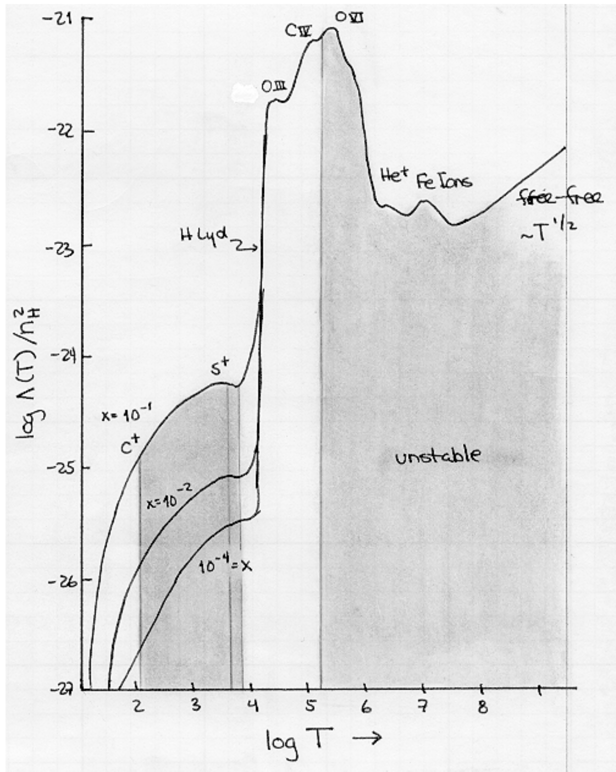

Figure I-13: Interstellar Cooling curve adapted from Dalgarno & McCray (1972).

Thermal Stability and Equilibrium – The Two-Phase ISM Model of Field, Goldsmith & Habing (1969)

Consider gas with density, *n*, a cooling rate per unit volume of $n^2\Lambda(T)$, and a heating rate per unit volume of *nG*. If the gases in different thermal phases are in thermal contact, and in *thermal* pressure equilibrium (i.e., ignoring non-thermal pressure sources like magnetic fields), then the thermal balance between heating and cooling is expressed in terms of a **Generalized Loss Function**, L:

$$L(n,T) = n^2\Lambda(T) - nG$$

where:

$$L > 0 \Rightarrow \text{ Net Cooling}$$
$$L < 0 \Rightarrow \text{Net Heating}$$
$$L = 0 \Rightarrow \text{ Equilibrium}$$

For a gas at constant (thermal) pressure nT in equilibrium with density ρ_0 and temperature T_0, in terms of the Generalized Loss Function, equilibrium occurs when

$$L(\rho_0, T_0) = 0$$

Is the gas stable? If either the density or the temperature of this gas is perturbed while holding some thermodynamic variable (like the pressure) fixed, the equilibrium will be **unstable** if:

$$\left(\frac{\partial L}{\partial S}\right)_X < 0$$

where X is the fixed variable (e.g., Pressure), and S is the entropy of the gas. For isobaric (constant pressure) perturbations in a perfect gas, this condition for thermal instability becomes:

$$\left(\frac{\partial L}{\partial T}\right)_P = \left(\frac{\partial L}{\partial T}\right)_\rho - \frac{\rho_0}{T_0}\left(\frac{\partial L}{\partial \rho}\right)_T < 0$$

For example, if heating is dominated by cosmic rays and cooling by collisions, the loss function is:

$$L = n^2\Lambda(T) - n_H\zeta_{CR} = 0$$

Since the cosmic-ray ionization rate ζ_{CR} is constant, the criterion for isobaric instability above is

$$\left(\frac{d\ln\Lambda}{d\ln T}\right)_P < 1$$

(The proof of this is left as a homework exercise). If we were to substitute photoelectric heating from dust grains, we'd get a similar criterion, as this cooling depends on the ISRF intensity which to a first approximation is about constant in the diffuse ISM.

At constant pressure (nT=constant) and constant heating, we can plot the equilibrium condition, *L*(n,T)=0 in the log(Λ(T)/T) versus log(T) plane as shown below.

