Lecture 8 - Warm Ionized Medium (WIM)

(“Measure by Measure”)

1. Introduction to the WIM
2. Pulsar Dispersion and the DM
3. Hα Emission and the EM
4. Tentative Summary

References

Spitzer, Sec. 3.3a, 3.6a
Tielens, Sec 8.4
Ferriere, Sec. IIID*
ay216_2006_06.1_WIM.pdf (JRG)
ay216_2006_07.2_WIM.pdf (CFM)

*K. Ferriere, Rev Mod Phys, 73, 1031, 2001 -
a good overview of the global Milky Way ISM

1. Introduction to the WIM

Ionized gas outside of localized HII regions has been known since 1938 (Struve and Elvey, ApJ, 88, 364). Significant progress awaited the discovery of pulsars (1968) and the capability to map optical emission lines, especially Hα (Reynolds et al. at the University of Wisconsin). In ay216_2006_06, **JRG listed the techniques used to study the WIM.** We focus on just the first few: the pulsar dispersion (DM) and emission lines and the emission measure (EM).

- Pulsar dispersion measure
  - + Cordes et al. 1991 Nature 354 121
  - + Taylor & Cordes 1993 ApJ 411 674
- Optical emission lines: Hα, [SII], [NII]
  - + WHAM: Reynolds 1985 ApJ 294 256, Haffner et al. 2003 ApJSS 149 405
- COBE
  - + N^+ 205 μm
- Radio recombination lines (ELDWIM)
  - + Heiles Reach & Koo 1996 ApJ 466 191
- Models
  - + McKee & Ostriker 1977 ApJ 218 148
  - + Kulkarni & Heiles 1988 Galactic & Extragalactic Radio Astronomy
  - + Reynolds 1991 ApJL 372 17
  - + Slavin McKee & Hollenbach 2000 ApJ 541 218

2. Refraction by the Interstellar Plasma

Rybicki & Lightman (Ch.8) show that an EM wave traveling in an ionized gas satisfies the following form of Maxwell's Equations

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\varepsilon\vec{E} = 0 \quad \text{where} \quad \varepsilon\vec{E} = \vec{E} + 4\pi\vec{P}$$

Propagating wave solutions with definite wave-vector and frequency

$$E = E_0 e^{i(\vec{k}\cdot\vec{r} - \varpi t)}$$

then satisfy a condition relating the dielectric coefficient ε and the Index of refraction *n*

$$k^2 = \varepsilon\, k_0^{\ 2} = n^2\, k_0^{\ 2} \qquad k_0 \equiv \frac{\varpi}{\mathrm{c}}$$

It is easy to derive the index of refraction for a collisionless plasma by solving the equation of motion for an electron

$$m_{\mathrm{e}}\ddot{\vec{r}} = -e\vec{E}_0 e^{-iwt} \quad \text{to get} \quad \vec{r} = \frac{e}{m_{\mathrm{e}}\omega^2}\vec{E}_0 e^{-iwt}$$

Refraction by the Interstellar Plasma (cont'd)

The resultant polarization Is

$$\vec{P} = n_e(-e)\vec{r} = -\frac{n_e^2}{m_e \varpi^2}\vec{E} \quad \text{and} \quad \varepsilon E = E + 4\pi\left(-\frac{n_e^2}{m_e \varpi^2}E\right)$$

so that

$$\varepsilon = 1 - \frac{4\pi n_e^2 e^2}{m_e \varpi^2} = 1 - \frac{\varpi_{pl}^2}{\varpi^2} \quad \text{where} \quad \boxed{\varpi_{pl}^2 = \frac{4\pi n_e^2 e^2}{m_e}}$$

defines the plasma frequency with numerical values

$$\varpi_{pl} = 5.64 \text{x} 10^4 \; n_e^{1/2} \text{ Hz}, \qquad \nu_{pl} = 8.979 \text{x} 10^3 \; n_e^{1/2} \text{ Hz}$$

According to the formula,

$$\varepsilon = 1 - \frac{\varpi_{pl}^2}{\varpi^2}$$

frequencies higher than the plasma frequency travel without attenuation; likewise the dielectric coefficient and index of refraction are real:

Index of Refraction and Group velocity

$$n = \sqrt{\varepsilon} = \sqrt{1 - \frac{\varpi_{\rm pl}^{\;2}}{\varpi^2}}$$

The phase and group velocities are

$$v_{\rm ph} = \frac{\varpi}{k} = \frac{\varpi}{k_0}\frac{1}{n} = \frac{c}{n} \qquad v_{\rm gr} = \frac{d\varpi}{dk} = \frac{1}{\frac{d\varpi}{dk}} = \frac{1}{\frac{d}{d\varpi}k_0 n} = \frac{c}{\frac{d}{d\varpi}\varpi n}$$

The last equation can be transformed

$$\frac{d}{d\varpi}\varpi n = \frac{d}{d\varpi}\sqrt{\varpi^2 - w_{\rm pl}^{\;2}} = \frac{\varpi}{\sqrt{\varpi^2 - w_{\rm pl}^{\;2}}} = \frac{1}{\sqrt{1 - w_{\rm pl}^{\;2}/w^2}} = \frac{1}{n}$$

so that

$$\boxed{v_{\rm ph} = \frac{c}{n} \quad \text{and} \quad v_{\rm gr} = cn \quad \text{and} \quad v_{\rm ph}v_{\rm gr} = c^2}$$

NB: These are equations for the phase and group velocities (not frequencies)

Dispersion Measure

Radio waves with frequencies greater than the plasma frequency travel at the group velocity, which increases with frequency

$$v_{gr} = nc = c\sqrt{1 - \frac{\varpi_{\rm pl}^{\;2}}{\varpi^2}}$$

The time to travel a distance *d* is, to first order in $(\omega_{\rm pl}/\omega)^2$,

$$\tau(\varpi) = \int_0^d ds \frac{1}{c\sqrt{1 - w_{\rm pl}^{\;2}/w^2}} \cong \frac{1}{c}\int_0^d ds \left(1 + \frac{1}{2}\frac{w_{\rm pl}^{\;2}}{w^2}\right) = \frac{d}{c} + \frac{4\pi e^2}{2m_e c\varpi^2}\int_0^d ds\, n_e$$

