Lecture 12 Summary of the Diffuse ISM

1. Thermal instability reconsidered
2. Review of the observations
3. Interstellar pressure
4. Evaluation of the Two-Phase Model

References

D P Cox ARAA, 43, 337, 3005
K M Ferriere, RMP, 73, 1031, 2001

Thermal Instability: A Simple but Useful Model

The abstract statement of Field's instability condition

$$\left(\frac{\partial \Lambda_{\mathrm{m}}}{\partial s}\right)_A < 0$$

can be elucidated using the model from Lec11. The net cooling function per unit mass

$$\Lambda_m = \rho^{-1}(\Lambda - \Gamma) \text{ with } \Lambda = \lambda n_{\mathrm{H}}{}^2 \text{ and } \Gamma = \gamma n_{\mathrm{H}}$$

becomes

$$\Lambda_m = m^{-1}(\lambda n_{\mathrm{H}} - \gamma)$$

where λ is a strong function of T and γ is constant.

For constant pressure $p = nk_{\mathrm{B}}T$, this is

$$\Lambda_m = m^{-1}\left(\frac{\lambda}{k_{\mathrm{B}}T}p - \gamma\right).$$

Model Instability Condition

Differentiate this form at constant pressure:

$$\left(\frac{\partial}{\partial s}\right)_p \Lambda_m = \left(\frac{\partial}{\partial T}\right)_p \frac{1}{(5/2k_B/m')} m^{-1}\left(\frac{\lambda}{k_B T} p - \gamma\right)$$

or

$$\left(\frac{\partial}{\partial s}\right)_p \Lambda_m \propto \left(\frac{\partial}{\partial T}\right)_p \frac{\lambda}{k_B T} p \propto \frac{d}{dT}\frac{\lambda}{T} = \frac{1}{T}\frac{d}{dT}\lambda - \frac{\lambda}{T^2}.$$

The constant pressure instability condition in this case is

$$\left(\frac{\partial}{\partial s}\right)_p \Lambda_m \propto \frac{d\lambda}{dT} - \frac{\lambda}{T} < 0$$

Let's go further with a **"toy model"** where $\lambda = \lambda_0 T^a \lambda$
and the **instability condition** becomes

$$\frac{d\lambda}{dT} - \frac{\lambda}{T} = (a-1)\frac{\lambda}{T} < 0 \quad \text{or} \quad a < 1.$$

Toy Model Instability Condition

In addition to the **instability condition, *a* < 1**, we can obtain the temperature by solving the thermal balance equation:

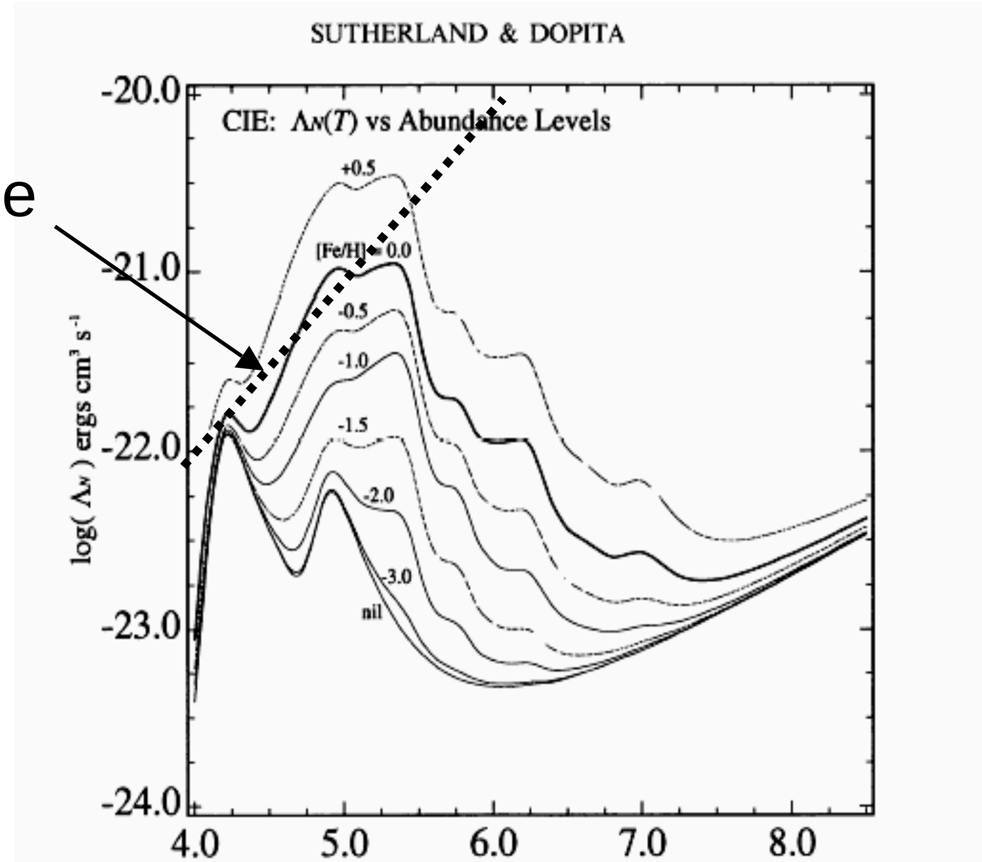
$$\lambda n_{\mathrm{H}} = \gamma \;\; \Rightarrow \;\; \lambda_0 T^a n_{\mathrm{H}} = \gamma \;\; \Rightarrow \;\; \frac{\lambda_0}{k_B} T^{a-1} p = \gamma$$

