Ay126: Introduction to H I and l-v diagram

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Chapters 8 & 29 of Draine.

1 Absorption Spectroscopy

As discussed in the class (also Chapter 8 of Draine) the basic radiative transfer for H I studies is

$$\frac{dT_A}{d\tau} = -T_A + T_{\rm spin} \tag{1}$$

where T_A is the "antenna temperature" (this is the intensity as measured by a radio telescope) and $T_{\rm spin}$ is the "spin" temperature. It is understand that $T_{\rm spin}$ is a function of optical depth and ν. Next,

$$\tau_\nu = 2.19 \frac{N(H\ I)}{10^{21}\,{\rm cm}^{-2}} \frac{100\,{\rm K}}{T_{\rm spin}} \frac{{\rm kms}^{-1}}{\sigma_v} \exp(-u^2/2\sigma_v^2) \tag{2}$$

Say we point to an H I cloud. Assume that the H I in the cloud has the same spin temperature throughout the cloud and it is isolated. Now, for convenience, imagine a pulsar behind the cloud. We can get two spectra: when the pulsar is "ON" and when the pulsar is "OFF" and which can be represented as

$$T_{\rm off}(\nu) = T_{\rm spin}\Big[1 - \exp(-\tau)\Big], \tag{3}$$

$$T_{\rm on}(\nu) = T_{\rm psr}\exp(-\tau) + T_{\rm spin}\Big[1 - \exp(-\tau)\Big]. \tag{4}$$

Here, $T_{\rm psr}$ is the continuum intensity from the pulsar.[1] The difference between the two spectra is

$$Y_\nu \equiv \frac{T_{\rm on}(\nu) - T_{\rm off}(\nu)}{T_{\rm psr}} = \exp[-\tau(\nu)] \tag{5}$$

[1]For the cognescenti: We will assume that the receiver is stable and so it will not be explicitly included in the discussion ($T_{\rm sys}$).

