The Neutral Atomic Phases of the Interstellar Medium

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Main issue

- How do obtain pressure equilibrium of WNM and CNM from calculation?
- $P/k = T\boldsymbol{\Sigma}n_i$ → Calculate n_i at selected n and T
- Previous works
  - 1969 Field et. al.: cosmic ray only → estimated ionization rate too high
  - 1970s, 1978 Draine: photoelectric heating of dust → can heat CNM only
  - 1988 Ferrière et. al.: hydrodynamic wave dissipation → estimated pressure too low
  - 1994 Bakes and Tielens (BT): Photoelectric heating of small dust grain & PAH
- This work try to deliver the first “complete picture” for all dominating physical process

WNM and CNM

	Wolfire		Draine	
	WNM	CNM	WNM	CNM
Temperature	~8000K	>~50K	~5000K	~100K
Density	0.37 cm^{-3} *	61 cm^{-3} *	0.6 cm^{-3}	30 cm^{-3}
n_e/n	~0.1			
Pressure P/k	~10^3-10^4 $K \cdot cm^{-3}$		~3000 $K \cdot cm^{-3}$	

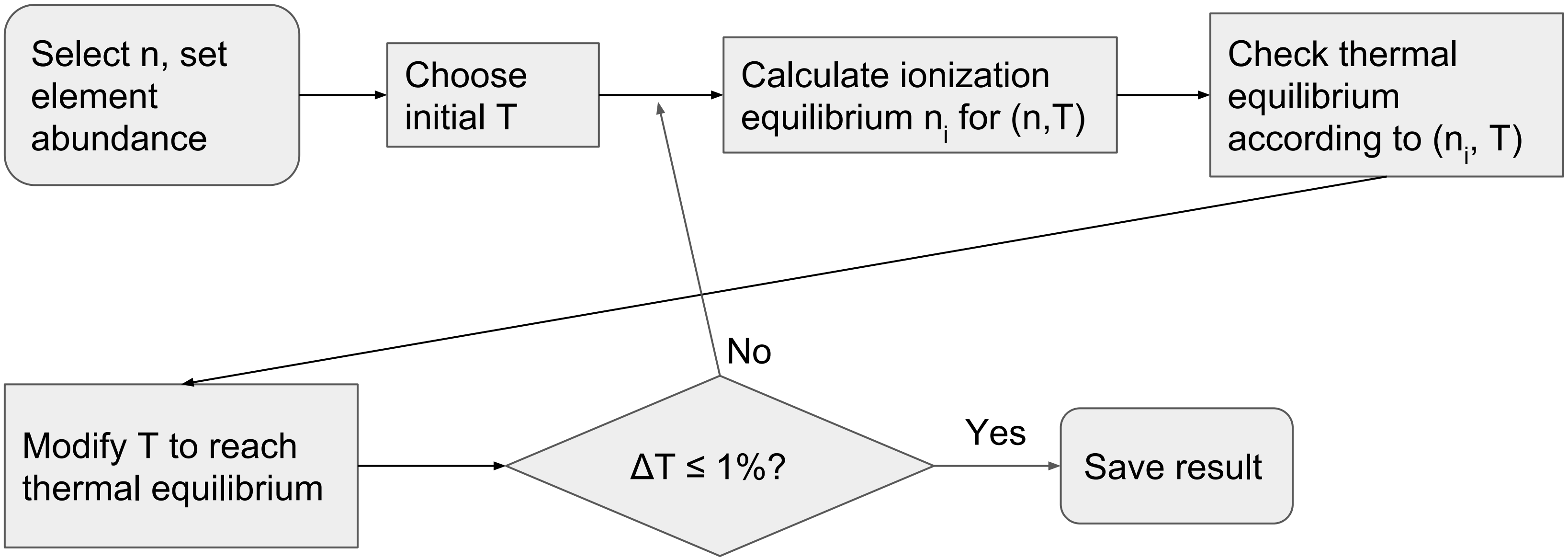
Involved physical processes

		Wolfire	Draine	
			WNM	CNM
Heating	Photoelectron from dust	O (mainly small grain)	O	O
	Cosmic rays	O		
	Soft X-ray	O		
Ionizing	Cosmic rays	O	O	O
	Soft X-ray	O	O	O
	Collisional	O (H and He)		
Cooling	Fine structure lines	O	O	O
	Optical lines	WNM only	O	
	Recombination	O		

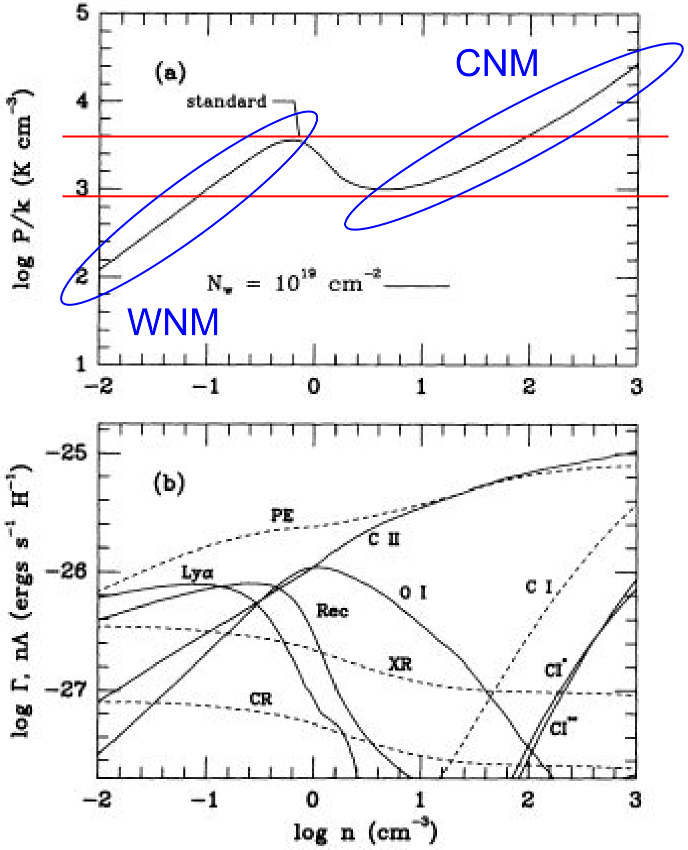
Dominant Thermal and Ionization Processes (Standard Model)