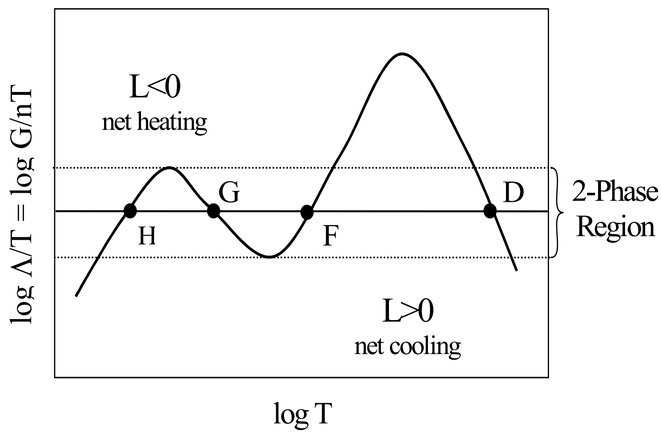

Figure I-14: Schematic Generalized Loss Function. The curve indicates the equilibrium condition, L=0. The horizontal line in the middle of the 2-phase region shows a line of constant pressure (nT).

A line of constant G/nT intersects the *L*=0 curve at 4 points, labeled H, G, F, and D as shown in Figure I-14 above.

At points H and F:

$$\left(\frac{\partial L}{\partial T}\right)_P > 0$$

which implies *stable* phases at T=100 K (cold) and 8000 K (warm).

At points G and D:

$$\left(\frac{\partial L}{\partial T}\right)_P < 0$$

which implies *unstable* phases at these points. Let's examine what is happening at point G and its neighbors (H and F) more closely to see why it is unstable. This is shown in Figure I-15.

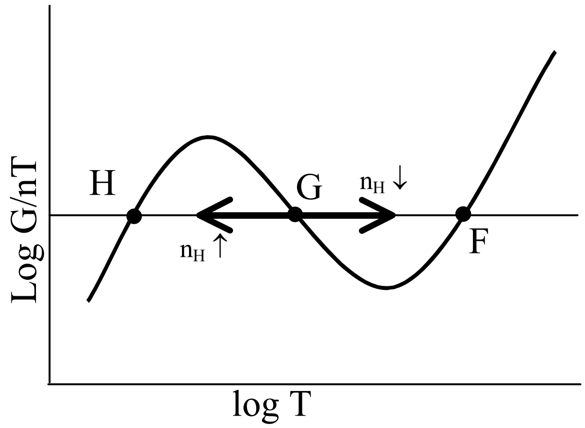

Figure I-15: Region around point G, showing perturbations in density from the equilibrium point.

To maintain constant pressure, nT, this requires that n vary like T^{-1}. For perturbations from equilibrium about point **G**,

1. **If n *increases* ⇒ T must *decrease*** (cloud collapses).

   The isobaric perturbation to higher density and lower temperature drives the cloud at point G into the region of net cooling (L>0). This causes T to decrease further, which at constant pressure means the density must increase, sending the cloud into a runaway collapse caused by runaway cooling.

2. **If n *decreases* ⇒ T must *increase*** (cloud expands).

   The isobaric perturbation to lower density and higher temperature drives the cloud at point G into the region of net heating (L<0). This causes T to increase further, which at constant pressure means the density must decrease further, sending the cloud into a runaway expansion caused by runaway heating.

By contrast, at the stable points H and F, isobaric perturbations in density that lead to net heating (cooling) produce a compensatory response in the temperature. For example, compression leading to cooling drives the cloud into the region of net heating, which drives it back to the original temperature.

The parameters of each of these phases of the original FGH model are as follows:

Phase	n_H (cm^{-3})	T (K)	$x=n_e/n_H$	Identification
F	≤0.1	≥8000	0.1	Warm Intercloud Medium
G	0.2	8000	—	**UNSTABLE**
H	≥10	≤300	0.001	Cold Neutral Clouds

In general, the agreement was pretty good considering the state of the observational data in 1969. Recent observational work, however, suggests that non-thermal pressures from magnetic fields, turbulence, etc. may in fact dominate over thermal pressure, and the assumption of pressure equilibrium is not relevant for the real ISM. While illustrative of the basic physics at play, the FGH model is not the whole story.

The Hot ("Third") Phase

The history of the third phase is more varied. In the 1950s, Spitzer predicted a hot "coronal" gas that was in pressure equilibrium with the cold and warm ionized gas seen locally. McCray & Buff (1972, ApJ, 175, L65) suggested a hot phase heated by cosmic rays. Cox & Smith (1974, ApJ, 189, L105) suggested instead that Supernova Remnants could produce this very hot phase. Maps of the local ISM show it to have numerous "loops" and "bubbles" (see schematic next page). The Sun resides in one such "Local Bubble", a hot ($\sim 10^6$K) low-density (0.005 cm^{-3}) region characteristic of this phase.

Based on a thermal stability argument like that presented above, it is clear that this hot phase cannot be stable. However, it is such a low-density medium that the cooling time is very long, $\sim 10^9$ years, much longer than the mean time between supernovae (about 1 per 50 years), thus new explosions would continually reheat the ISM before it could cool by very much.