$$p/k_B = \frac{\gamma}{\lambda_0} T^{-(a-1)} \quad \text{or} \quad T = \left(\frac{\gamma}{\lambda_0} \frac{k_B}{p} \right)^{1/a-1}$$

To be at all useful, the toy model can only apply over a limited range. It does make sense for the original FGH model, where the low-temperature cooling is due to the CII fine structure line. Since the cooling varies with a Boltzmann factor, it is less rapid than a linear function of *T* for small *T*, and it therefore supports an unstable region.

High Temperature Instability

dashed unit slope line



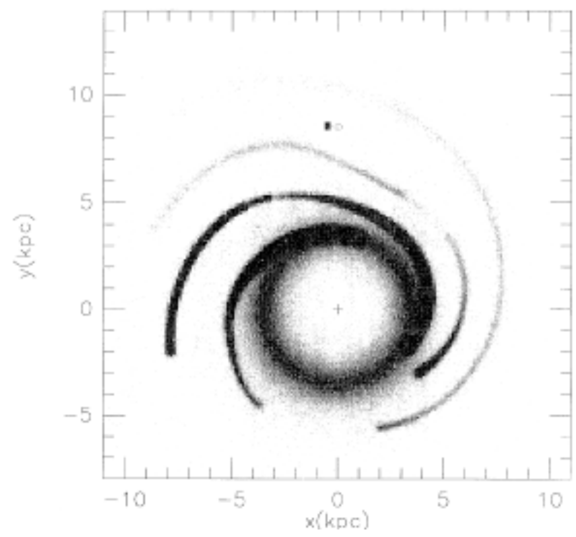
Low density cooling curve for
T > 10^4K & varying metallicity
Sutherland & Dopita,
ApJ 88, 253,1993.

Just above 10^4K and especially above 10^5K, the slope of the cooling curve is less than unity, so the gas is predicted to be thermally unstable. But there is also a stable regime in between, associated with the HIM.

2. Review of the Observations

WIM - Pulsar DM, Hα EM, Spectral line mapping

PULSAR DISTANCES AND FREE-ELECTRON DISTRIBUTION



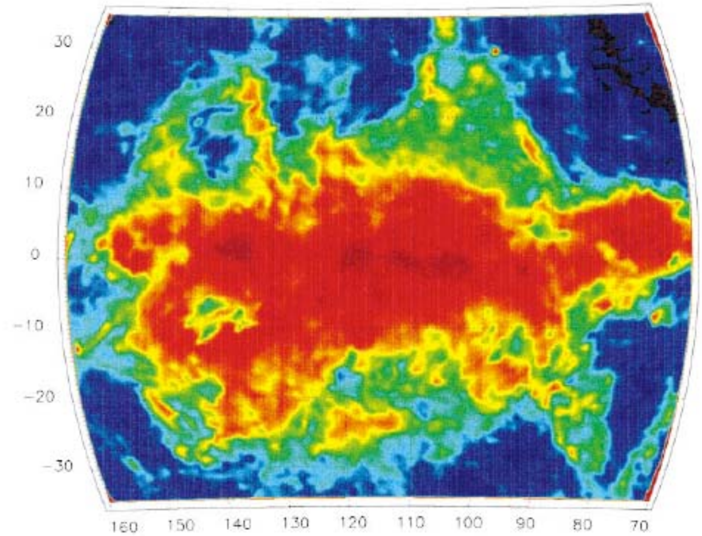


FIG. 6. High-resolution Hα map of a 90°×70° portion of the sky centered on (l=115°, b=0°) at velocities between −60 and 40 km s^{-1}, from the *WHAM* survey. Figure courtesy of L. M. Haffner. [Color]

Electron density looking down on the galaxy. (Taylor & Cordes 1994)

