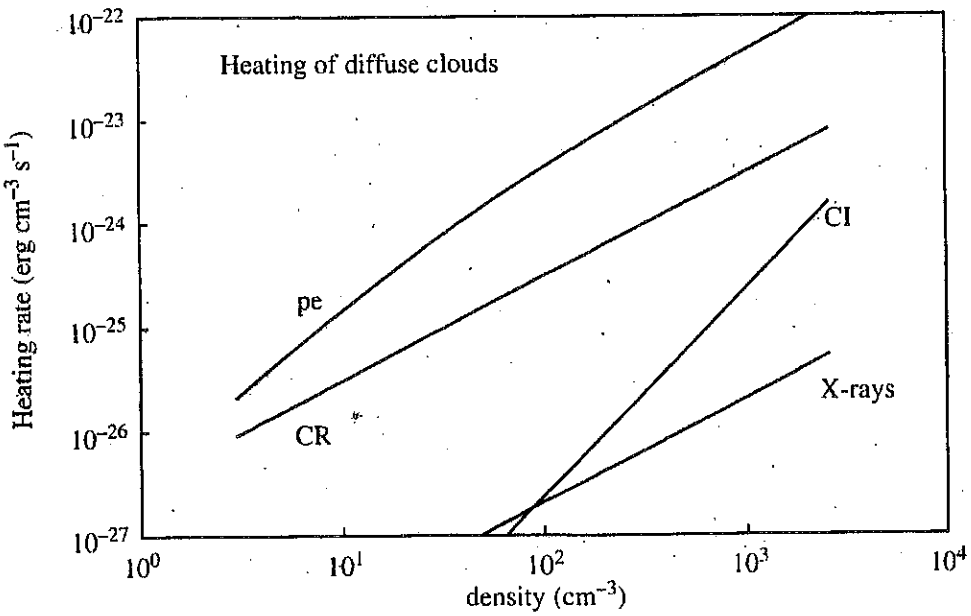
Tielens: HI heating



The HI in the cold neutral medium

Tielens 2005

Figure 3.8 Heating processes in diffuse interstellar clouds as a function of the density. The processes displayed are the photo-electric effect (pe), photo-ionization of neutral carbon (CI), cosmic-ray ionization (CR), and X-ray ionization (X-rays).

pe: $n\Gamma_{pe} = 10^{-24} \varepsilon n G_0$ erg/cm^3/s

heating efficiency (ε); G_0 ← radiation field

$\sim 0.05 < \varepsilon < 0.003$ (lower at higher density)

CR: $n\Gamma_{cr} = 3\times10^{-27} n \left[\frac{J_{CR}}{2\times10^{-16}}\right]$ ← c.r. ionization rate

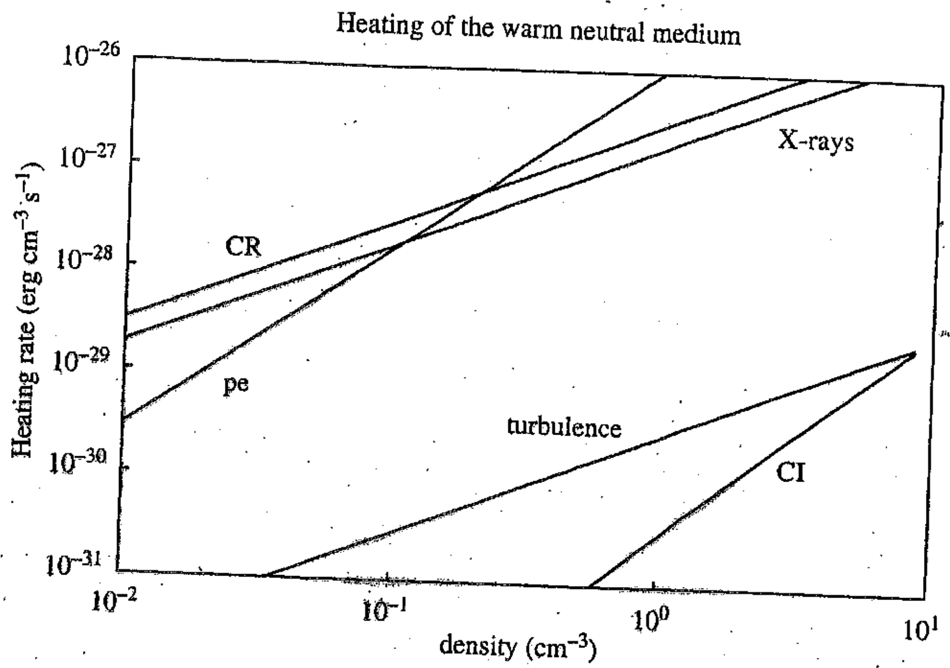
p.e. for CI: $n\Gamma_{CI} = 2.2\times10^{-22} f(CI) A_c n G_0 e^{-2.6 A_V}$