Cox & Smith asked how many hot, low-density supernova bubble are needed to fill the ISM? They defined "fill" in terms of a porosity factor, q, which if q>1 the bubbles all overlap and merge into a pervasive, hot, low-density component of the ISM. Cox & Smith estimated that

$$q > 0.1 S_{-13}$$

where S_{-13} is the supernova rate in units of 10^{-13} SN pc^{-3} yr^{-1} (essentially a SN rate/volume). In 1974, this was thought to be of order unity in these units, so the porosity was ~0.1

McKee & Ostriker (1977, ApJ, 218, 148) re-examined the Cox & Smith model and suggested an improved estimate of the porosity:

$$q = 0.5 S_{-13} E_{51}^{1.28} n_0^{-0.14} \tilde{p}_{04}^{-1.3}$$

where:

$$\begin{aligned} S_{-13} &= \text{ SN rate/volume in } 10^{-13} \text{ SN pc}^{-3} \text{ yr}^{-1} \\ E_{51} &= \text{ SN blast energy in } 10^{51} \text{ ergs} \\ n_0 &= \text{ ambient ISM density in cm}^{-3} \\ \tilde{p}_{04} &= (p_0 / k) \times 10^{-4} \text{ cm}^{-3} \text{ K, and} \\ p_0 &= (n_e + n)_0 k T_0 \text{ pressure of the ISM in } 10^4 \text{ cm}^{-3} \text{ K} \end{aligned}$$

For their assumptions, S_{-13}=1, E_{51}=1, $n_0 \leq 0.3$ cm^{-3}, $T_0 = 10^4$ K, and there is purely thermal pressure, hence $\tilde{p}_{04} \approx n_0$. Under these assumptions, they derived a porosity of q>3. This implies that the supernova bubbles overlap and that interactions between bubbles are important in ISM physics.

The subsequent McKee & Ostriker (MO for short) picture is of a 3-phase ISM, as follows:

The **third phase** is a hot (10^6 K), low-density (~0.002 cm^{-3}) intercloud medium composed of overlapping supernova bubbles filling most of the ISM (filling factor of *f*=0.7–0.8).

The **second phase** is the "warm medium" composed of both ionized and neutral components, both at temperatures of 8000 K and with densities of 0.1–1 cm^{-3}. The ionization fraction varies between x<0.15 ("neutral") to x≥0.68 ("ionized").

The **first phase** is the "Cold Neutral Medium", consisting of cold (T=80 K), dense (n≥40 cm^{-3}) HI clouds with an ionization fraction of x≤0.001. This phase fills only a small volume of the ISM (*f*≈0.05), but it contains most of the *mass* of the ISM.

The basic assumptions of the MO 3-phase model are:

1. **Supernovae** heat and disrupt the entire ISM (porosity, q, is >1)

2. **Local thermal Pressure Balance** between the different phases
3. **Mass Exchange** occurs between the hot and cold phases:
   - Supernova blast waves run over cold clouds, ablating them and adding their mass to the hot bubble
   - Old supernova bubbles cool and the shells condense back into cold clouds.

The important difference with the FGH 2-phase model is the predominant role of collisional heating due to supernovae in the MO picture. FGH assumed that ionization from the ISRF was the determining factor in the ionization balance of the cold and warm phases.

The problem is, neither picture is complete or correct.

<u>Assumption #1</u>: Supernovae disrupt & dominate ISM physics.

Slavin & Cox (1993, ApJ, 417, 187) re-examined supernova models and porosity estimates, and found

$$q = 0.176 S_{-13} E_{51}^{1.17} n_0^{-0.61} \tilde{p}_{04}^{-1.06}$$

Using more recent estimates of *local* SN rates and blast energies yields numbers like $S_{-13}\approx 0.4$, $E_{51}\approx 0.75$ (midrange of 0.5–1).

A better estimate of the density for the arm neutral and ionized mediums gives $n_0\approx 0.1$–$0.2\ \mathrm{cm}^{-3}$, and if you now include an estimate of the magnetic field pressure contribution:

$$\tilde{p}_{04} = 10^{-4}\left[\frac{B_0^2}{8\pi k} + (n_e + n_p)_0 T_0\right]\ \mathrm{cm}^{-3}\ \mathrm{K}$$

$$\approx 9000\ \mathrm{cm}^{-3}\ \mathrm{K}\ \text{for}\ T_0 = 10^4\ \mathrm{K}\ \&\ B_0 = 5\mu G$$

Then the porosity is $q\approx 0.18$, or 18% filling factor, which is way down from the $q>3$ computed by McKee & Ostriker.