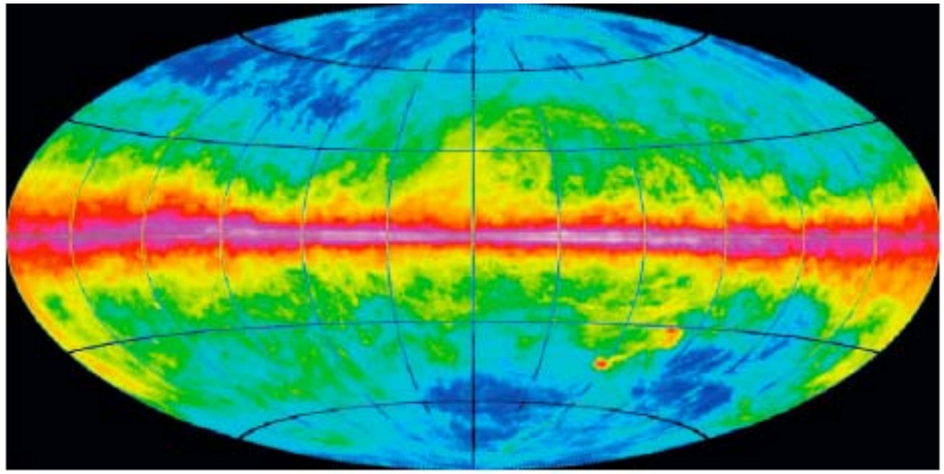
WHAM Hα Map

The Hα maps are particularly useful for providing insights into the vertical distribution of the WIM. They demonstrate clearly how non-uniform the ISM is.

Summary of WIM Properties

1. $< n_e > \; = \; 0.025 \text{ cm}^{-3}$, $H = 1$ kpc
2. $n_e = 0.18\text{-}0.46 \text{ cm}^{-3}$, $\phi = 0.05\text{-}0.15$
3. $T = 6{,}000\text{-}10{,}000$ K
4. Vertical column density of WIM H^+ is comparable to HI
5. EUV ionizes N and S, but is softer than in HII regions
6. Pervasive, inhomogeneous, near fully-ionized, medium in a thick (2 kpc) disk with streamers or chimneys to high latitudes and links to mid-plane HII regions.
7. Volume occupied by the WIM is a variable mix of other phases that changes with height above the midplane

CNM/WNM - 21cm HI



Integrated 21-cm Emission of the Milky Way

Note the complex high-*b* structures

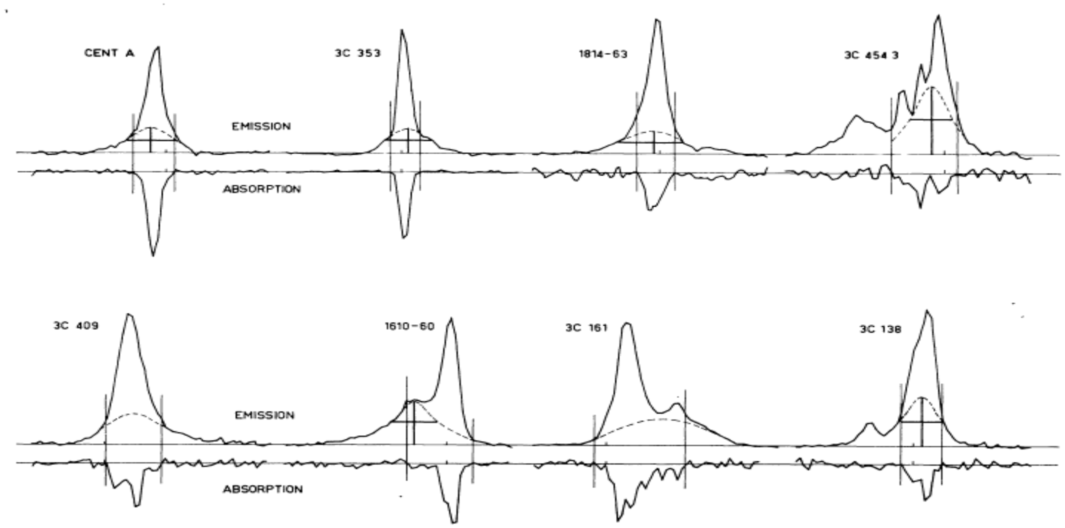
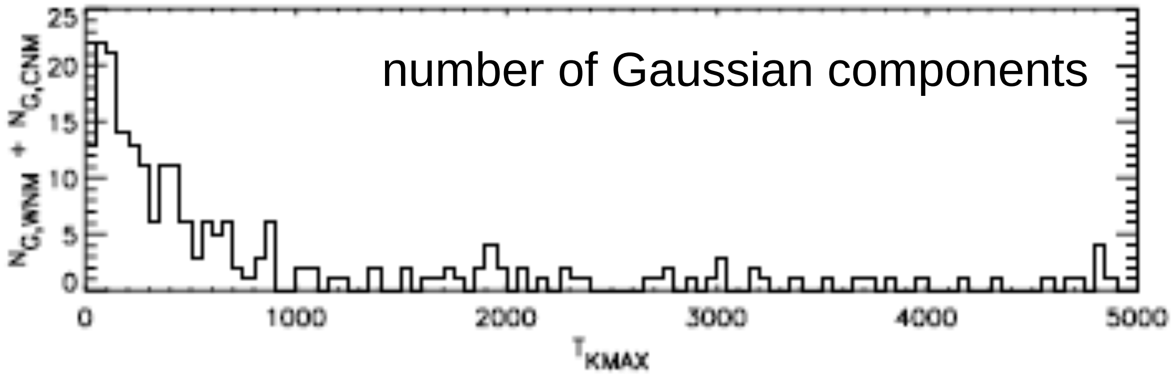


Fig. 32.—Comparison of eight emission and absorption spectra obtained at intermediate latitudes and selected on the basis of high signal-to-noise ratio. The velocity limits of the absorption spectra are demarcated, showing clearly the presence of an optically thin component in every emission spectrum. These components are shown by dashed lines. In six cases (*crosses*) the parameters of the low, wide component were determined by a computer analysis into Gaussians. See text for discussion.