A_c = gas phase C abundance f = neutral carbon fraction

Xray → see Fig 3.7

$n\Gamma_{XR} \sim \left[10^{-26} - 10^{-29}\right] n$ depending on e^- fraction and H absorbing column

HI in the warm neutral medium



Tielens 2005

Figure 3.9 Heating processes in the warm neutral medium as a function of the density. The processes displayed are the photo-electric effect (pe), photo-ionization of neutral carbon (CI), cosmic-ray ionization (CR), decay of turbulence (turbulence), and X-ray ionization (X-rays).

Xray heating higher because lower N_{HI} attenuation

CR, pe → same relations as for CNM, but extended to lower density

pi → photo-ionization of HI is dominant term (not plotted here)

Wolfire et al. 1995 ApJ 443, 152

→ a more modern treatment of two-phase ISM

- cosmic ray ionization rate 1/20th that of FGH

→ primary heating source is photoelectric effect

  - eject e^- from dust particles by interstellar radiation field G_0
  - very small grains and large molecules (PAHs) make important contribution
    ↳ "polycyclic aromatic hydrocarbons"

Photo-electric heating

- use power law distribution of grain sizes

$$n(a)\,da \propto a^{-3.5}\,da \qquad 3\,\text{Å} < a < 100\,\text{Å}$$

- when $G_0 T^{1/2}/n_e$ is small, heating rate is regulated by FUV field and grain density

$$n\Gamma \propto n G_0$$

Other heating sources

- cosmic rays : ionization rate $n\zeta_{CR} = 1.8\times10^{-17}\,n$ $\text{cm}^{-3}\,\text{s}^{-1}$
- soft X-rays → more important for ionization than heating