The relevant quantity is the derivative of the time delay with frequency, not its absolute value. Defining the ***dispersion measure,***

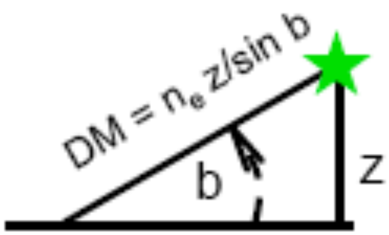
$$DM \equiv \int_0^d ds\, n_e$$

the differential time delay is

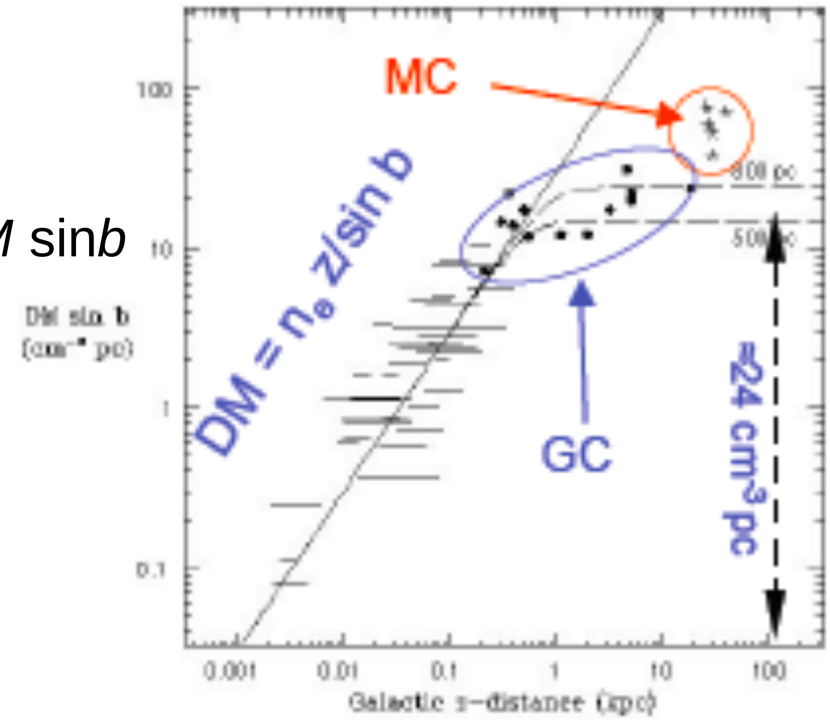
$$\frac{dt(\varpi)}{d\varpi} = -\frac{4\pi e^2}{m_e c \varpi^3}\; DM$$

DM Towards Pulsars in Globular Clusters (GC) and The Magellenic Clouds (MC)

Solid line is n_e = 0.03 cm^{-3}
Dashed line is:
n_e = 0.03 cm^{-3} cosh^{-2} (z/h)
with h = 500 and 800 pc



DM sin*b*



z (kpc)

With precise timing capability, pulsars help map the electron distribution of the Milky Way: **The WIM extends vertically ~ 1 kpc above the galactic plane.**

Longitudinal Variation of the *DM*

One difficulty with pulsars is the uncertainty in distance, needed to convert *DM* to electron density. Methods to consider are:

- association with SNRs
- HI absorption
- parallax
- distance to binary companion

Using n_e ~ 0.03 cm^{-3} is not a bad way start.

To analyze the *DM* pulsar data, Cordes & Taylor invoke a model of the spiral structure of the Milky Way based on other observations.

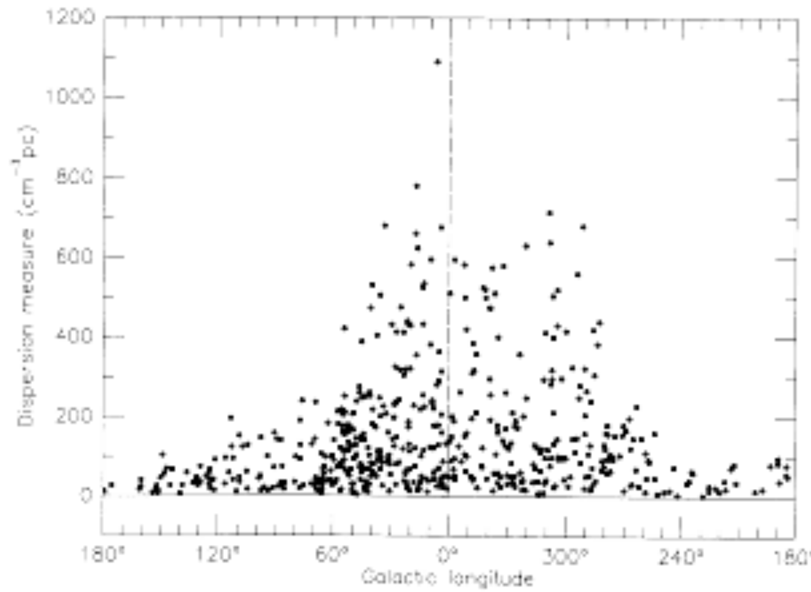


FIG. 2.—Dispersion measures of 553 pulsars as a function of Galactic longitude. Note the deficit of high-dispersion pulsars at longitudes 50°–80°, compared with the corresponding zone 280°–310° on the other side of the Galactic center.