Process	Notes	Reference
Photoelectric heating from small grains and PAHs		
FUV field	Draine field; $G_0 \approx 1.7$ in units of Habing field	1
Heating	$n\Gamma = 10^{-24} G_0 n\epsilon$ ergs cm^{-3} s^{-1}	2
	$\epsilon = 4.9 \times 10^{-2}[1.0 + 4.0 \times 10^{-3}(G_0 T^{1/2}/n_e)^{0.73}]^{-1} + 3.7 \times 10^{-2} (T/10^4)^{0.7}(1.0 + 2.0 \times 10^{-4} G_0 T^{1/2}/n_e)^{-1}$; n_e from ionization equilibrium	2
Ionization and heating by cosmic rays		
Primary ionization	$n\zeta_{CR} = 1.8 \times 10^{-17} n$ cm^{-3} s^{-1}	3
Secondary ionization	Primary $E = 35$ eV, n_e from ionization equilibrium	4
Heating	Primary $E = 35$ eV, n_e from ionization equilibrium	4
Ionization and heating by soft X-rays		
1. Unabsorbed component	$T_1 = 10^{6.16}$ K, EM$_1 = 5.3 \times 10^{-3}$ cm^{-6} pc, $N_1 = 0.0$ cm^{-2}	5, 6
2. Absorbed component	$T_2 = 10^{6.33}$ K, EM$_2 = 2.5 \times 10^{-3}$ cm^{-6} pc, $N_2 = 3.6 \times 10^{20}$ cm^{-2}	5, 6
3. Extragalactic component	$I_\nu \propto (h\nu)^{-0.4} e^{-\sigma N_3}$, $N_3 = 3.9 \times 10^{20}$ cm^{-2}	5, 6
Spectrum calculated for foreground absorption	Absorbing column = N_w	
Primary ionization	$n\zeta_{XR}$ from H, He, C, N, O, Ne, Mg, Si, S, Fe	7
Secondary ionization	From H and He, n_e from ionization equilibrium	4
Heating	n_e from ionization equilibrium	4
Recombinations		
Radiative recombination	H^+, He^+, C^+	8
Ion recombination on grains	H^+, He^+, C^+, neutralization, charge exchange, adsorption	9
Cooling by fine-structure lines		
C II	Impacts with H^0 and e^-, $\mathscr{A}_C = 3 \times 10^{-4}$	10, 11
O I	Impacts with H^0, e^-, and H^+, $\mathscr{A}_O = 4.6 \times 10^{-4}$	12
C I, Si I, Si II, S I, Fe I, Fe II	Minor coolants	8
Cooling by resonance lines		
Lyα	Important at $T \gtrsim 8000$ K	13
Cooling by metastable lines		
C I, C II, O I, O II, Si I, Si II, S I, S II, Fe I, Fe II	O I most important coolant	8
Cooling by recombination onto small grains and PAHs		
...	$n^2\Lambda = 4.65 \times 10^{-30} \eta n_e n$ ergs cm^{-3} s^{-1}	2
...	$\eta = T^{0.94}(G_0 T^{1/2}/n_e)^\beta$; $\beta = 0.735/T^{0.068}$; n_e from ionization equilibrium	

Computational flow chart



Phase diagram and physical processes



- dlog(P)/dlog(n)>0 → stable
- Equilibrium region: 990<P<3600, 8700>T_{WNM}>5500, 210>T_{CNM}>41
- Photoelectric heating dominates heating process; smaller dependence on density
- Dominating cooling process depends on density (temperature)

References

1. Wolfire, M. G., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, ApJ, 443, 152

2. Draine, B. T. 2011, Princeton University Press

3. Field, G. B., Goldsmith, D. W., & Habing, H. J. 1969, ApJL, 155, 149

4. Wolfire, M. G., Mckee, C. F., & Hollenbach, D. 2003, ApJ, 587, 278

End

Gas phase abundance

Element	Gas-phase Abundance[a]	$A = n_i / n$	Elemental Abundance[a]
He	-1.00	$1.0 \cdot 10^{-1}$	-1.00
C	-3.52	$3.0 \cdot 10^{-4}$	-3.44
O	-3.34	$4.6 \cdot 10^{-4}$	-3.34
Si	$-5.45-0.45 \times (\log n + 0.5)$		-4.45
Mg	$-4.84-0.28 \times (\log n + 0.5)$[b]		-4.41
Fe	$-6.15-0.38 \times (\log n + 0.5)$		-4.49
S	-5.10		-4.73
N[c]	...		-3.95
Ne[c]	...		-3.91

Problems

- Thermal time scale of WNM is longer than pressure fluctuation timescale