Classic on-off 21-cm spectra towards extragalactic radio continuum sources

Troland & Heiles: Arecibo Millennium Survey II



1. Emission is ubiquitous - absorption is not
2. CNM & WNM are observationally distinct
3. WNM is 60% of total HI
4. Median columns: CNM 0.5×10^{20} cm^{-2}
   WNM 3×10^{20} cm^{-2}
5. Broad temperature ranges:

   CNM - T_S = 100-200 K

   WNM - T_S = 500 - 20,000 K

Summary of CNM & WNM (Heiles & Troland II)

6. CNM median (column density weighted) temperature is ~ 70 K
7. WNM temperature distribution has peak near 8,000 K,
8. ~ 50% of WNM is thermally unstable (500-5,000 K)
9. CNM clouds are sheet like
10. Assuming pressure equilibrium (p/k_B = 2250 cm^{-3} K)

phase	T (K)	n(HI) (cm^{-3})
CNM	~ 40	~ 56
WNM	~ 4000	~ 0.56

Somewhat higher temperatures and pressures are usually chosen.

Magnetic Field - pulsar RM, synchrotron emission, Zeeman

- RM and Zeeman measure parallel component (to the l.o.s)
- Synchrotron and starlight polarization measure the perpendicular component (plane of the sky).
- Although Zeeman is the "coin of the realm", it is difficult to use, but it does give the most accurate value in the solar neighborhood ~ 6 μG
- For global information, synchrotron radiation is the most useful. The magnitude of the field cannot be determined without making assumptions about the electron density, since the flux is proportional to $B^2 n_e$.
- For the Milky Way, the results in the solar neighborhood are $B \sim 5\ \mu$G, $H_z \sim 4.5$ kpc , $H_R \sim 12$ kpc.
  Take note of the large vertical scale height

Rough Physical Properties of Phases

Phase	Observations	*T*	*n*
CNM	HI absorption	75	40
WNM	HI emission	"4,000"	"0.075"
WIM	DM, EM, Hα em.	8,000	0.0375
HIM	UV abs., soft X-rays	10^6	0.003

- The numbers are only meant to be suggestive.
- Poorly known filling factors have been ignored.
- *Assumed* pressure equilibrium for all phases is $\boldsymbol{nT = 3{,}000\ \mathrm{cm^{-3}\ K}}$, rather than the 2,250 $\mathrm{cm^{-3}}$ K used by Heiles & Troland .
- 50% of the WNM is in the thermally unstable range from 500-5,000 K.

3. The Problem of the Interstellar Pressure

Ferriere (in "The interstellar environment of our galaxy" 2001) **and Cox** (in "The Three Phase ISM Revisited" 3005) summarize data on the global ISM and give fits for the vertical distribution of hydrogen nuclei in the solar neighborhood. (units cm^{-3}):

molecular: $0.58\ \exp[-(z/81\,\mathrm{pc})^2]$ — dense gas

cold HI: $0.57 * 0.7\ \exp[-(z/127\,\mathrm{pc})^2]$ — **CNM**

$$\left.\begin{array}{l}\text{warm HIa: } 0.57 * 0.18\ \exp[-(z/318\,\mathrm{pc})^2] \\ \text{warm HIb: } 0.57 * 0.11\ \exp(-|z|/403\,\mathrm{pc})\end{array}\right\}\ \textbf{WNM}$$

HII Regions: $0.015\ \exp(-|z|/70\,\mathrm{pc})$ — star forming regions

diffuse HII: $0.025\ \exp(-|z|/1000\,\mathrm{pc})$. — **WIM**

The densities of atoms and molecules at the midplane are about equal (0.6 cm^{-3}). The WIM density of electrons (and H$^+$) is down by 23, but it decreases more slowly with *z*. The molecular gas and the star forming region form thin disk.

First Consideration of Forces on the ISM

In terms of a static disk, the most important force for consideration of large scale (kpc) structure is the gravity field generated by the stars (with a mass an order of magnitude larger than the gas. component).

See Spitzer Sec.1.6 to see how the velocity dispersion of stars vs.. height *z* can be used to find the gravity just above the disk.