Asymmetric distribution of *DM* values toward 500 pulsars.
Taylor & Cordes, ApJ 411 674 1993
Typical values are 100 cm^{-3} pc, but some approach 500 cm^{-3} pc

Milky Way Spiral Arms

spiral arm labels
1. Norma
2. Scutum-Crux
3. Sgr-Carina
4. Perseus

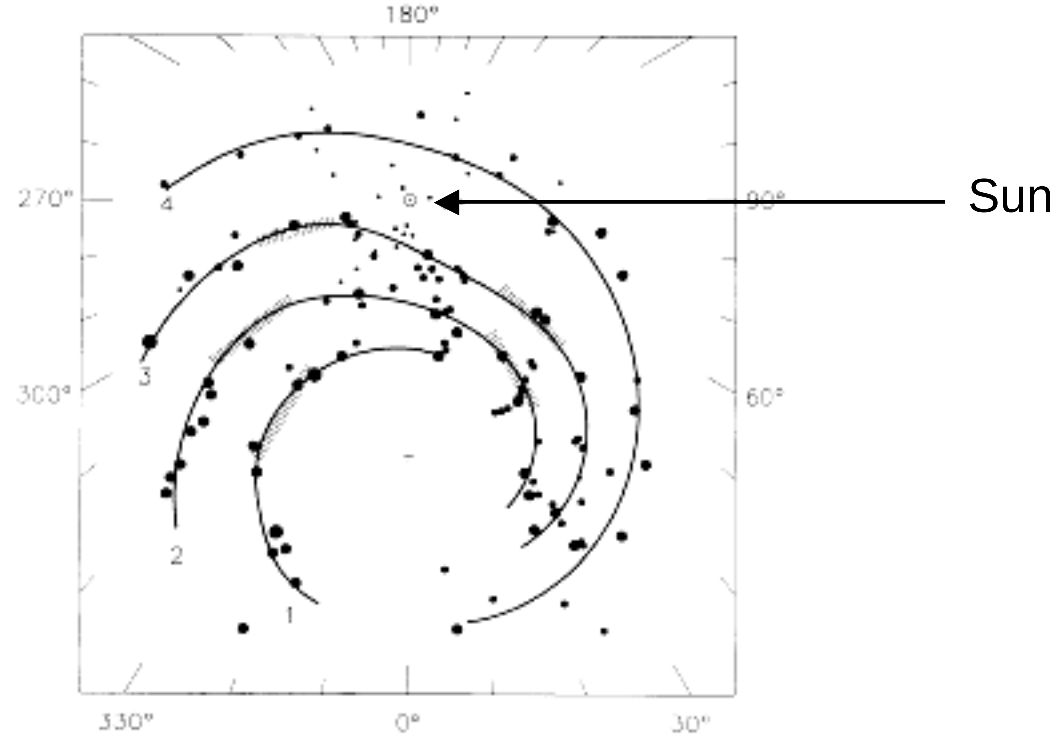
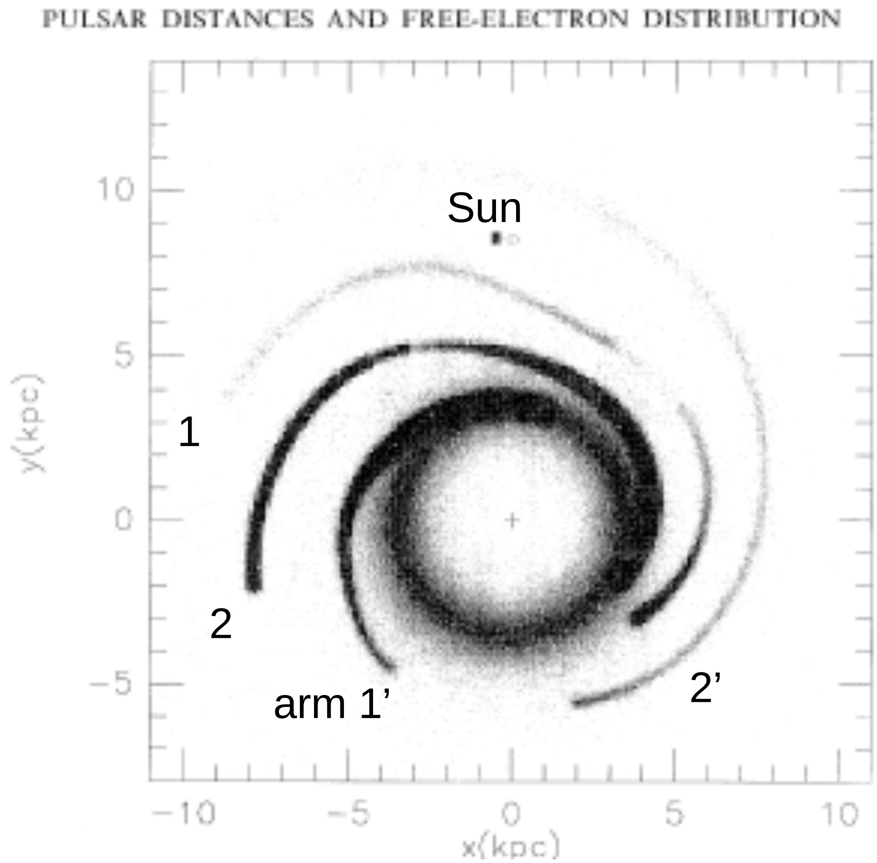


FIG. 1.—Spiral model of the Galaxy after Georgelin & Georgelin (1976), with updates. Circles represent H II regions, and hatched areas correspond to the directions of intensity maxima in the thermal radio continuum and neutral hydrogen emission. The spiral pattern traces the arms defined by interpolating Table 1 with a cubic spline.

Modification by Taylor & Cordes of spiral arm picture of Georgelin & Georgelin (A&A, 49, 57, 1976) that combines observations of HI and radio continuum emission with the locations of giant HII regions.

Results of Taylor & Cordes Analysis



spiral arm names
1. Sgr-Carina
2. Scutum-Crux
1'. Norma
2'. Perseus

Electron density looking down on the center of the galaxy. Sun is at the top. Distance scales cover -10 to +10 kpc. n_e ~ 0.02 near the Sun and ~ 0.2 in the outer part of arm 2

Galactic Distribution of Electron Density

Taylor & Cordes (1993)

