THE INTERSTELLAR MEDIUM: XIII
Multi-phase models

Nissim Kanekar
National Centre for Radio Astrophysics, Pune

Outline

- Background.
- The baryonic components of the ISM.
- The notion of pressure equilibrium.
- Heating and cooling in the interstellar medium.
- The Field-Goldsmith-Habing model: Two-phase equilibrium.
- The McKee-Ostriker model: Three-phase equilibrium.
- Modern perspectives.

BACKGROUND

- Hot Ionized Medium proposed by Spitzer in 1956: Hot gas for pressure support of HI clouds far above the Galactic plane.
- Collisionally highly-ionized gas: Fills the Halo.
- Rate coefficients, cooling rates unknown: Assumed CIE + numerics.
- X-ray studies: (1) Local Bubble: Most of the 0.25 keV emission.
  (2) Gas in Local Bubble ~ 1.1×10^6 K.
  (3) Hot bulge at the Galactic Centre: T ~ 4×10^6 K, $n_e \sim 0.003$ cm^{-3}; Scale height ~ 2 kpc.
- Far-UV lines (OVI, NV, CIV): Abundances in different ionization states ⇨ Gas temperature, density.
- Large *FUSE* OVI survey: T ~ 3×10^5 K; scale height ~ 4 kpc.
- LMC-X3 sightline: Joint fit to OVI, OVII, OVIII data, with CIE:
  ⇨ T ~ 3×10^6 K; $n \sim 1.4 \times 10^{-3}$ cm^{-3}; Height ~ 2.8 kpc.

The Baryonic Components of the ISM

- Molecular gas clouds: Self-gravitating structures.
- Neutral HI clouds: (1) Cold phase, $T \sim 100$ K, $n \sim 1 – 30$ cm^{-3}.
  (2) Warm phase, $T \sim 10^4$ K, $n <\sim 0.1$ cm^{-3}.
- Warm ionized gas: $T \sim 10^4$ K, $n \sim 0.1 – 1$ cm^{-3}.
- Hot ionized gas: $T \sim 10^6$ K, $n \sim 0.001$ cm^{-3}.
- Supernova remnants (SNRs): Source of energy!
- Interstellar dust grains:
- Polycyclic Aromatic Hydrocarbons (PAHs).
- Cosmic rays.

Multi-phase Models of the ISM

Pressure equilibrium between the different phases!

(Spitzer 1956)

- If different large-scale phases are out of pressure equilibrium, pressure differences would drive gas motions that would equalize the pressures on relatively short time scales.

- Cornerstone of all theoretical models of the interstellar medium.

(e.g. Field, Goldsmith & Habing 1969; McKee & Ostriker 1977)

- Basic principle: Balance heating and cooling rates in the diffuse ISM and look for stable solutions in pressure equilibrium!

Heating in the Diffuse ISM

- Cosmic ray heating: Electrons emitted by cosmic ray ionization of neutral hydrogen have high kinetic energy, which winds up in thermal energy. But cosmic ray ionization rate too low.

(McKee 1994)

- X-ray photo-ionization of hydrogen, helium: Important near sources of X-rays, less important in the general ISM.

- Photo-ionization of small dust grains, PAHs by stellar UV photons. E.g. work function of graphite ~ 4.5 eV. Photons with energies ~ 5 – 13.6 eV can ionize small grains!

- Heating an order of magnitude larger than cosmic ray heating!
  ⇨ PAH photo-ionization dominates the heating of the diffuse gas!