J. M. Weisberg et al.: H I Absorption Measurements of Seven Pulsars

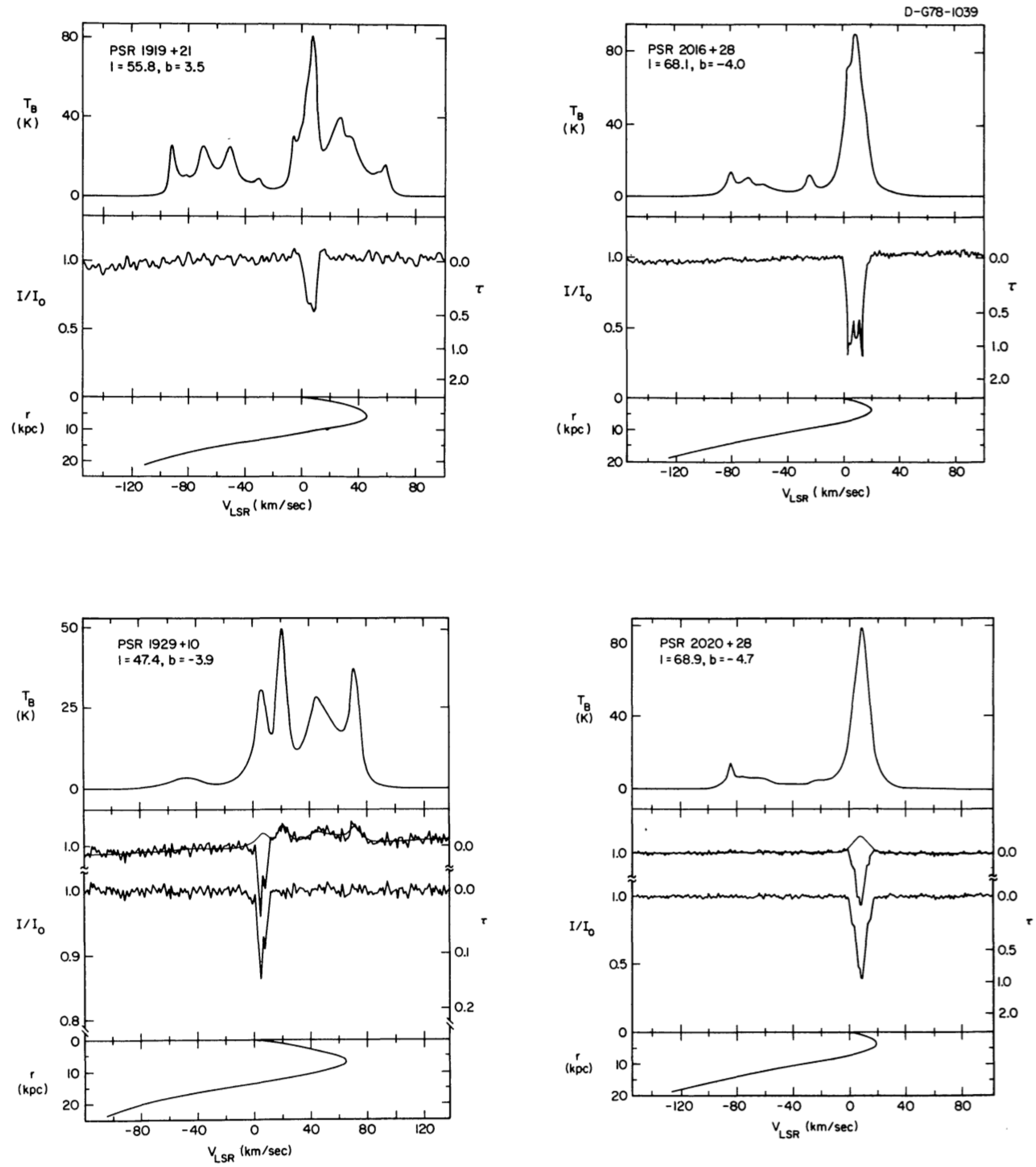

Figure 1: The emission and absorption spectrum towards various pulsars.