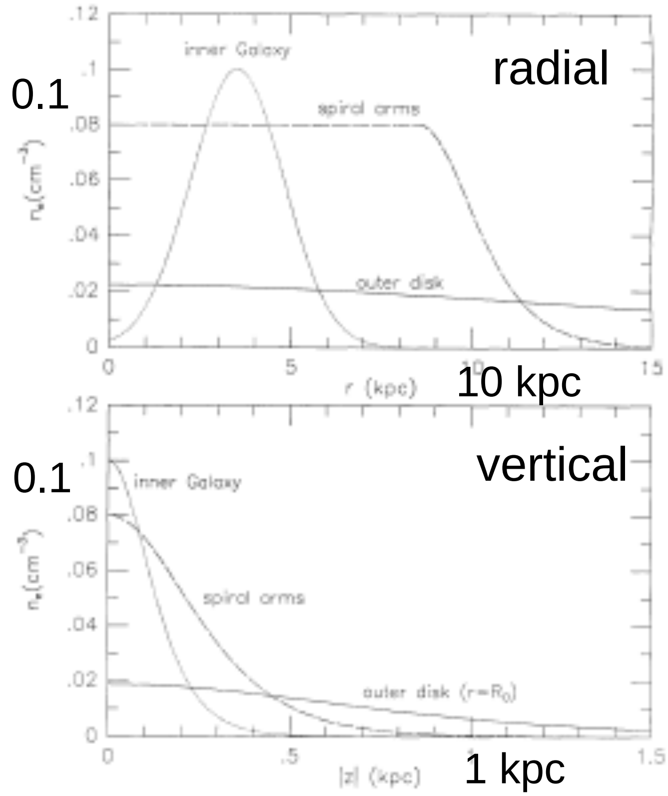


FIG. 3.—Electron densities as functions of Galactocentric radius, r, and distance from the galactic plane $|z|$, for the axisymmetric features of our model. (Note that although the model spiral arms have complicated shapes, the modulations with respect to r and z, defined by eqs. [11] and [17], are axisymmetric.) The z-dependence of the outer disk component is shown for $r = R_0 = 8.5$ kpc.

upper label: inner galaxy

middle curve: spiral arms

lower curve: outer disk

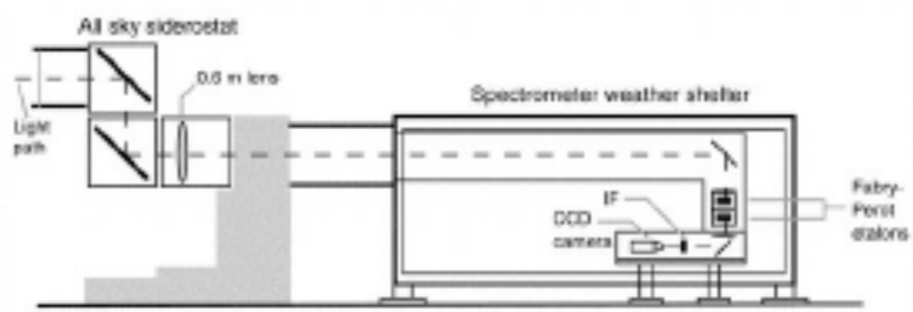
Pulsar *DM* show a substantial galactic electron density. Although thermal considerations indicate regions of low density and high temperature, other considerations are needed to show this.

3. Galactic H-Alpha Observations and EM

WHAM = Wisconsin H-Alpha Mapper

(a big name for a small telescope, but WHAM leads to WIM)

- The Wisconsin Hα Mapper surveys the distribution & kinematics (±100 km/s) of Galactic HII $\delta > -30°$
  - Angular resolution 1°
  - Velocity resolution 12 km/s
    - + First flux calibrated, kinematic maps of the WIM
  - He, S^{+}, N^{+}, O^{0}, & O^{++}
- 63-cm telescope
  - Dual etalon Fabry-Perot