In sum, this makes supernovae important enough to be interesting, but maybe not dominant.

<u>Assumption #2</u>: Local thermal pressure balance between phases.

EUVE observations of the local ISM have found a “shadow region” that permitted measurements of the hot component near the local warm medium (Bowyer et al. 1995, Nature, 375, 212). From this they measured the properties of the warm and hot components:

Warm Component: $(P/k)_{warm}=730\pm 30\ \mathrm{cm}^{-3}\ \mathrm{K}$

Hot (7×10^5 K) Component: $(P/k)_{hot} = 19000\ \mathrm{cm}^{-3}\ \mathrm{K}$

This demonstrates a factor of 26 thermal pressure mismatch between two regions in contact with each other. This suggests that pressure balance is *not* dominated by thermal pressure, but that other pressures (e.g., magnetic fields, cosmic rays, etc.) must be important.

<u>Assumption #3</u>: Significant mass transfer between the hot and cold phases.

Even modest magnetic fields could inhibit blast heating of cold clouds, shutting down mass exchange and thermal contact. We see little direct observational evidence in our own galaxy (or others) for mass exchange between supernova blast waves running over cold clouds.

The bottom line is that there is as yet no viable general model of the ISM, although we a lot of the observational and conceptual pieces. It is clear that thermal pressure equilibrium is not a good tool, and we must consider other pressure sources, the main contenders of which (magnetic fields, turbulence, and cosmic rays) all have comparable strengths, so no clear leading source emerges. The ISM is far more dynamic than the earlier models assumed, making it a fruitful area for new research.

Summary: The Five Thermal Phases of the ISM

Overall, interstellar gas can be in one of 5 thermal phases, roughly in order from coolest to hottest:

Molecular Clouds: H_2

These are H_2 clouds at temperatures of 10-20K, and densities $>10^3$ cm^{-3}. Molecular clouds comprise ~30% of the mass of the ISM, but occupy only ~0.05% of its volume. Most molecular clouds are gravitationally bound. The densest cores are likely unstable and sites of new star formation. The main tracers are mm-wavelength molecular emission lines (primarily CO).

Cold Neutral Medium (CNM): HI absorption

Cold neutral hydrogen (HI) gas is distributed in sheets and filaments occupying ~1-4% of the ISM with temperatures of ~80-100K and densities of ~50 cm^{-3}. The main tracers are UV and optical absorption lines seen towards bright stars or quasars. The CNM is approximately in pressure equilibrium with its surroundings.

Warm Neutral Medium (WNM): HI emission

Warm neutral atomic hydrogen occupies ~30% of the volume of the ISM, and is located mainly in photodissociation regions on the boundaries of HII regions and molecular clouds. It has characteristic temperatures of ~8000K and densities of ~0.5 cm^{-3}, and is traced by HI 21cm emission lines. It is often called the "warm intercloud medium" in some older papers.

Warm Ionized Medium (WIM): HII emission

Diffuse gas with temperatures of 6000-12000K, and densities ~0.1cm^{-3} occupying about ~25% of the volume of the ISM. While primarily photoionized (it requires about 1/6th of all of the ionizing photons emitted by the Galaxy's O and B stars), there is some evidence of shock or collisional ionization high above the plane of the Galaxy. It is traced by low-surface brightness Hα λ6563Å emission. Nearly 90% of the H^+ in the Galaxy resides in the WIM, with the remaining 10% in the bright high-density HII regions that occupy a tiny fraction of the ISM.

Hot Ionized Medium (HIM): X-ray and OIV absorption

Hot, low-density gas heated by supernovae, with temperatures $>10^6$ K and very low densities of <0.003 cm^{-3} occupying ~50% of the ISM. The vertical scale height of this gas is ~3kpc, so it is sometimes referred to in the literature as the hot "**corona**" of the galaxy. This hot gas is often buoyant and appears as bubbles and fountains high above the disk. Its primary tracers are absorption lines seen towards hot stars in the far-UV (e.g., OIV, NV, and CIV) in gas with $T \approx 10^5$ K, and diffuse soft X-ray emission from gas hotter than 10^6 K.

Dust

Mixed in with all but the very hottest phases is interstellar dust. Dust grains are an important source of interstellar extinction, gas-phase element depletion, sites of interstellar chemistry, etc. This is solid-phase rather than gas-phase material. Dust grains range in size from a few microns down to macromolecular scales (clumps of 50–100 atoms or less). We will treat dust in detail in a later chapter. While we will spend a lot of our time talking about gas-phase processes, it is important to keep dust in mind, since it plays a role often disproportionate to its share of the mass of the ISM.