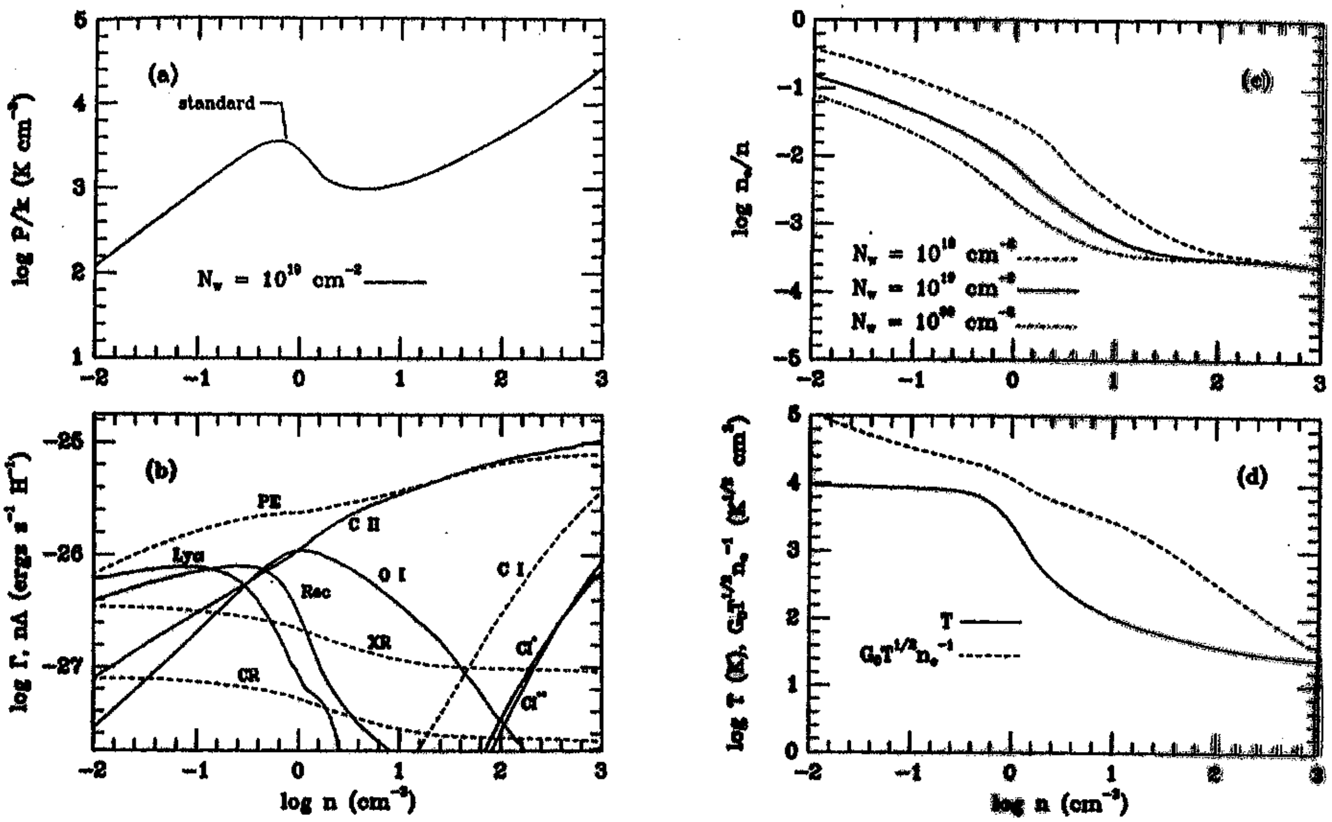


FIG. 3.—(*a*) Thermal pressure P/k vs. hydrogen density n for standard model (see § 3.1). Gas is thermally stable for $d \log P/d(\log n) > 0$. (*b*) Heating and cooling rates per hydrogen nucleus vs. density n for pressure curve of panel *a*. Heating rates (*dash*); Photoelectric heating from small grains and PAHs (PE); X-ray (XR); Cosmic ray (CR); photoionization of C (C I). Cooling rates (*solid*); C II fine-structure (C II); O I fine-structure (O I); Recombination onto small grains and PAHs (Rec); Lyα plus metastable transitions (Lyα); C I fine-structure 609 μm (C I*); C I fine-structure 370 μm (C I**). (*c*) Electron fraction n_e/n as a function of hydrogen density n for the pressure curve of panel *a* (*solid*). Also shown are curves for $N_w = 10^{18}$ cm^{-2} (*dash*), and $N_w = 10^{20}$ cm^{-2} (*dash-dot*). (*d*) Gas temperature T (*solid*) and ionization parameter $G_0 T^{1/2}/n_e$ (*dash*) as a function of hydrogen density n for the pressure curve of panel *a*.

Cooling → by fine structure lines of CII and OI

Gas is thermally stable where $\frac{d \log P}{d \log n} > 0$

→ can get two phase ISM for $990 < P/k < 3600$ K cm^{-3}

For $P/k = 3000$ K/cm^3

WNM: $T = 7300$K, $n = 0.37$ cm^{-3}, $n_e/n = 0.02$

CNM: $T = 45$K $n = 61$ cm^{-3} $n_e/n = 3 \times 10^{-4}$

Thermal instability arises from density and temperature dependence of cooling processes

① cooling by CII, OI insignificant at $n \lesssim 0.1\ cm^{-3}$

→ T rises to $\sim 10^4$ K where strong cooling by Lyα and recombination sets in

② CII, OI dominate cooling as density increases above $0.5\ cm^{-3}$

→ rapid drop in T and unstable region of phase diagram

③ when $T < 92$ K (energy of CII 158μm line), decline in temperature becomes more gradual

→ pressure rises in CNM region

Note that density at which gas first becomes unstable is influenced by T, n effects of heating, as well