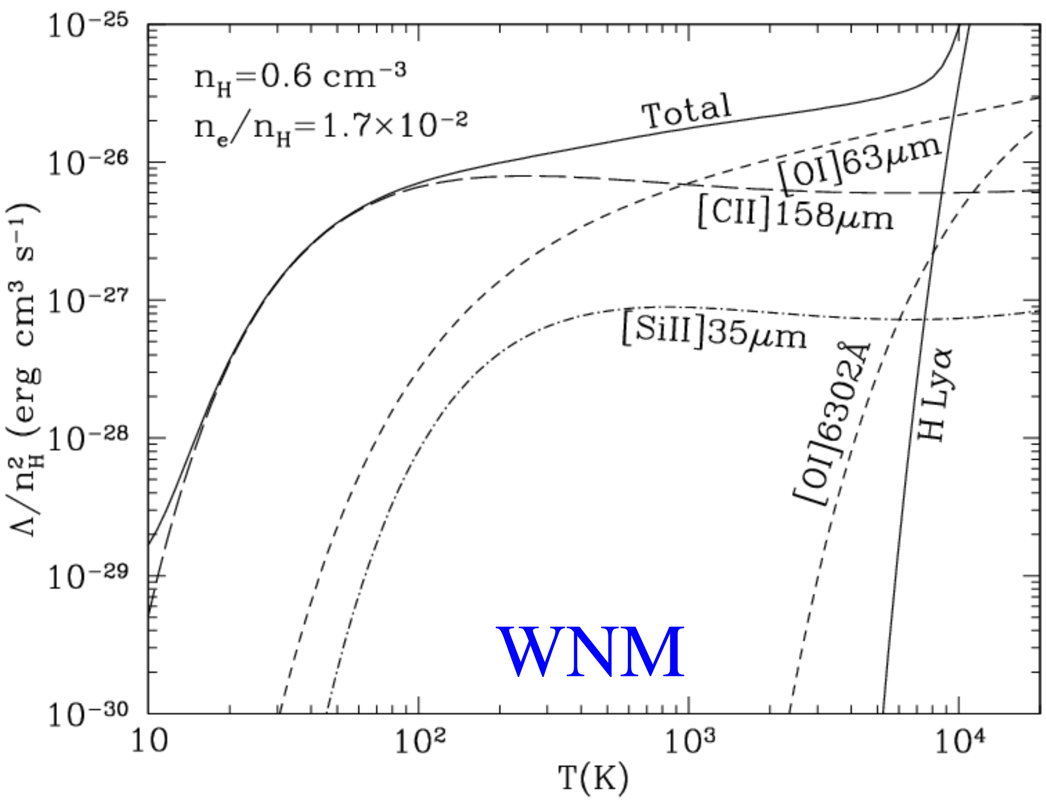
(Bakes & Tielens 1994)

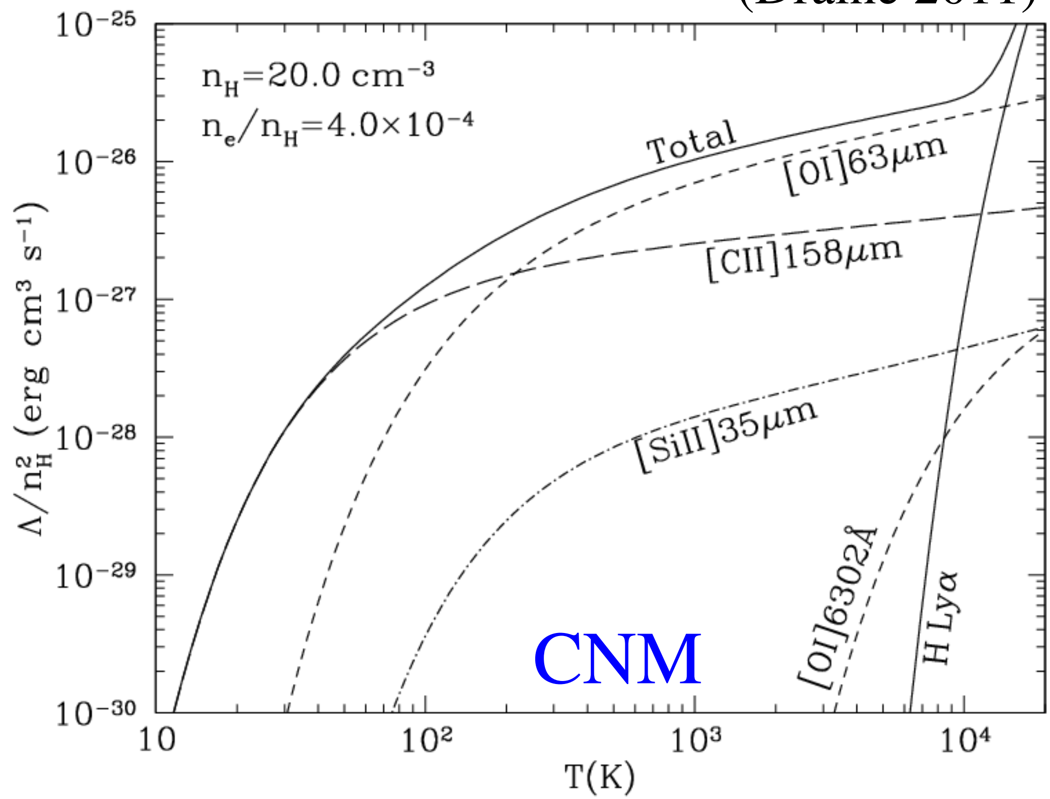
- Other sources: Photo-ionization of large atoms by UV photons, heating by shocks, MHD waves...