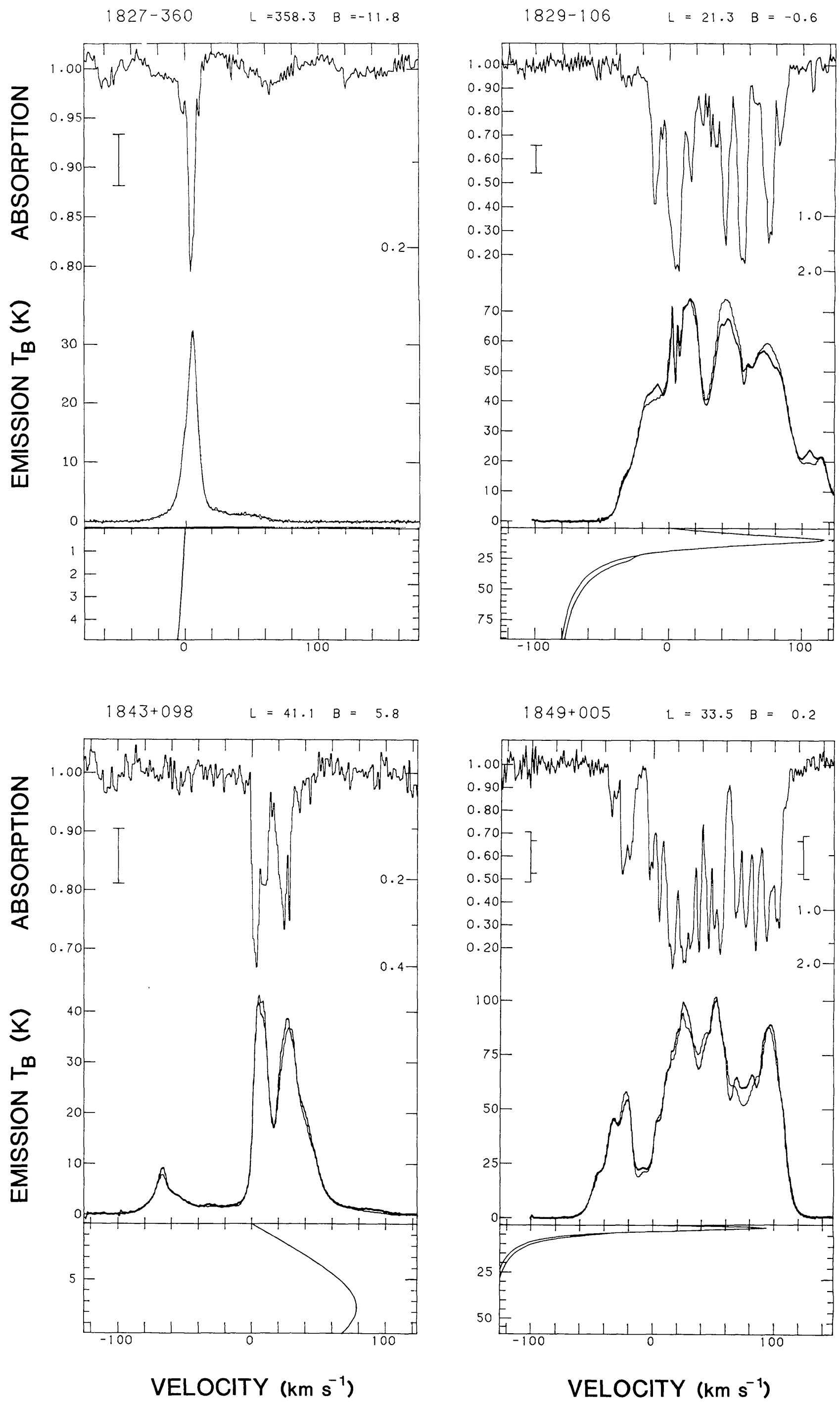

FIG. 6

Figure 2: The emission and absorption spectrum towards various radio bright quasars.