Cox quotes Dehnen & Binney (MNRAS 294 429 1998) for the following fit, accurate to 2% for *z* up to 10 kpc

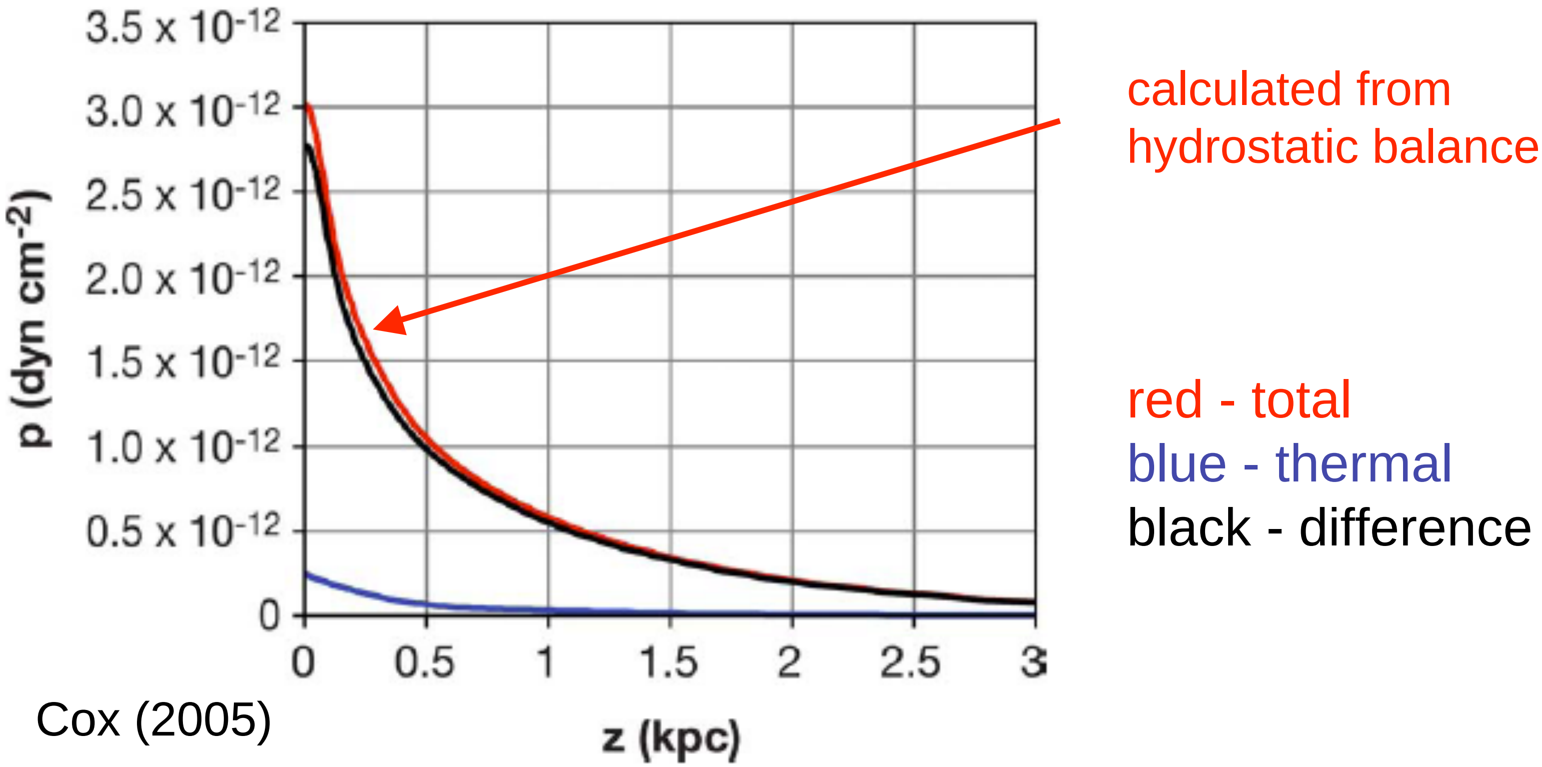
$$|\mathrm{g}| = 10^{-9}\,\mathrm{cm\ s^{-2}}\,\{4.2[1-\exp(-|\mathrm{z}|/165\ \mathrm{pc})] + 4.1|\mathrm{z}|/2\ \mathrm{kpc}\}$$
$$\cdot\,(1-|\mathrm{z}|/27\ \mathrm{kpc})/[1+(\mathrm{z}/6\ \mathrm{kpc})^2]^{1/2}.$$

The 1st term on the 1st line is from disk and the 2nd from halo stars. The pressure that the gas must supply can be found by integrating the equation for hydrostatic equilibrium,

$$\frac{dp}{dz} = -\rho(z)\, g(z)$$

The results are shown on the next slide assuming $p(10\ \mathrm{kpc}) = 0$.

Interstellar Pressure



Cox (2005)

Figure 2 Comparison of the total (*red*) and volume average thermal (*blue*) pressure distributions, and their difference (*black*) interpreted as the nonthermal pressure. In this case, the total is taken from the weight distribution of the ISM. The thermal pressure neglects any contribution from the hot component.

At the midplane, the thermal pressure, $p/kB = 3000\ cm^{-3}$ K, is deficient by a factor of 7 relative to the total of 22,000 cm^{-3} K. This deficiency grows with *z*. The contribution of the HIM is ignored.