Cooling in the Diffuse ISM

- Main coolants for $T \leq 10^4$ K: Radiative cooling by hydrogen and metal lines (e.g. Lyman-α, CII-158 μm, OI-63 μm, etc.)

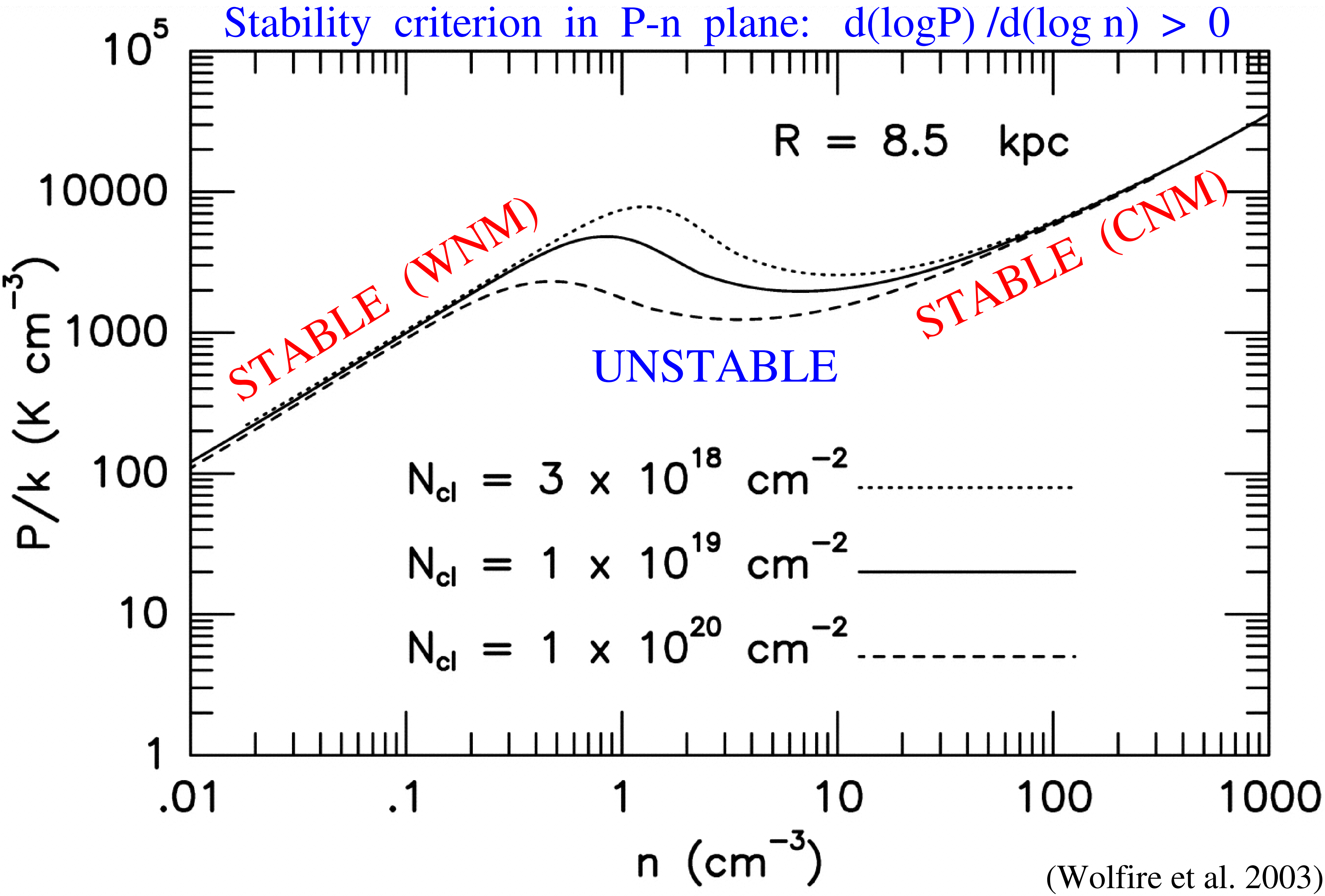
(Draine 2011)





- For $T \leq 8000$ K, main coolants: CII-158 μm and OI-63 μm lines.