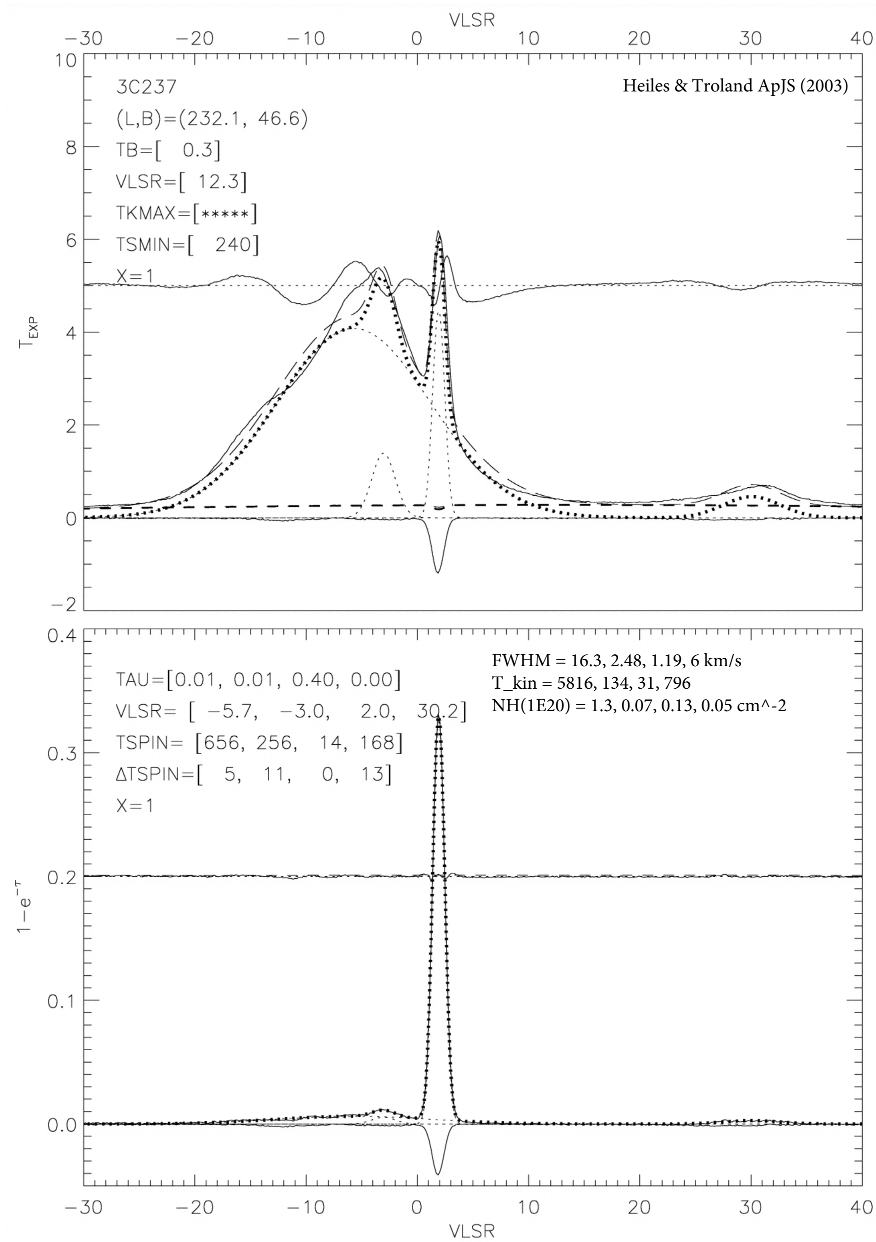

Figure 3: HI emission and absorption towards the bright radio source 3C273. Top is the emission spectrum (T_B) with the actual spectrum (thin line) and Gaussian decompositions (light dotted). The bottom is the optical $1-\exp(-\tau)$. The plots below zero and plots at mid-panel level are residuals or uncertainties and can be safely ignored for the purpose of this class. There are four components with parameters shown in the bottom panel. The optical depth of each component is fitted to a Gaussian model. The velocities wrt Local Standard of Rest (VLSR) of the four components are shown. TAU is the central optical depth, TSPIN is the spin temperature, FHWM is the full width at half maximum, NH is the column density and $T_{\rm kin} = 21{\rm FWHM}^2\,{\rm K}$ is the kinetic temperature inferred from the the FWHM. [Note that ${\rm FWHM} = 2\sqrt{\ln(4)}v_{\rm rms}$ where the latter is the rms velocity of a 1-D Gaussian]. From Heiles & Troland, ApJS (2003).

2 CNM & WNM

Emission and absorption studies have been undertaken over the past five decades (starting at actually OVRO[2]) and show that the H I has two phases: cold neutral medium (CNM) and the warm neutral medium (WNM).

The conclusions, briefly, are the following:

1. The typical temperature and column density CNM is 40 K and $0.5 \times 10^{20}\,\mathrm{cm}^{-2}$. There are clouds as cold as 15 K.

2. By combining measurements from fine structure lines (FSL) it is inferred that most CNM is in the form of sheets with condensations within the sheet. The sheets can be very thin with aspect ratios occasionally approaching a hundred or more. The sheets follow a power law, $dN/dN_H \propto N_H^{-1}$.

3. The observed line widths of CNM can be compared with that expected from the spin temperature. The motions ("turbulence") are clearly supersonic with Mach number of a few. The magnetic field strengths within the CNM is about $6\,\mu$G. The energy densities of magnetic fields and turbulence are comparable and as can be inferred vasty exceed that due arising from kinetic theory.

4. About two third of H I is distributed as WNM. Of this half has temperature in the range 500–5,000 K which is theoretically considered to be "unstable" (out of equilbirum). The filling factor of the WNM is 50% (locally on scales of perhaps a kiloparsec).

5. While most CNM clouds have associated not all WNM have CNM. This is contrary to the theoretical expectation that WNM are the outer sheet of CNM.

Understanding the physics and astronomy of WNM is perhaps one of the great mysteries of Galactic ISM (and a huge prize should you be able to make some progress). I suggest that the students read Heiles & Troland (2003, ApJ), Heiles & Troland (2005, ApJ), chapters 8 and 29 of Draine's book.

3 Other diagnostics of H I medium

Other diagnostics are Lymanα, the fine structure of OI. The OI/OII is similar to that of H I. Why? Particularly important are FSL of CI and CII whose study yields the thermal pressure. Read the important paper by Jenkins & Tripp (2011, ApJ). FSL of CII is very much in the vogue due to Herschel. Lines with IP less than that of ionization NaI or CaI are useful to study the kinematics but not column densities. Why?