The Non-Thermal Pressures

$$p = p_{\mathrm{th}} + (p_{\mathrm{turb}} + p_{\mathrm{mag}} + p_{\mathrm{CR}} + p_{\mathrm{dyn}})$$

- The terms in parentheses are the non-thermal pressures.
- The last term is associated with macroscopic flows and their ram pressure.
- The turbulent pressure is estimated to be too small to account for the total.
- Boulares & Cox (ApJ 365 544 1990) suggested that the last three terms are in rough equipartition. Although this would seem to solve the pressure problem, it conflicts with the vertical variation of the magnetic field obtained from the observations of synchrotron radiation.

Boulares & Cox Problem

• Vertical variation of the magnetic field determined by equipartition and the total pressure (Boulares & Cox 1990).
• It disagrees with the field strength determined from the synchrotron emission and measured densities associated with the cosmic rays, which permits breaking the ambiguity between n_e and B^2 Ferriere (2001).

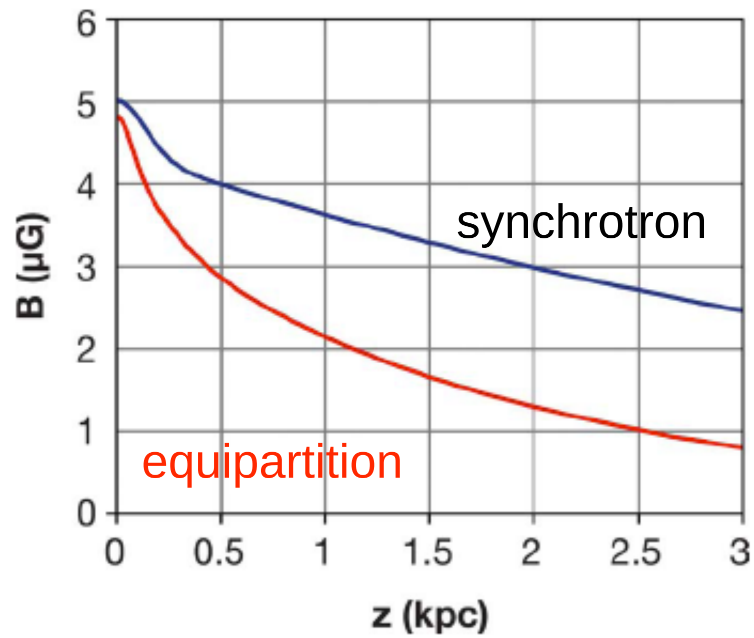
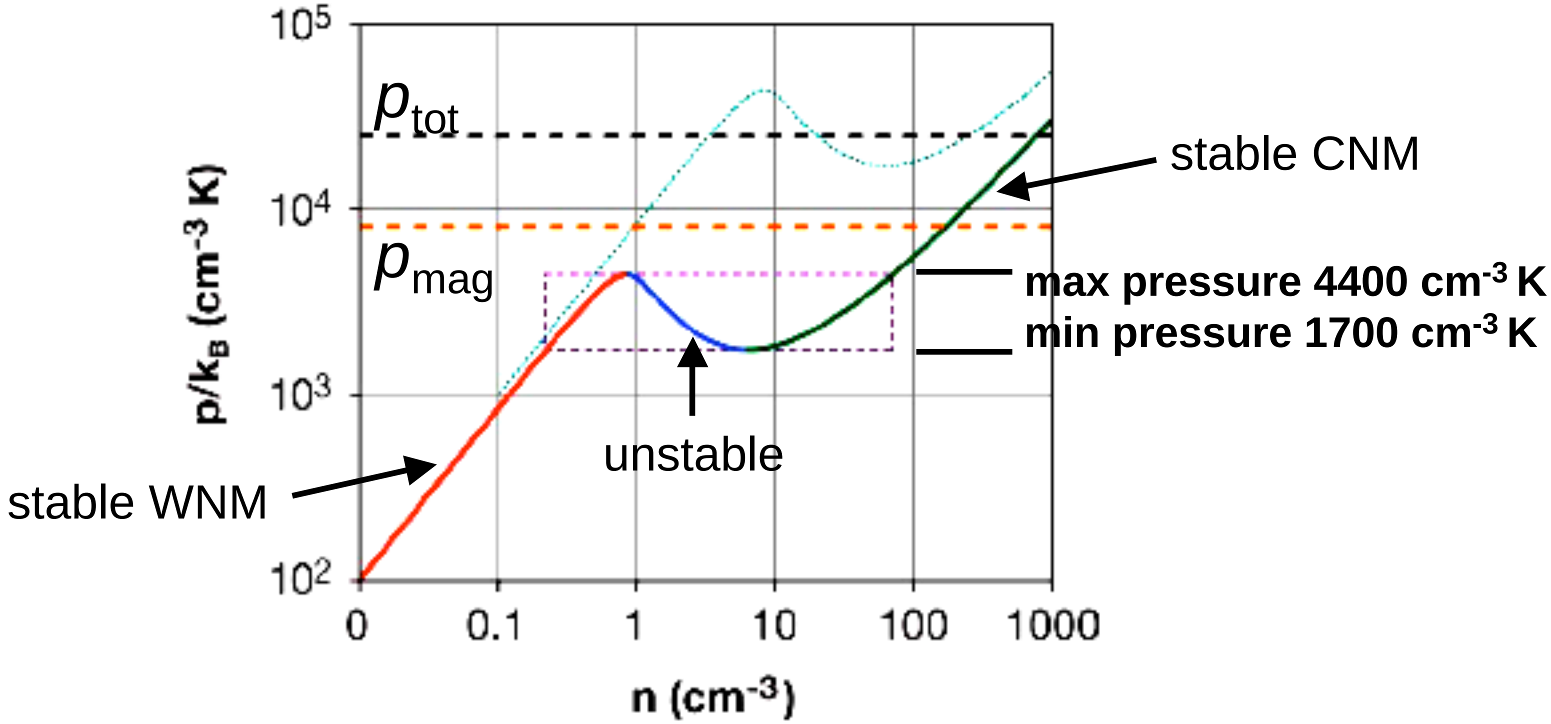