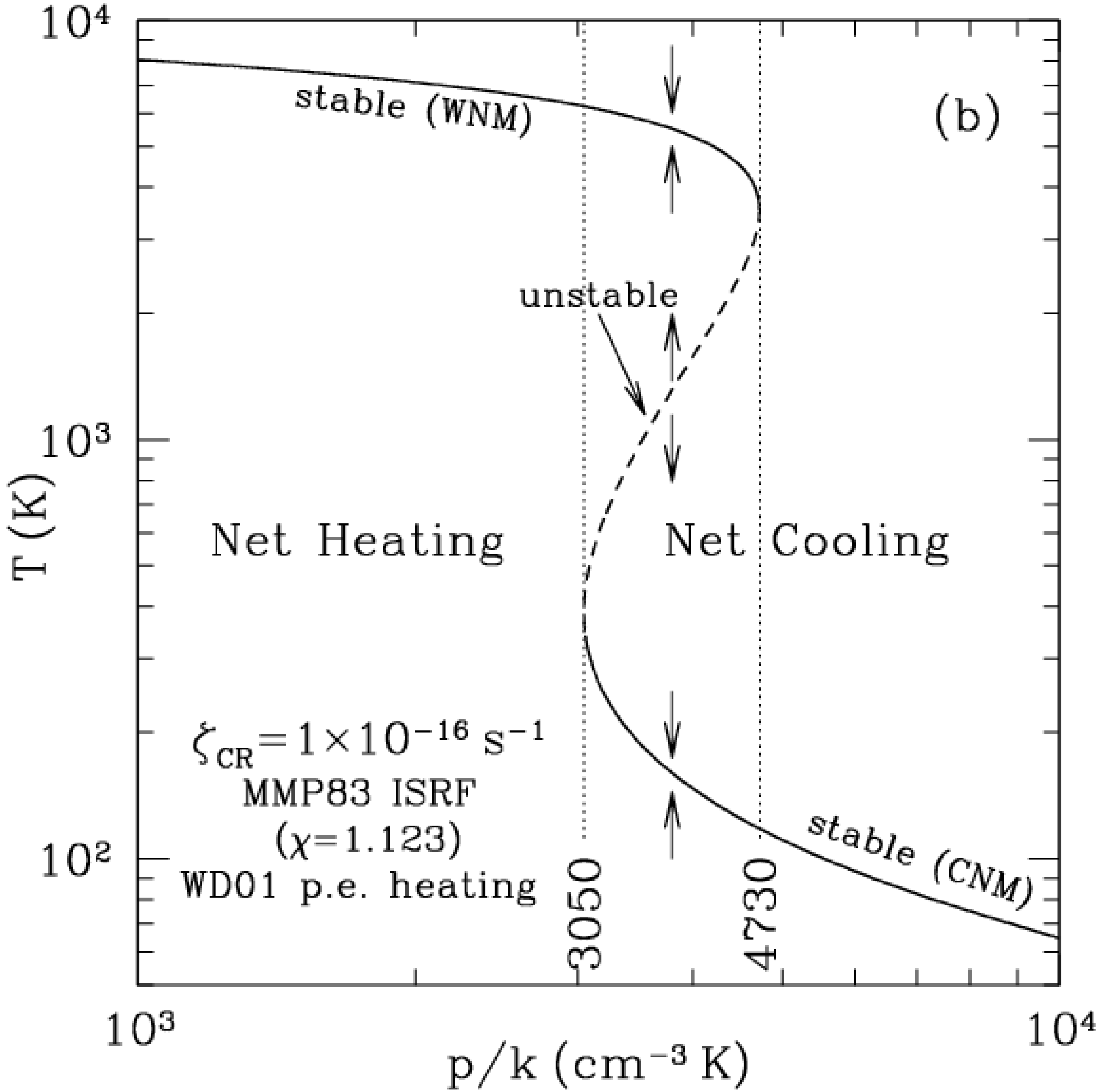
PRESSURE EQUILIBRIUM



(Wolfire et al. 2003)

PRESSURE EQUILIBRIUM

Stability criterion in T-P plane: $d(\log T)/d(\log P) < 0$



(Draine 2011)

MULTI-PHASE MODELS OF THE ISM-I

(Field, Goldsmith & Habing 1969)

- First two-phase model of the ISM, including WNM and CNM.
- Cosmic rays assumed to be the dominant heating source, with a cosmic ray ionization rate of $\zeta_{CR} = 4 \times 10^{-16}\ s^{-1}$.