[2] The Caltech thesis project of the legendary Barry Clark (and also your instructor).

4 Infrared Cirrus

Another tracer of ISM that became apparent was infrared emission first detected by IRAS ("cirrus"). The dust in CNM and WNM is heated by star light and radiated in the FIR bands. DIRBE on COBE has led to using cirrus as a surrogate tracer of the ISM.

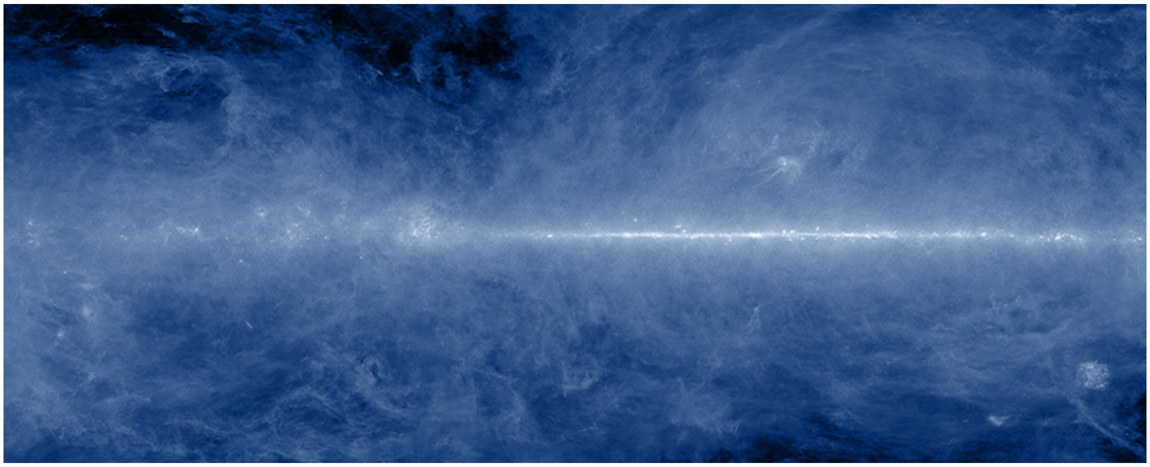

Figure 4: IRAS 100 μm radiation.

5 Large Scale Distribution of ISM

Summary: The local ISM is dominated by H I and is about $10\,M_\odot\,\mathrm{pc}^{-2}$. This surface density is maintained in the inner Galaxy to $R = 5\,\mathrm{kpc}$. Within this radius the mean surface density is $2\,M_\odot\,\mathrm{pc}^{-2}$. For $R > 11\,\mathrm{kpc}$ the surface density falls exponentially (see Draine, Chapter 29).

In order to study the large scale structure of atomic and molecular medium (traced via CO) you need to become familiar with l-v diagram. Using Figure 6 show that the radial velocity of gas, $v(R)$, towards Galactic longitude of l. It is reasonable to assume that the gas is rotating in circular orbit around the center of the Galaxy as a function of the galacto-centric radius (R) is

$$v(R) = R_0\Big[\Omega(R) - \Omega_0\Big]\sin(l) \qquad (6)$$

Here, I have switched the notation from that given in the figure (which I borrowed from Hale Bradt's book) to the conventional symbols for the distance to the center of the Galaxy as $R_\odot$ and the angular velocity as $\Omega(R)$.

We divide the Galaxy into four quadrants (first through four); $0^\circ < l < 90^\circ$, $90^\circ < l < 180^\circ$, $180^\circ < l < 270^\circ$ and $270^\circ < l < 360^\circ$. Consider a line-of-sight in the first quadrant.