→ see flatter portion of PE curve in Figure 3b

Features of the cooling curve

① steep rise below 100° K and between 10^4 and 10^5 K

② Flat portion : $10^2 - 10^4$ K

③ Falling portion: $5.3 < \log T < 7.0$

④ High temperature portion $\mathcal{L} \propto T^{1/2}$ due to thermal bremsstrahlung

Due to:

- excitation of [CII] IR fine structure line at low temperature
- excitation of [CII] and optical forbidden lines at moderate T
- HI (Lyα) excitation above 7000 K
- excitation of permitted and semi-forbidden lines of C, O, Fe at T > 20,000 K
- between 10^6 and 10^8 K, cooling dominated by iron ions

Interstellar Process

Shull, in "Interstellar Processes" Thronson & Hollenbach

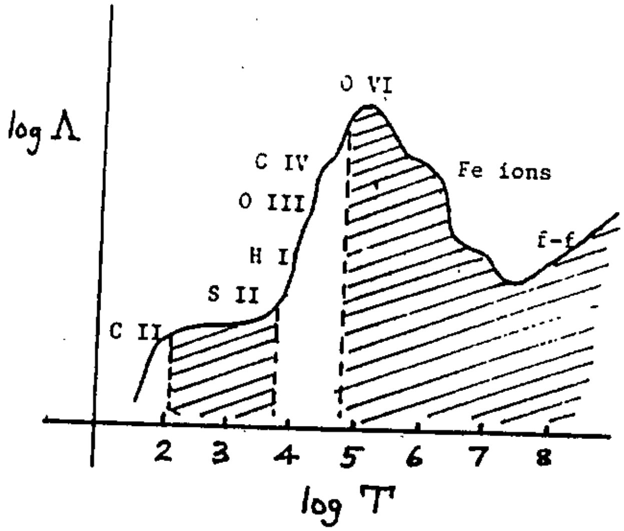


Figure 1: Radiative cooling curve for optically thin, low density interstellar gas. Regions prone to thermal instability are cross-hatched. Dominant coolants are shown.

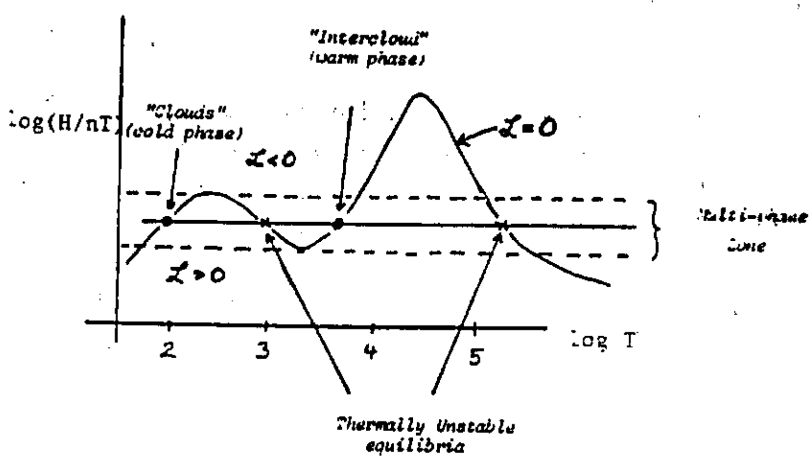


Figure 2: Locus of equilibria for interstellar gas with constant heating rate $\mathcal{H}$ and constant pressure nT. Two of the equilibria are thermally stable and two are unstable.

Problems with 2 Phase Theory

① Difficult to explain 40-100 K temperature of diffuse clouds with cosmic ray heating

→ need $\xi \sim 10^{-15}\,s^{-1}$: MUCH TOO HIGH (believe $\approx 10^{-17}\,s^{-1}$)

② Partially ionized intercloud medium not observed

→ inconsistent with $\langle n_e \rangle$ deduced from pulsar dispersion measures

③ ISM dominated by SNRs and OB star winds

→ NOT quiescent

→ highly violent

⇒ Cox & Smith 1974

Cox & Smith 1974

An isolated supernova remnant ($E \sim 4 \times 10^{50}$ ergs) expands into homogeneous ISM ($n_0 \sim 1$ cm^{-3})