  (Hayakawa et al. 1961; Field 1962)
- Cooling dominated by Lyman-α in the WNM and metal lines (CII, OI) in the CNM.
- For a thermal pressure of ~ 1800 cm^{-3} K, three allowed phases: (F) $T \sim 10^4$ K, (G) $T \sim 5000$ K, and (H) $T \sim 100$ K.
- Argued that phase-G is thermally unstable: $d(\log P) / d(\log n) < 0$!
- Identified the 100 K phase with the CNM and the 10^4 K phase with the WNM. Most of the ISM is filled with the WNM.
- Also argued for an additional stable phase at $T > 10^6$ K!

Multi-phase Models of the ISM-II

(McKee & Ostriker 1977)

- Type Ia supernovae: Kinetic energies ~ 10^{51} ergs, Mass ~ 1.4 $M_{\odot}$.

- (1) Free expansion at high, near-constant velocity: Forward shock driven into the circumstellar medium.

  (2) Pressure of the circumstellar medium larger than pressure of the ejecta: Reverse shock drives into the ejecta, heating the material.

  (3) Sedov – Taylor phase: SNR pressure $\gg$ ISM pressure. Shock radius, $R \propto E^{1/5}.\rho^{-1/5}.\, t^{2/5}$.

  (4) Snowplow phase: Thermal pressure of the shell comparable to the ISM pressure. But hot gas in the SNR interior at much higher pressure, driving the expansion ⇨ Dense shell of cool gas sweeping up more gas and enclosing a hot core.

  (5) Fadeaway: Shock speed ~ ISM sound speed; t ~ 2 Myr.

- Supernovae naturally give rise to hot ($T \sim 10^6$ K), low-density gas !

(Cox & Smith 1974)

Multi-phase Models of the ISM-II

(McKee & Ostriker 1977)

- Type Ia Sne rate ~ 1 per 40 yrs ⇨ SNRs overlap in 2 Myr, giving large, hot dilute interiors, with dense overlapping walls.
  ⇨ Uniform WNM of FGH model destroyed in ~ 2 Myr !
  ⇨ Multi-phase ISM: Low-density hot gas and cool, dense gas!

- McKee – Ostriker model: Supernovae regulate the ISM pressure! For low ISM pressure, SNRs expand to larger sizes before overlapping, thus increasing the net ISM pressure!

- Use supernova rate and average energy to estimate the mean pressure for overlap by *one* SNR ⇨ Pressure ~ 6600 cm^{-3} K, Hot ionized gas at $T \sim 6 \times 10^5$ K, $n \sim 0.007\ cm^{-3}$.

- Decent match between model predictions and observations! But predicts very little (~ 4%) gas in the WNM...

(McKee & Ostriker 1977)