WHAM Hα Map

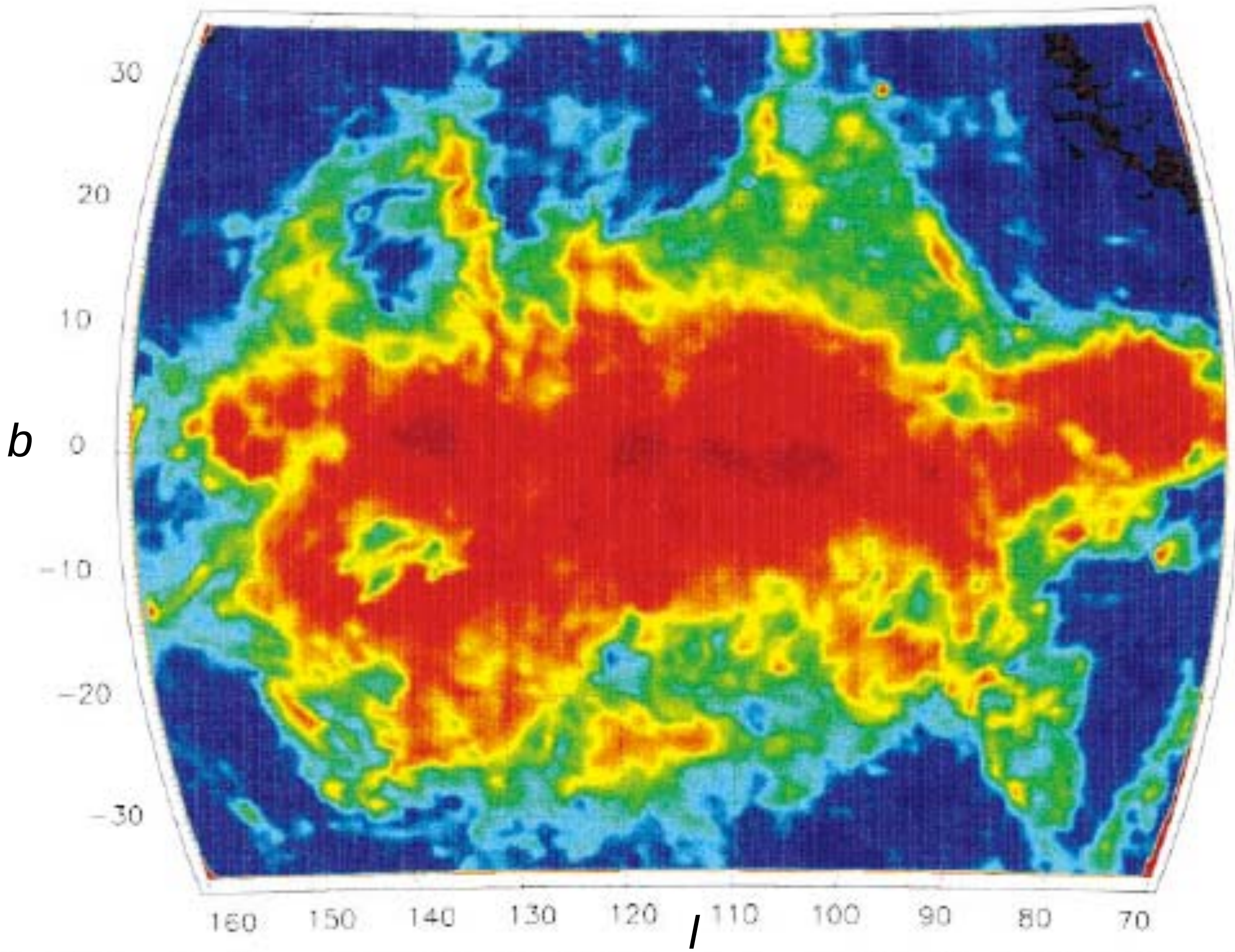
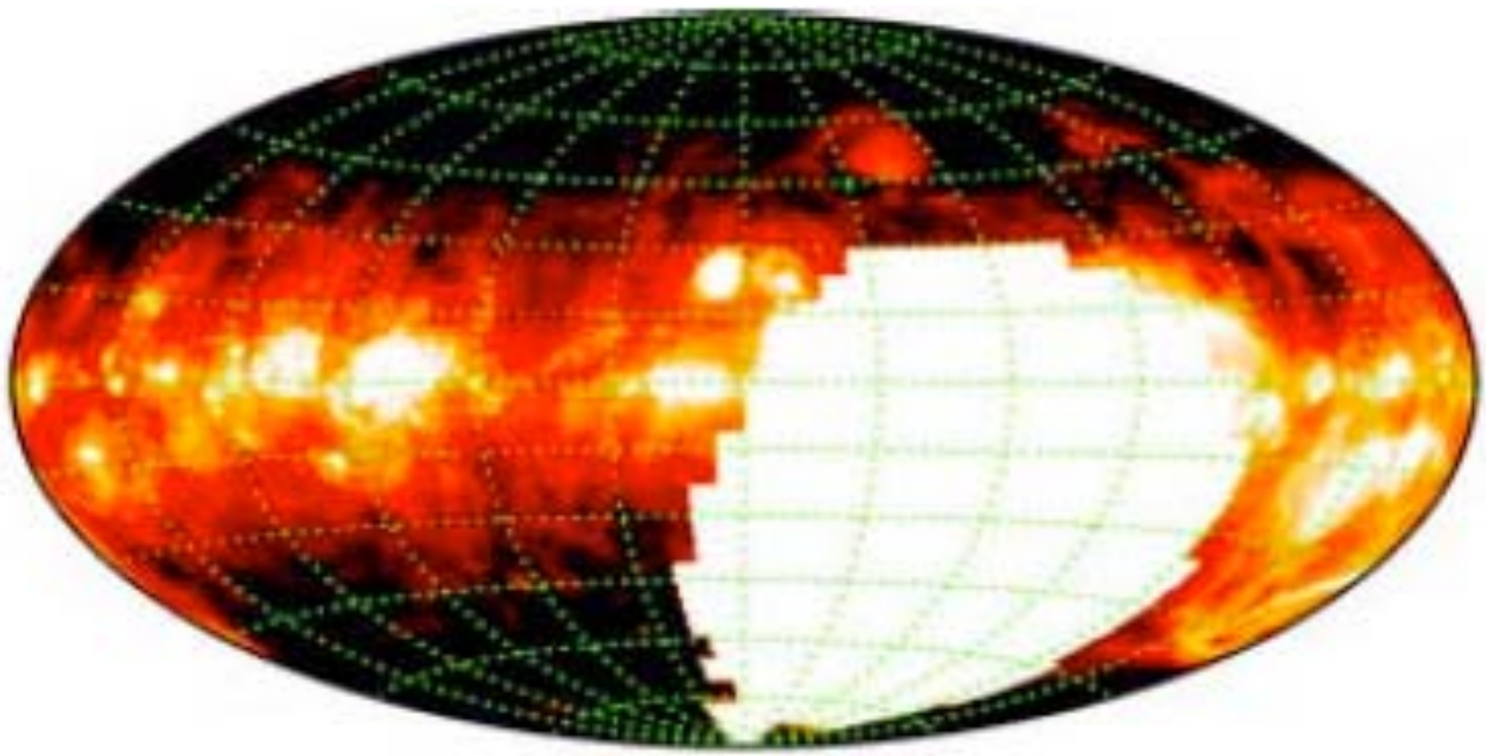


FIG. 6. High-resolution Hα map of a 90°×70° portion of the sky centered on (l=115°, b=0°) at velocities between −60 and 40 km s^{-1}, from the *WHAM* survey. Figure courtesy of L. M. Haffner. [Color]

90ºx70º map centered at (l = 115º, b = 0º)

WHAM Hα Global Map



NB Diffuse white regions are the brightest. Other white areas are unmapped.

The Emission Measure

Hα line emission is recombination radiation (discussed in Lec03). Ignoring absorption (n = 2 H atoms, dust, etc.), its intensity is

$$I_\nu(\mathrm{H}\alpha) = \frac{h\nu(\mathrm{H}\alpha)}{4\pi} \int ds\, n_\mathrm{e} n(\mathrm{H}^+)\alpha(\mathrm{H}\alpha)$$

where α(Hα) is the rate at which recombining electrons and protons produce Hα photons. This quantity is almost the same as α_2 (c.f. Lec03). Osterbrock & Ferland (Table 42.) express it terms of an effective recombination coefficient to produce Hβ and the Hα/ Hβ ratio:

$$\alpha(\mathrm{H}\alpha) \cong 7.86\mathrm{x}10^{-14}\, T_4^{\ -1} \mathrm{cm}^3\ \mathrm{s}^{-1}$$