- radiative cooling important at $t = 5 \times 10^4$ yr
  - → remnant divides into
    - cool ($T < 10^3$ K) dense shell
    - hot ($10^6 - 10^8$ K) diffuse cavity
  - → has $R \sim 20$ pc, $P \sim 100 \times P_{ISM}$
- shell continues to expand for $1-4 \times 10^6$ yr to $R \sim 40$ pc

BUT if SNR encounters an older SNR bubble → shock will propagate into old cavity $\frac{V_{s1}}{V_{s2}} \sim \left(\frac{\rho_2}{\rho_1}\right)^{1/2}$

- → thermal energy of new SNR reheats old one
- → combined bubble has larger volume, more likely to be struck by a third SNR, etc

Monte Carlo simulations suggest can form a persistent network of tunnels

$$q \equiv r \tau V_{SNR}$$

r = SN rate per unit volume

τ = lifetime of SNR

V_{SNR} = average final volume of SNR

$q \ll 0.1$ → low overlap probability
→ isolated SNR

$q \gtrsim 1$ → SNR fill very large fraction of volume
→ galactic wind disperses ISM

$0.14 < q < 0.5$ → form network of tunnels

For Milky Way, estimate $q \sim 0.1$

→ value quite uncertain since $q \propto R^4$
(and $R \propto n_0^{-1.7}$)

Supernova Regulated ISMs

(McKee & Ostriker 1977)

Detection of - soft X-ray background
- ubiquitous O VI absorption lines

⇒ large amounts of hot, low density material in Galactic disk

Standard 2-phase model cannot be maintained for reasonable SN rate $S \sim 10^{-13}\ pc^{-3}\ yr^{-1}$

because → cool ($T \sim 10^4$, $n \sim 10^{-5}$) medium swept up into dense shells in $\lesssim 10^7$ yr

→ replaced by hot phase

Basic Idea

- all phases of ISM kept in pressure balance

  ambient P = P inside SNR at time when overlaps with another remnant (little further energy loss after overlap)

- accompany this by mass and energy balance

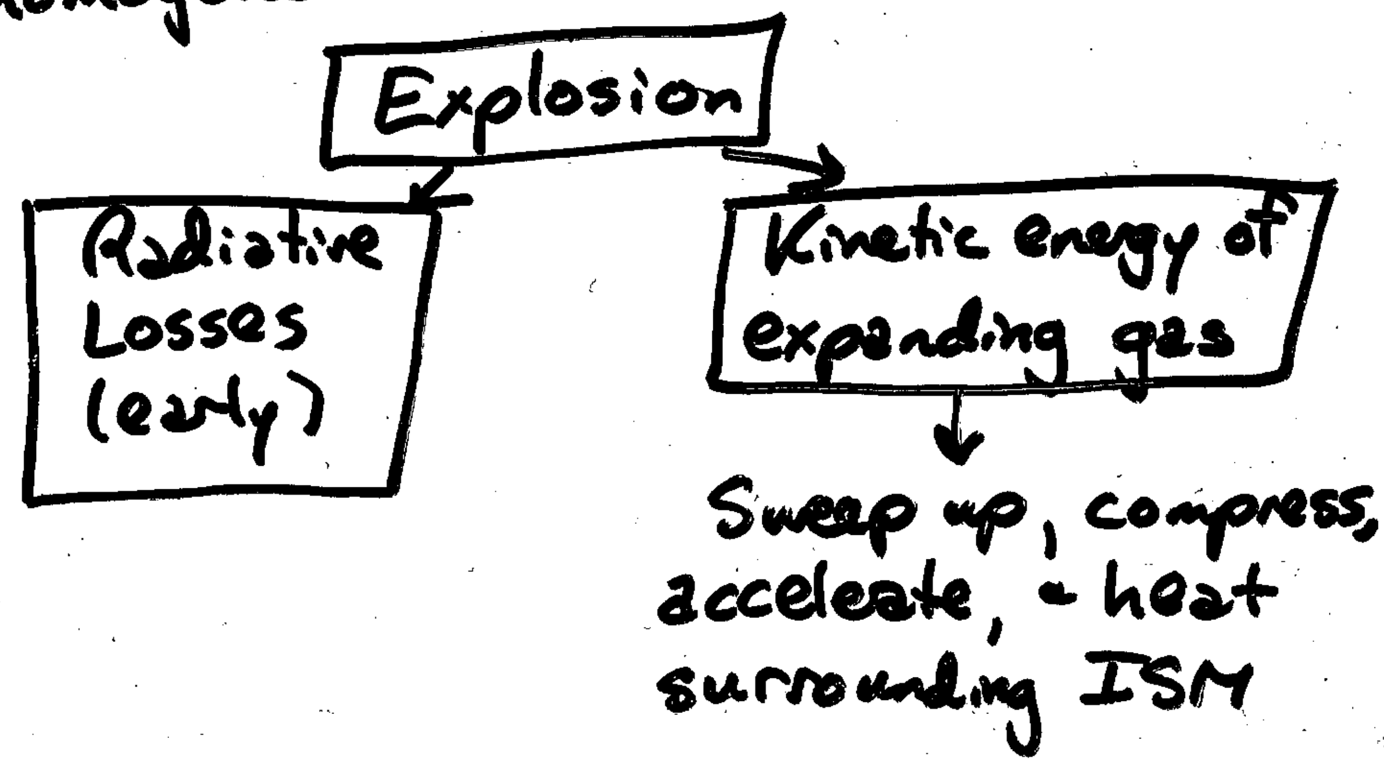
(1) evaporation of cloud material by hot gas balanced by dense shells depositing mass onto clouds