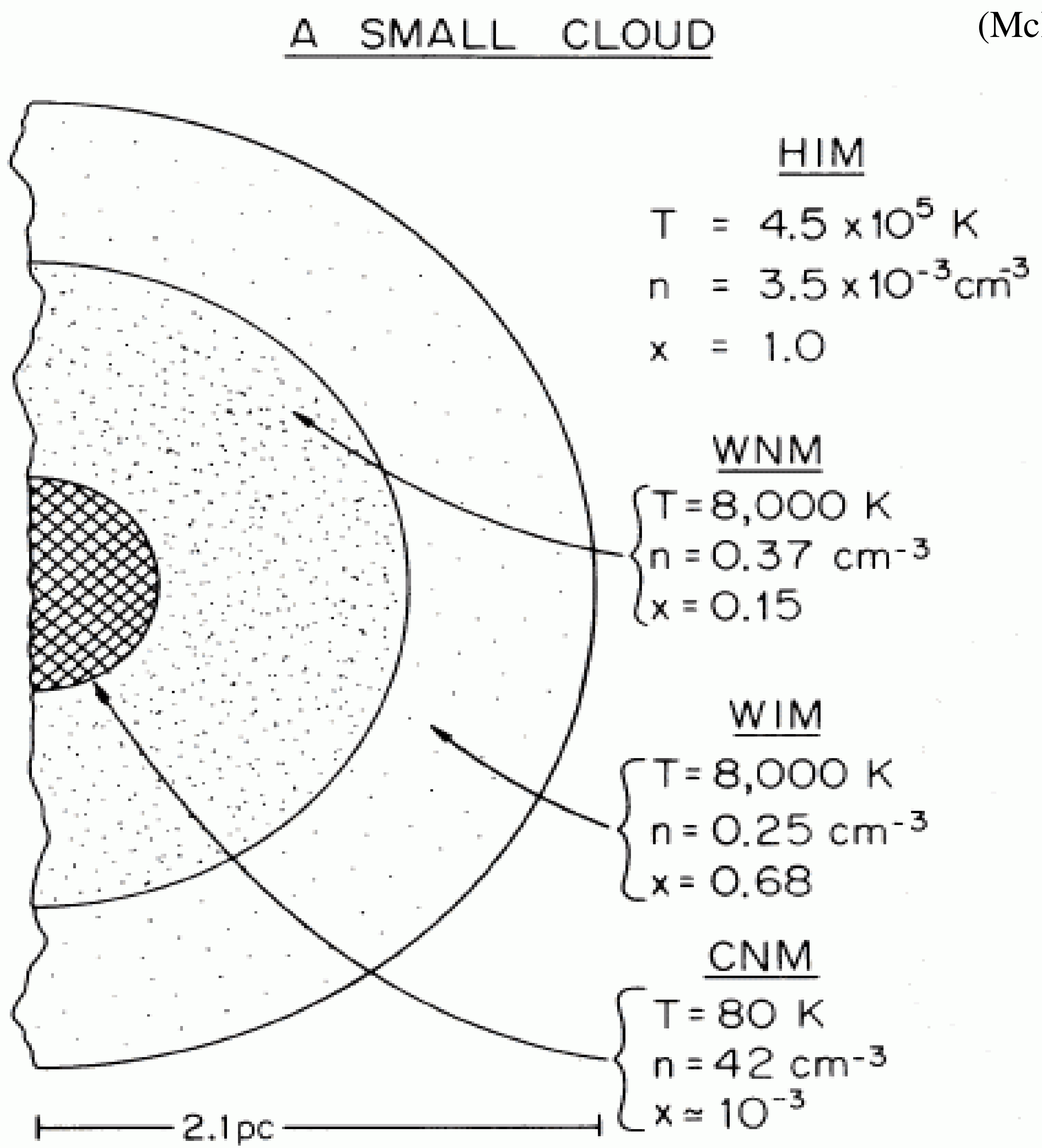


FIG. 1

Multi-phase Models of the ISM-III

(Wolfire et al. 1995, 2003)

- Consider a two-phase HI model a la Field et al. (1969).

- Dominant source of heating: Photo-electric ejection of electrons from small dust grains and PAHs. (Bakes & Tielens 1994)

- Highly complex code, solving iteratively for the temperature of ionization equilibrium, while balancing heating and cooling rates.

- Stable two-phase HI medium at pressures $(990 < P < 3600)\ \mathrm{cm}^{-3}\ \mathrm{K}$:
  For the cold phase: $T \sim 40 - 200\ \mathrm{K}$, $n \sim 4 - 80\ \mathrm{cm}^{-3}$.
  For the warm phase: $T \sim 5000 - 8700\ \mathrm{K}$, $n \sim 0.1 - 0.6\ \mathrm{cm}^{-3}$.

- Equilibrium timescale $\ll$ Timescale between shocks ⇨ Expect most of the neutral atomic gas to be in either the CNM or the WNM!

- For the Weingartner-Draine dust model, and $P = 3800\ \mathrm{cm}^{-3}\ \mathrm{K}$,
  CNM: $T \sim 160\ \mathrm{K}$, $n \sim 22\ \mathrm{cm}^{-3}$.
  WNM: $T \sim 5500\ \mathrm{K}$, $n \sim 0.6\ \mathrm{cm}^{-3}$.

(Draine 2011)

Observations versus Theory

- CNM pressure ~ 3800 cm^{-3} K. (Jenkins & Tripp 2011)
- Median CNM temperature ~ 70 K. (Heiles et al. 2003)
- Warm ionized medium: $T \sim 10^4$ K, $n \sim 0.1$ cm^{-3}.
- Hot ionized medium: $T \sim 10^6$ K, $n \sim 0.001$ cm^{-3}.
- Large gas mass in the WNM, ~ 60 %. (Heiles et al. 2003)

  Significant gas fraction in the unstable phase, $T \sim 500 - 5000$ K. (Roy et al. 2013)

  Over-pressured cold gas, with $P \sim 3 \times 10^5$ cm^{-3} K. (Jenkins & Tripp 2011)
- What about magnetic fields ??? Not part of any model! (Rohit 2013, private communication)
- McKee – Ostriker model, with Wolfire modifications, the best game in town. Critical: Observations of HIM, WNM, CNM pressures!