This is ~ 2/3 α_2. If we assume that the physical conditions do not vary over the line of sight, and that $n_\mathrm{e} = n(\mathrm{H}^+)$, the H$\alpha$ intensity is determined by the line integral of the square of the electron density, called the *emission measure*:

$$EM = \int ds\, n_\mathrm{e}^{\ 2}$$

WIM from WHAM

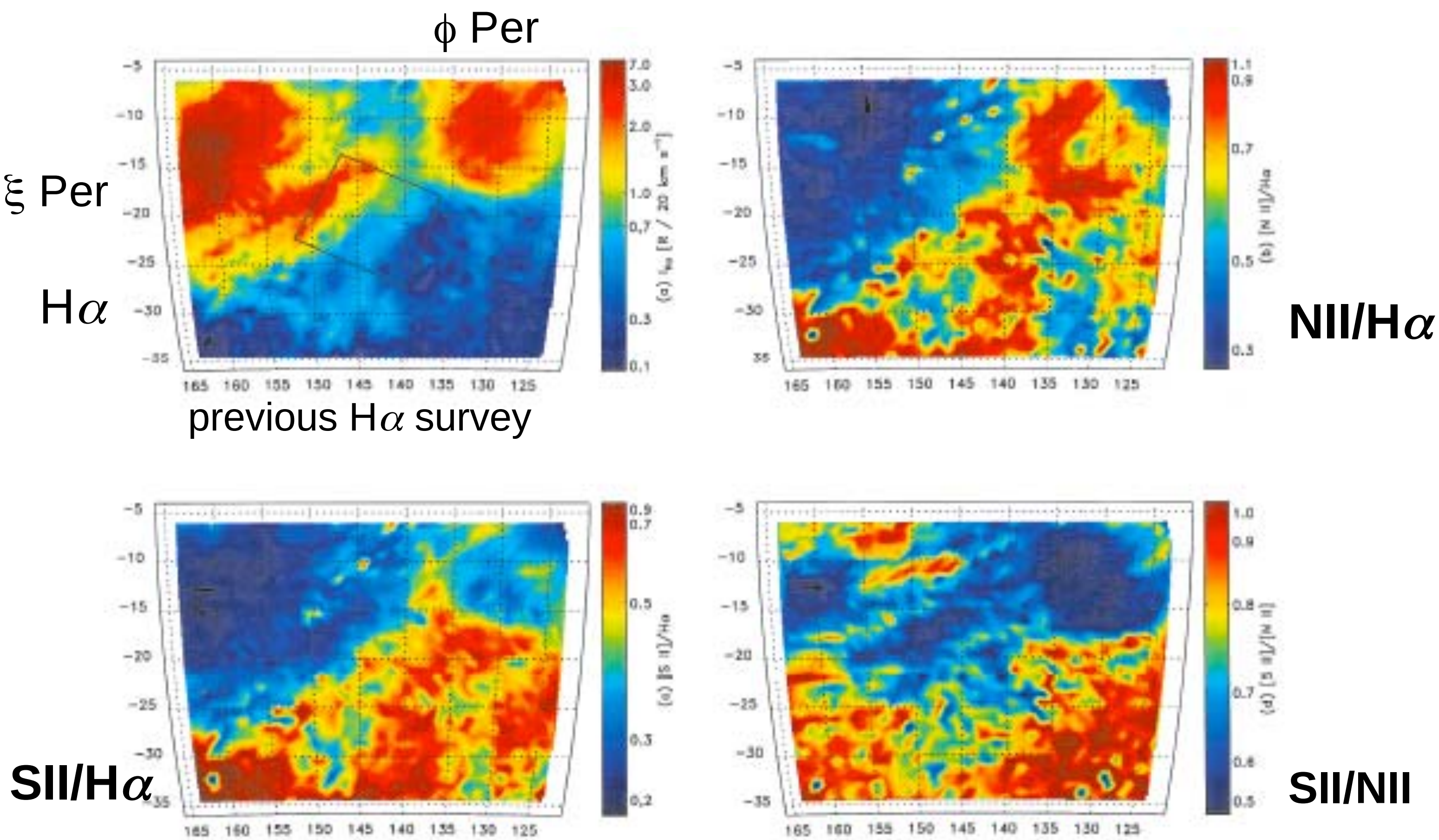
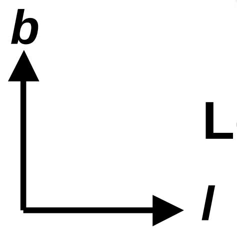


FIG. 2.—(a) Hα emission from the local Orion arm. This pseudocolor image shows the Hα emission integrated over $v_{LSR} = -10$ to $+10$ km s^{-1}. The axes are Galactic longitude and latitude. The overplotted box shows the location of the original Hα background survey in this region (see text). Emission-line ratio maps of (b) [N II]/Hα, (c) [S II]/Hα, and (d) [S II]/[N II] are also shown for the same velocity band. The color scale in each image is histogram-equalized to enhance spatial detail.