(2) radiative losses from hot gas balance energy injected by SN (assume radiative losses dominate over shocks ← Cox & Smith)

Model depends on dynamics of SNR in an inhomgeneous medium

<u>Dynamics of SNR</u>

homogeneous medium (Spitzer 12.2)



Stages in a SN Blast

① Initially ISM has little effect because of its low density compared to that of the ejecta

⇒ velocity of expansion nearly constant with time

→ phase lasts until

Mass of ISM swept up by shock = Initial mass expelled by SN (M_s)

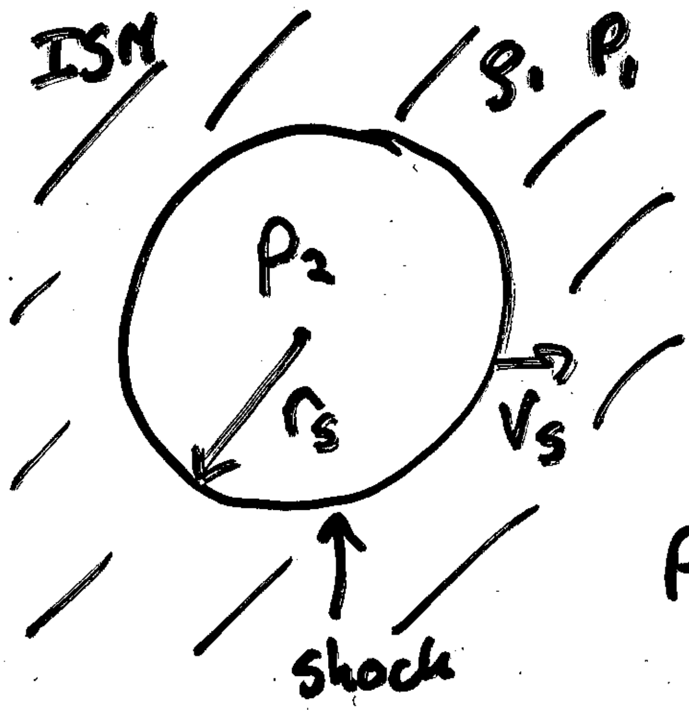
$$\frac{4\pi r_s^3}{3}\rho_1 = M_s$$

for $M_s = 0.25\, M_\odot$, $\rho_1 = 2\times10^{-24}\,\text{gm/cm}^3$

→ $r_s \sim 1.3\,\text{pc}$

② Intermediate → Energy conserving

- shock velocity drops due to swept up ISM mass
- can still assume most energy with shock front & is constant = initial energy E



let P_2 be pressure immediately behind shock

Define

K_1 = fraction of total energy in form of heat

$P_2 = K_2 \times$ mean pressure of heated gas within shock

Then (perfect gas)

$$P_2 = K_2 \times \left(\frac{2}{3} \times K_1 \times \frac{E}{\frac{4}{3}\pi r_s^3}\right) \equiv \frac{KE}{2\pi r_s^3}$$