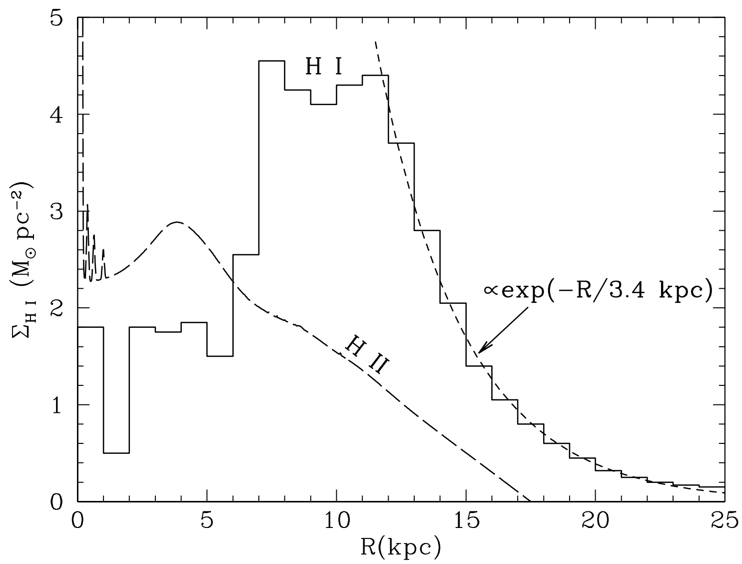

Figure 5: Galactic radial distribution of atomic HI. Figure 29.3 from Draine

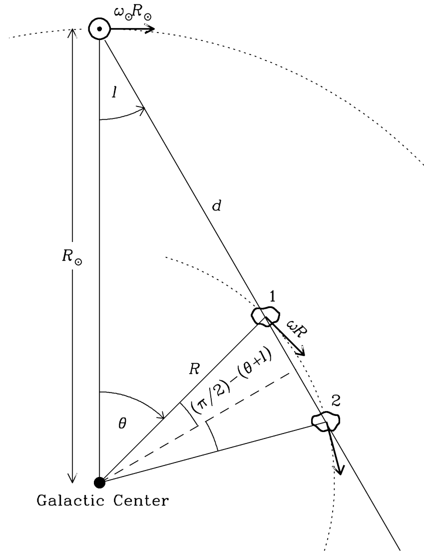

Figure 6: Using this curve (and from explanations in the class) derive Equation 6. The dashed line is the smallest value of R for the line-of-sight which is directed along l. The intersection of the dashed line and the line-of-sight is the "tangent" point.

The velocity increases as go along the path. It will reach maximum (positive) velocity and will reach zero when the line-of-sight crosses the solar circle and attain negative velocity. However clouds located at 1 ("near") and 2 ("far") in Figure 7 have the same radial velocity. This ambiguity arises because the radial velocity depends only on R and both these points are on the same circle. Gas at the "tangent" has the most extreme velocity and does not suffer from ambiguity in distance. It is not easy to disentangle the near clouds from the far clouds unless there you have some additional information (e.g. self-absorption; Figure 9).

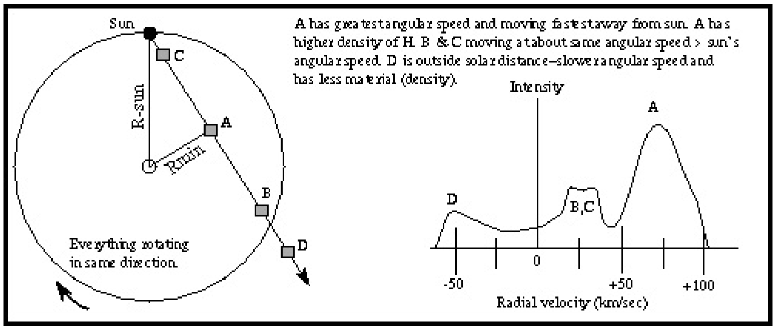

Figure 7: l-v ambiguity.