Haffner, Reynolds, & Tufte ApJ 533 233 1999

Local Orion arm: *b* = -5º to -35º, *l* = 65º - 125º , *v* = -10 to +10 km /s

WHAM to WIM

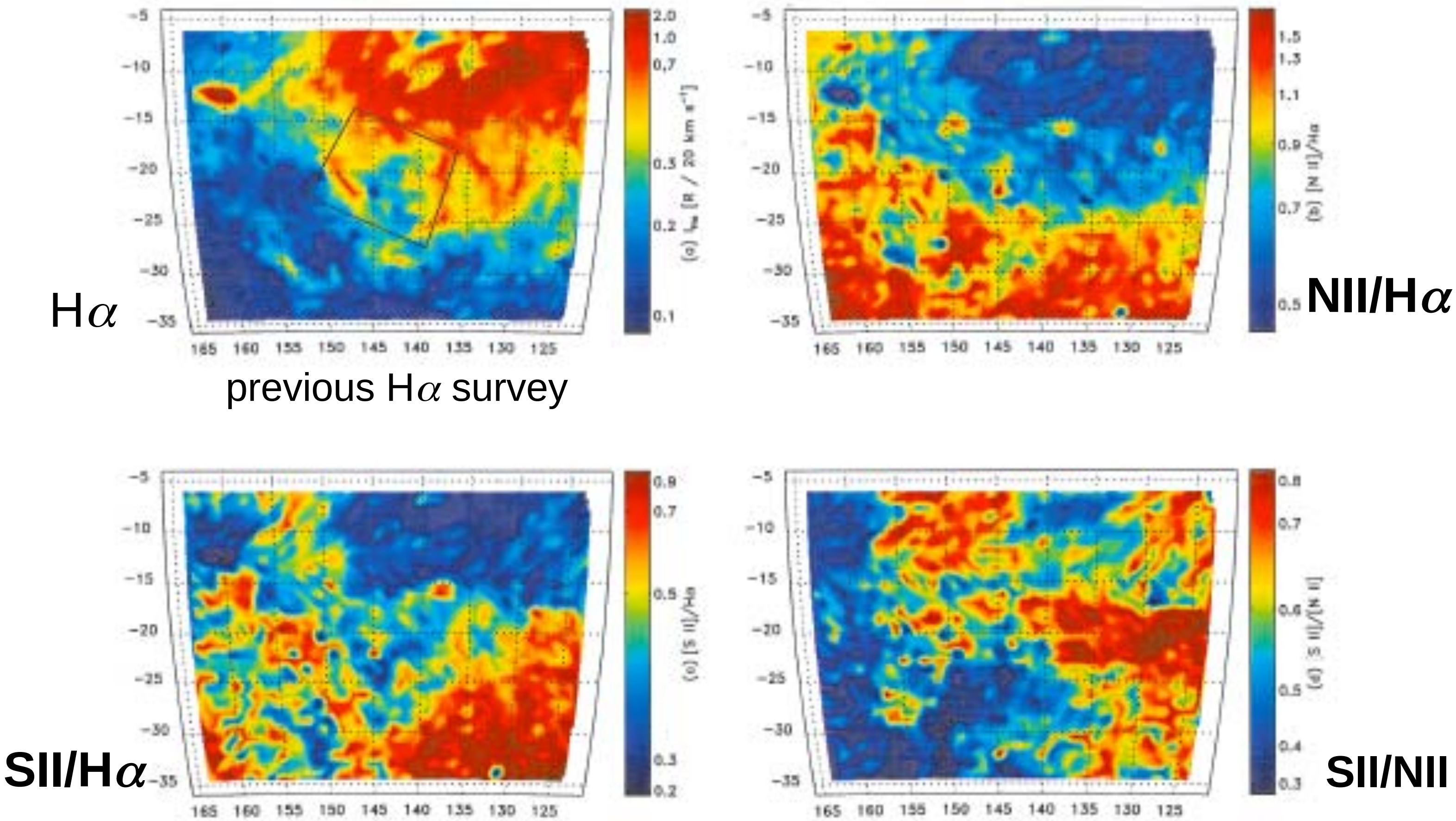


FIG. 3.—(a) Hα emission from the Perseus arm, approximately 2.5 kpc distant. This pseudocolor image shows the Hα emission integrated over v_{LSR} = −50 to −30 km s^{-1}. The axes are Galactic longitude and latitude. The overplotted box shows the location of the original Hα background survey in this region (see text). Emission-line ratio maps of (b) [N II]/Hα, (c) [S II]/Hα, and (d) [S II]/[N II] are also shown for the same velocity band. The color scale in each image is histogram-equalized to enhance spatial detail.

Haffner, Reynolds, & Tufte ApJ 533 233 1999

Perseus arm: *b* = -5º to -35º, *l* = 65º - 125º , *v* = -50 to -30 km /s

Main Results of Haffner et al. (1999)

1. SII 6716 and NII 6583 anti-correlate with Hα.
2. Hα decreases with z
3. SII 6716/NII 6583 is approximately constant
4. OI 6300 is weak

Conclusions (for low density & optically thin lines):

- Hα is determined by $\langle n_e^2 \rangle$; it may also be sensitive to T through α(Hα) ~ 1/T.

  HRT find an exponential decline of n_e with z and that the WIM extends to 2 kpc above the plane (slide 20)

2. SII and NII are individually sensitive to T through the standard collisional rate coefficient

$$k_{lu} \sim \Omega_{ul} T^{-1/2} \exp(-T_{ul}/T).$$

But T_{ul} is 22,000 K for both transitions, and the collision strengths are similar.

Sulfur and nitrogen may be largely in S^+ and N^+

Results of Haffner et al.

3. S+ is produced by FUV photoionization of S
   N+ is produced by EUV photoionization of N

But IP(S^+) = 23.3 eV and IP(N^+) = 29.6 eV, so EUV photo-ionization of S is likely.

HRT SII/NII ratio data suggest that only some of the sulfur is S+

4. The OI 6300 Å line is weak.

The likely explanation is fast near-resonant charge exchange (Lec07):

$$\frac{n(\mathrm{O}^+)}{n(\mathrm{O})} = \frac{k(\mathrm{H}+\mathrm{O}^+)}{k(\mathrm{O}^+ + \mathrm{H})} \frac{n(\mathrm{H}^+)}{n(\mathrm{H})} \rightarrow \frac{9}{8} \frac{n(\mathrm{H}^+)}{n(\mathrm{H})} \quad (T >> 300K)$$

This is consistent with the expectation that x(H+) >> x(H), and implies x(O+) >> x(O). If most of the oxygen is in O++, the OII 3700 Å line should be strong -- something that could be checked observationally.

5. The HRT analysis of line ratios yields *T* ~ 8,000 *K* (6,000-10,000 K), consistent with the line widths.

Scale Height of the WIM

HRT fit the WHAM Hα intensity for the Perseus arm after subtracting the local emission. The bottom line is a large scale Height: H = 1 kpc

$$n_{\rm e}(z) = n_{\rm e}(0)e^{-|z|/H}$$

$$H = 1 \text{ kpc}$$

Over the entire galaxy, the emission measure ranges from

EM ~ 9 - 23 cm^{-6} pc

at the equator to

EM ~ 4.5 cm^{-6} pc

above the plane.