(energy density = pressure)

$K_1 = 0.72$
$K_2 = 2.13$
$K = K_1 K_2 = 1.53$

From shock-jump conditions (large Mach number)

$$P_2 = \frac{2\rho_1 u_1^2}{\gamma+1} \Rightarrow \boxed{V_s^2 = \frac{2KE}{3\pi \rho_1 r_s^3}}$$

Integrate:

$$V_s = \frac{dr_s}{dt} \rightarrow \frac{dr_s}{dt} = \left(\frac{2KE}{3\pi\rho_1}\right)^{1/2} r^{-3/2}$$

$$\Rightarrow r_s = \left(\frac{2.02\,KE}{\rho_1}\right)^{1/5} t^{2/5}$$

or in units of $\bar{E} = E / 4 \times 10^{50}$ ergs

$$r_s = \frac{0.26\,\bar{E}^{1/5}}{n_H^{1/5}} (t/yr)^{2/5} \text{ pc}$$

ie $\boxed{r_s \propto t^{2/5}}$

Can also find

$$T_2 = 1.5 \times 10^{11} \frac{\bar{E}^{2/5}}{n_H^{2/5}} (t/yr)^{-6/5}$$

$$\boxed{T_2 \propto t^{-6/5}}$$

③ Late Isothermal (Momentum Conserving)

When $T < 10^6$ K → CNO recombine
→ radiative cooling becomes important
→ temperature T_2 drops to low value

⇒ shock not driven by pressure P_2

BUT

by momentum
(shock itself is isothermal now)

ie "Snow Plow" phase

$$\boxed{M_t V_t = Mv}$$

for shell; M_t, V_t are mass and velocity of shell when phase commences

Now $M \propto r_s^3$ (most of mass due to swept up ISM)

so $M_t V_t = \text{const} \propto r_s^3 \, dr_s/dt$

$$\Rightarrow \boxed{r_s = \left(\frac{3 M_t V_t}{\pi \rho_1}\right)^{1/4} t^{1/4}}$$

McKee & Ostriker theory

- effect of SN strengthened if medium is inhomogeneous → expands into lower n component

→ SNR will gradually evaporated cold clouds that are swallowed up

→ early in adiabatic phase

$R \propto t^{3/5}$ for a while

$n(SNR) > n_0$ n_0 = density of large filling factor medium

→ in late stages ($R > 100pc$), evolution of SNR modified by radiative cooling, anisotropy, extenal pressure, overlap/ multiple events, and cloud-shell collisions

$\Sigma(\text{shell}) < \Sigma(\text{cloud})$

→ clouds punch holes in shell

→ if shock velocity large, is not enough time for shell to reform

⇒ estimate evaporated mass ≈ swept up mass

Inputs to model are

E/SN, $\bar{n}$, $\mathcal{E}_{uv}$, T_c, T_w, cloud mass spectrum parameters, 4 theor. param

$\mathcal{E}_{uv}$ = uv radiation field (from SNR, B stars, PN central stars, O stars?)