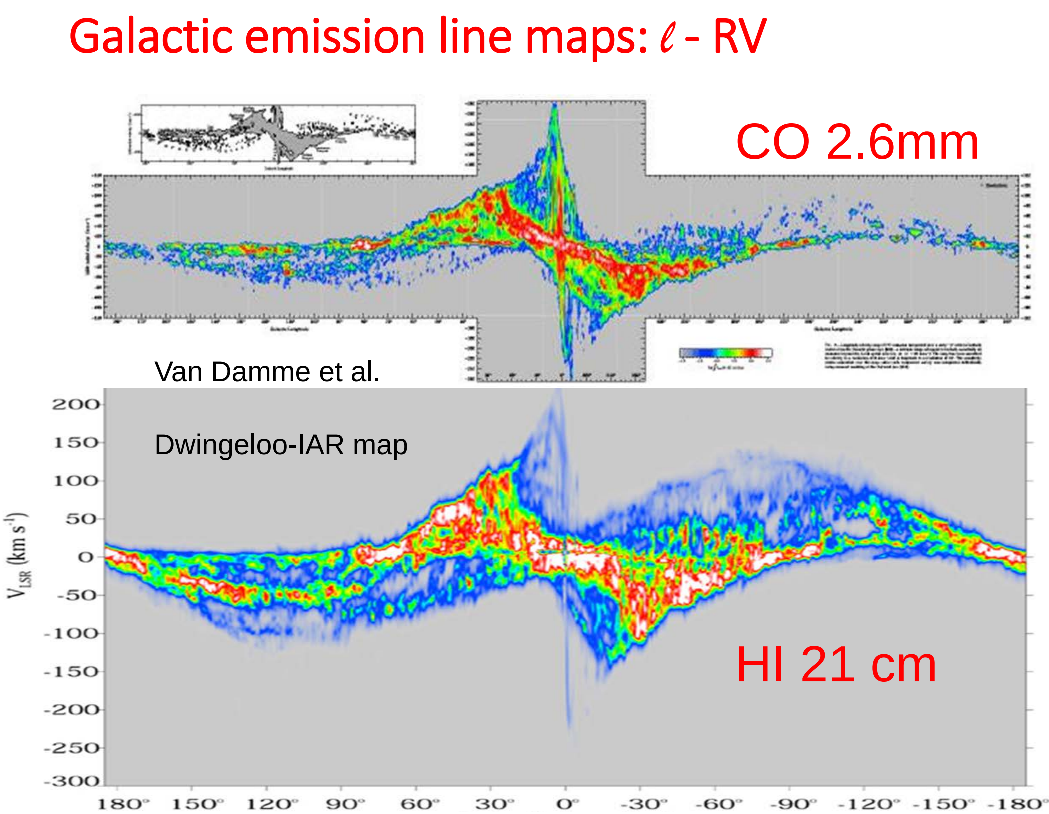

Figure 8: l-v diagram for H I and CO.

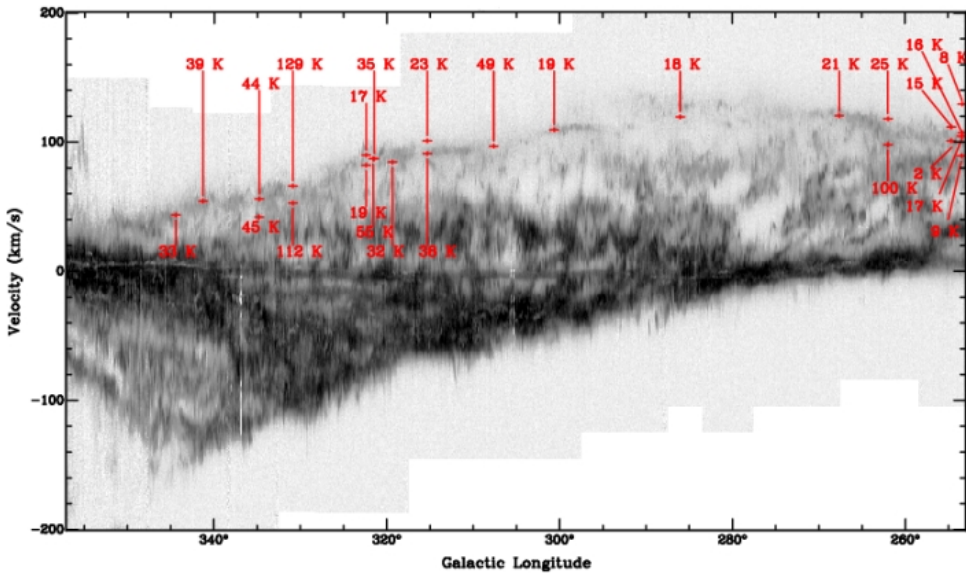

Figure 9: HI in self-absorption. `http://www.ras.ucalgary.ca/GPS/news/vol34/figures/fig02.jpg`