Figure 3 The vertical distribution of magnetic field strength. The *red curve* follows from assuming that one third of the nonthermal pressure of Figure 2 is magnetic, with the field parallel to the plane. The *blue curve* arises from the vertical distribution of the synchrotron emissivity, which implies that the rms field drops much more slowly with height.

Solutions mentioned in Cox's review:

1. Generalize the hydrostatic balance by including vertical as well as horizontal fields (with respect to the plane of the galaxy). This is the subject of Boulares & Cox (1990)
2. Add other mass components to counter the additional pressure implied by the upper curve of the figure.

4. Evaluation of the Two-Phase Model



Two-phase model for the Solar Neighborhood
Wolfire et al. (2003)

- **Top aqua curve is for a 10 times larger heating rate.**
- **Model depends on location in the galaxy and on which galaxy.**
- **Unstable regime: n_H =1 - 7 cm^{-3} and T = 275 - 5500 K**

Comments on the Phase Diagram

1. Measured local mean density ~ 1 cm^{-3} is in unstable regime, which might suggest that this material evolves (or driven into the WNM and CNM phaes.
2. The CNM branch lies below both the total and the magnetic pressure, which guarantees enough external pressure to make and confine clouds.
3. With increased heating, the mean density corresponds to the WNM, and cool clouds become difficult to confine.
4. Clouds are generally hard to form because of the large difference in the CNM and WNM densities, which requires large volumes of low density warm material be gathered together; thermal instability can't do the job by itself.