Get three essential components

1. Most of space filled with hot, low density HIM

$(n, T) = 10^{-2.5}\ cm^{-3},\ 10^{5.7}\ K$

$f_{HIM} \sim 0.7 - 0.8$

2. Cold neutral clouds CNM

$(n, T) = 10^{1.6}, 10^{1.9}$

$f_{CNM} = 0.02 - 0.04$

3. Surrounding each cloud is a warm ionized corona (heated by B stars + X-rays)

$T \sim 8000\ K$ WIM

$f \sim 0.2$ WNM

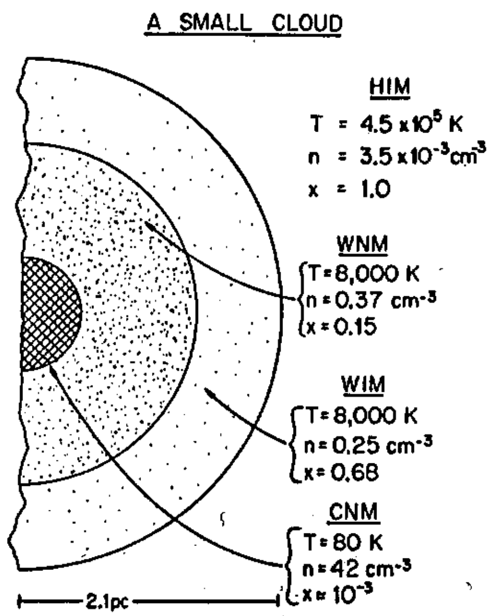


FIG. 1

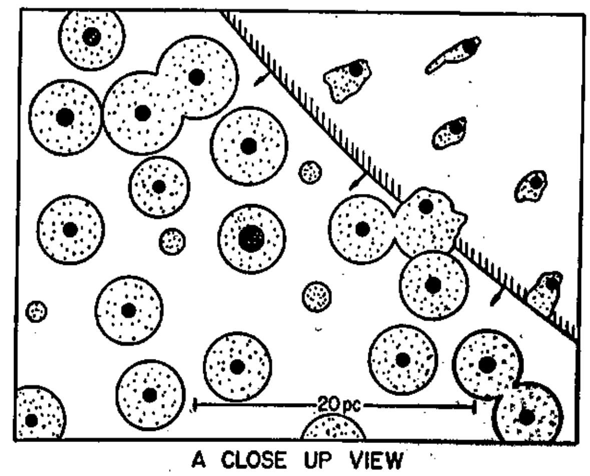


FIG. 2

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (dotted regions) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

compensate for it in the previous work in this paper by simply decreasing the assumed supernova energy E_{51} by ~30%, a change which would have negligible effect on any of the calculated quantities.

b) *Warm Neutral Medium*

We estimate from Chevalier's (1974) calculations that soft X-ray photons in the energy range 40–120 eV ($h\bar{\nu} \approx$ 60 eV) are produced in amount $\epsilon_x = 1.1 \times 10^{-16} S_{-13} E_{51}$ photons cm^{-3} s^{-1}. These will penetrate through the

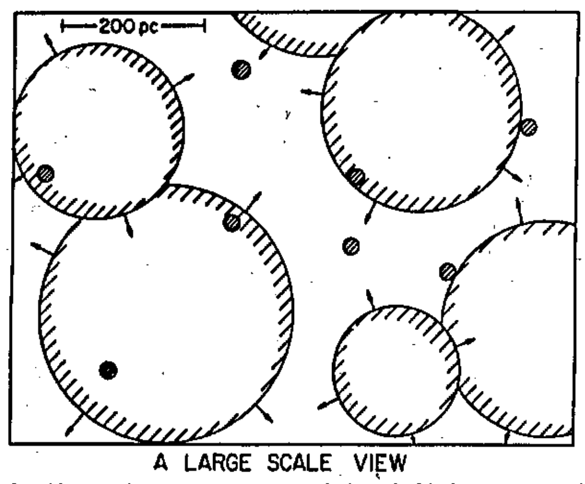


FIG. 3.—Large-scale structure of the interstellar medium. The scale here is 20 times greater than in Fig. 1: the region is 600 × 800 pc. Only SNRs with $R < R_c = 180$ pc and clouds with $a_0 > 7$ pc are shown. Altogether about 9000 clouds, most with $a_w \sim$ 2.1 pc, would occur in a region this size.

Comparison with observations

- SN can accelerate clouds through cloud-shell collisions → predict $V_{rms} \sim 8$ km/s (observe ~10 km/s)
- evaporation in SNR dynamics → predict $n \sim R^{-5/3}$ whereas Sedov $n \sim$ const
  ↖ some observational support
- O VI linewidths + dispersion ~20 km/s → from cloud interfaces + some outflow
- n, T of HIM excellent agreement with X-ray
- derive R_{ISM} from first principles → agrees w. 21cm
- $\langle n_e \rangle$, $\langle n_e^2 \rangle$ near what is measured for pulsars
- predict cold & warm neutral medium spatially correlated (different from FGH) → matches 21 cm data

→ possible problem is filling factor of WNM (predict 4% vs 14% observed)
  → but this component is the most uncertain theoretically