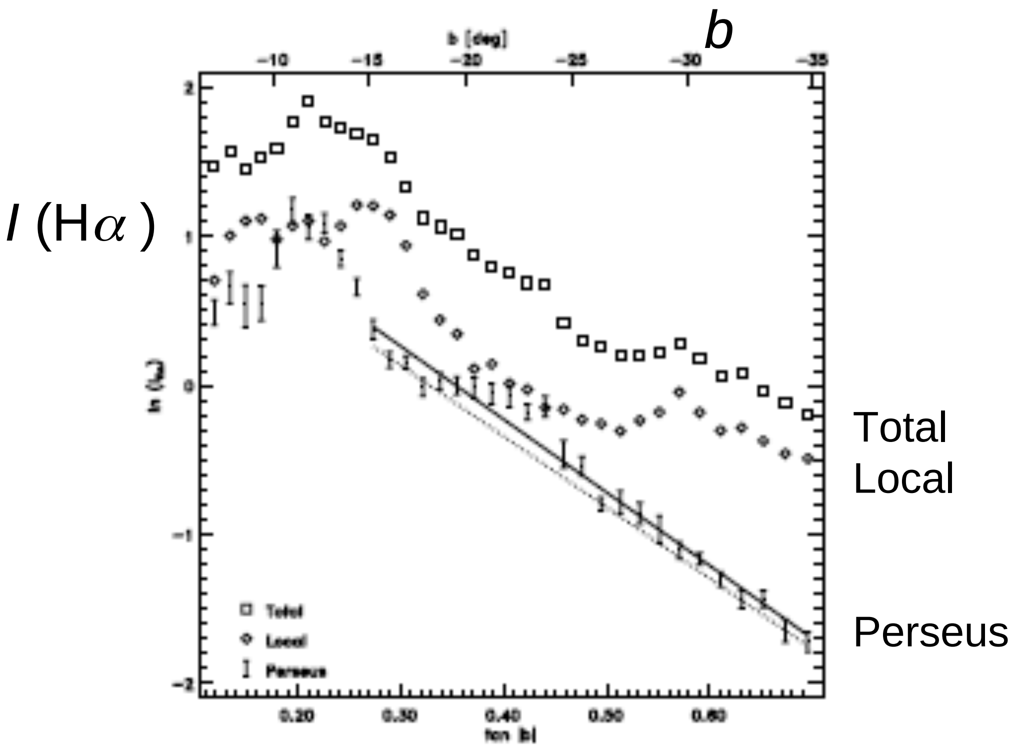


FIG. 4.—Natural logarithm of the median Hα intensity between l = 125° and 152° plotted vs. the tangent of Galactic latitude. Total ($v_{\rm LSR}$ = −100 to +100 km s^{-1}), Local ($v_{\rm LSR}$ = −25 to +100 km s^{-1}), and Perseus arm ($v_{\rm LSR}$ = −100 to −25 km s^{-1}) emission are denoted by squares, diamonds, and vertical bars, respectively. A linear best fit to the Perseus arm emission above b = −15° is displayed as a solid line. The dotted line is a fit to the lower envelope of the data (see § 3.2).

Haffner, Reynols, & Tufte
ApJ 533 233 1999

Comparison of EM and DM

Near the plane, we have these rough values:

$$EM = \int ds\, n_e^2 \sim 10 \text{ cm}^{-6} \text{ pc}$$

$$DM = \int ds\, n_e \sim 100 - 200 \text{ cm}^{-6} \text{ pc}$$

The DM studies also give $n_e \sim 0.03$ cm^{-3}. But all these results are mean values for a very inhomogeneous medium - as shown in the WHAM maps.

Suppose the WIM extends 1 kpc above the mid-plane of the Milky Way. If it were completely uniform, then the *DM* and the *EM* would be, using $n_e = 0.03$ cm^{-3}:

$$EM = 0.9 \text{ cm}^{-6} \text{ pc} \quad \text{and} \quad DM = 30 \text{ cm}^{-6} \text{ pc}$$

These are off by an order of magnitude, indicating that the electrons are in localized regions. To describe this situation, we introduce a ***filling factor*** ϕ.

Filling Factor of the WIM

Follow Ferriere Sec. IIID:

$$\phi\, n_e^2 = < n_e^2 > \; = \; 4.5 - 11.5 \text{ cm}^{-6} \qquad \text{(c.f. } DM\text{)}$$
$$\phi\, n_e = \; < n_e > \; = \; 0.025 \quad \text{cm}^{-3} \qquad \text{(c.f. } EM\text{)}$$

Division gives the electron density and substitution gives the filling factor:

$$n_e = 0.18\text{-}0.46 \text{ cm}^{-3}$$
$$\phi = 0.05\text{-}0.15$$

These are meant to be order of magnitude estimates.

Note that $<n_e>$ times 1 kpc ~ 10^{20} cm^{-2} so there is a substantial column of H+ above the mid-plane.

Energetics

The number of ionizing photons can be estimated from the recombination rate

$$\int ds\, n_e^2 \alpha_2 \approx EM\ \alpha_2(8000\text{K}) \approx (10\ \text{cm}^{-6}\text{pc})\ (3\text{x}10^{-13}\text{cm}^3\text{s}^{-1})$$

$$= 3\text{x}10^{-12}\text{cm}^{-3}\text{pc s}^{-1} \approx 10^7\text{cm}^{-2}\text{s}^{-1} = 10^{50}\ \text{photons s}^{-1}\ \text{kpc}^{-2}$$

This is a very high rate, more than 1 O5 star per square kpc, (or more than100 B0 stars). It corresponds to a luminosity density of $5\text{x}10^5$ Lsun kpc^{-2} which, when integrated out 15 kpc, is $3\text{x}10^8$ Lsun -- or 5% of the hot star luminosity of the Milky Way.

Thus O stars are able to ionize the WIM (other obvious sources of Ionizing radiation are weaker), but how do the ionizing photons get from the location of these stars in the thin disk of the Milky Way to far above the mid-plane?

- leakage from HII regions
- HII regions get large enough to break out into the WIM
- both the HI and the WIM provide low-density pathways for escape (some possibilities can be seen in the WHAM images).

Summary of WIM Properties

1. Main tools: pulsar *DM* and Hα *EM* (plus forbidden lines)
2. Strong influence of HII regions and spiral arms
3. $< n_e > \; = \; 0.025 \text{ cm}^{-3}$, $H = 1$ kpc
4. $n_e = 0.18\text{-}0.46 \text{ cm}^{-3}$, $\phi = 0.05\text{-}0.15$
5. $T = 6{,}000\text{-}10{,}000$ K
6. EUV ionizes N and S, but is softer than in HII regions
7. Pervasive inhomogeneous, near-fully ionized, medium in a thick (2 kpc) disk with streamers (chimneys?) to high latitudes and links to mid-plane HII regions.
8. Vertical column density of WIM H^+ comparable to HI