5. Suggested *volume filling factors* (Cox Sec. 4.4) are roughly:

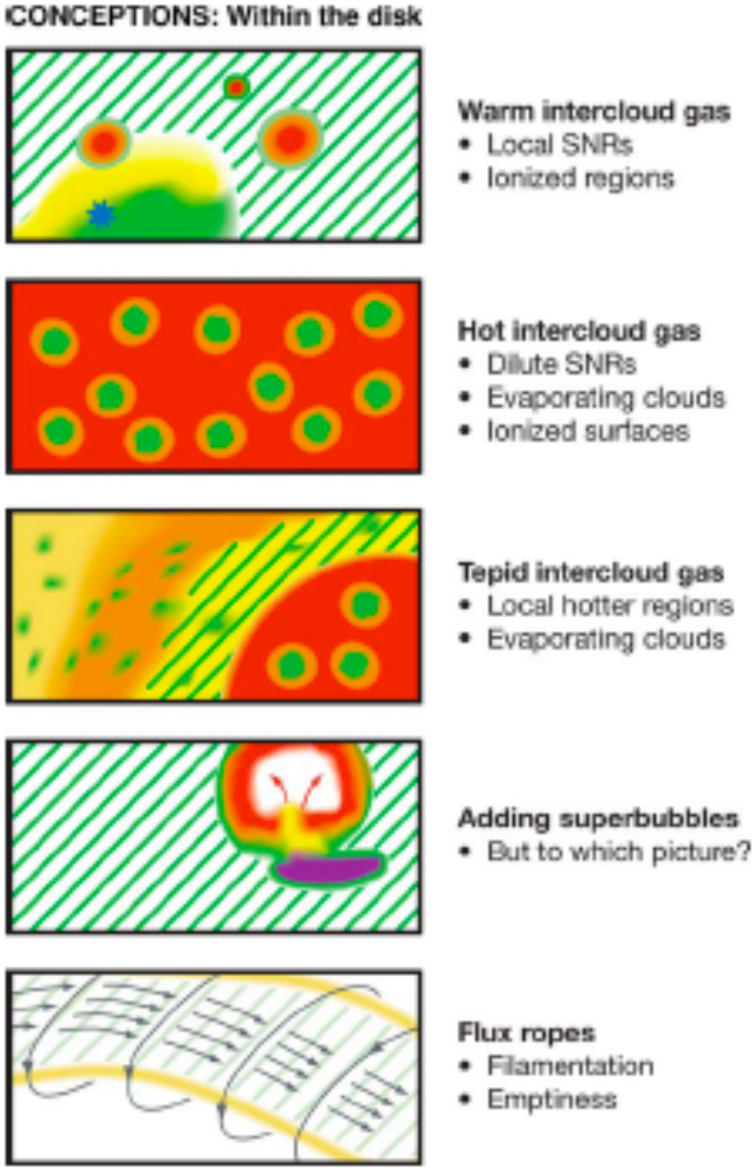
CNM: 1%, WNM: 40%, WIM 9%

About 50% of the ISM must be occupied by very low density gas, or else the warm phases occupy more volume at lower densities

Bottom Line on the Two-Phase Model

- Provides a framework for discussing interstellar clouds and the inter-cloud media.
- The observed phases do not correspond closely to well-defined phases at a common pressure; Heiles & Troland find a wide range of temperature, especially for the WNM.
- The mean gas density in the solar neighborhood is in the unstable regime, as are many of the WNM components detected by Heiles & Troland.
- The measured thermal pressure, ~ 3000 cm^{-3} K, is much smaller than the total pressure.
- Magnetic, cosmic-ray, and dynamical pressures are more important; they must play an important role in the formation and stability of interstellar clouds.

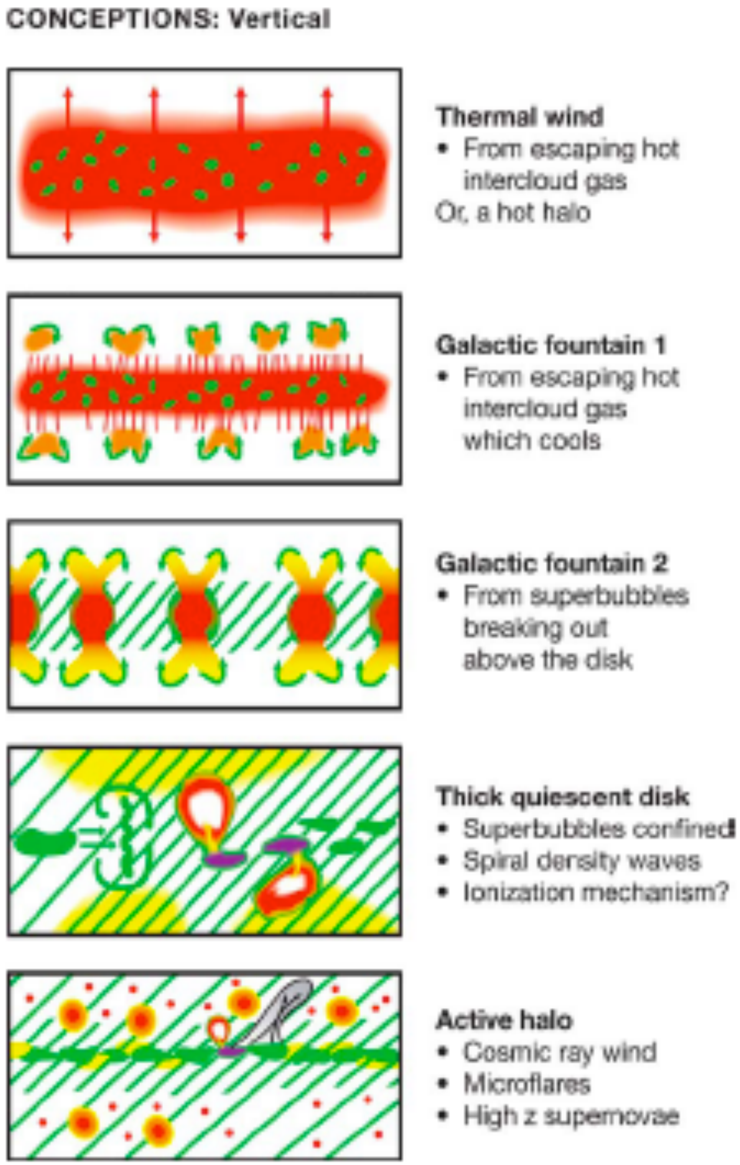
Cox's Conceptions About the Disk



Color code
Hatched green: WNM
Solid green: CNM
Solid purple: dense star-forming clouds
Hatched green over yellow: WIM
Orange: HIM producing OVI
Red: hotter WIM emitting X-rays

These pictures show how common conceptions need to be examined together and reconciled in order to understand the complex structures observed in the disk ISM.

Cox's Conceptions on Vertical Structure



Color code

Hatched green: WNM
Solid green: CNM
Solid purple: dense star-forming clouds
Hatched green over yellow: WIM
Orange: HIM producing OVI
Red: hooter WIM emitting X-rays

These pictures show how common conceptions need to be examined in concert in order to understand the complex structures observed above the disk.