Distribution and motion of hydrogen gas in the Milky Way galaxy

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DISTRIBUTION AND MOTION OF HYDROGEN GAS IN THE MILKY WAY GALAXY

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16 ECTS thesis submitted in partial fulfillment of a
Baccalaureus Scientiarum degree in physics

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Abstract

We explored methods of observing hydrogen gas within the Milky Way galaxy and its motion. We derive expression for velocity of observed gas relative to local standard of rest to model the motion of the interstellar matter and show how we use this model to find the distribution of neutral hydrogen gas throughout the galaxy. We use the LAB data of the 21-cm neutral hydrogen line and apply this model to the data. This model is quite simple and we are ignoring things like turbulence of the gas and we assume the gas moves around the galactic center in perfect circular motion. We calculate the column density of the gas of annuli and find that the distribution of the gas is most concentrated in the galactic plane. As we move out from the center the gas distributes more above and below the plane. We also find that the galactic plane warps at the outer edges of the Milky Way.

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1 The Milky Way galaxy

1.1 Looking into the sky

On a dark and clear night one can look up to the sky and see a luminous band running across the dark sky. This luminous band is our galaxy and we have given it the name the Milky Way. Our sun is only one of a hundred billions of stars that make the Milky Way. The Milky Way not only consists of stars but also gas, dust and dark matter. Dark matter has not been directly observed but observations of motion of gas and dust within the Milky Way have shown that there is something there that we can not see. Our solar system is located $\sim$8.5 kpc (about 27.700 light years) from the galactic center in one of the Milky Way's spiral arms. The reason why we see the Milky Way as a band running across the sky is that the solar system is in the galactic plane. One can not see the whole structure and distribution of gas and dust in the Milky Way without sending a satellite to photograph the Milky Way from high above the galactic plane, but that is not going to happen any time soon because of the wast distances in outer space. To put it into perspective our nearest neighbouring solar system is Proxima Centauri little over 4 light years away and getting there with modern technology, traveling at speeds of 40.000 km/h, would take 110.000 years and another 110.000 years back. We can on the other hand see the structure from the inside and we have developed methods to find the structure and distribution of gas and dust in the Milky Way that will be discussed in this paper. We now know with observation and modeling [8] of our own galaxy and other galaxies that the Milky Way has distribution of gas, dust and stars that forms a spiral like structure [2].

1.2 The Interstellar medium

The wast space between the stars in the galaxy is filled with gas and dust. All this gas and dust we call the Interstellar medium (ISM). This gas and dust can condense into stars and form new solar systems. In the end of the life of the star it will expel its gas back into space. The gas within the ISM is composed of multiple different phases depending on whether the gas is molecular, atomic or ionized. Most common element in the ISM is hydrogen followed by helium and trace amounts of carbon, oxygen and nitrogen. Interstellar matter accounts for ∼10-15% of the total mass of the galactic disk and it spreads in the galactic plane along the spiral arms. About 90.8% of the gas in the Interstellar matter are hydrogen atoms, 9.1% helium and the 0.12% are heavier elements [5].

Molecular clouds have density of $10^2 - 10^6$ atoms cm^{-3} and temperatures of 10-20K, they are dark and block off light from stars behind them [5]. The density and size of the clouds permits the formation of molecules, most commonly molecular hydrogen (H_2). To detect the mass of H_2 one uses the luminosity of carbon monoxide (CO) [1]. Molecular clouds have sometimes been called stellar nurseries because of frequent star-formation within the clouds [7].

Cold Neutral Medium (CNM) clouds have density of $20 - 50$ atoms cm^{-3}, temperatures of about 20-400K and are usually denoted by H I. H I emission can not be directly observed at optical wavelengths but absorption can be seen at optical wavelengths. In neutral atomic clouds particle collisions are so rear that almost all hydrogen atoms have their electron in the lowest energy level [5] and it can be observed by its emission and absorption of the 21-cm hydrogen line which will be discussed in chapter 2.1.

The Warm Neutral Medium (WNM) has density of $0.2 - 0.5$ atoms cm^{-3} and temperatures of 6000-10000K [5] and can be observed by the emission of the 21-cm hydrogen line.

The Warm Ionized Medium (WIM) has the same density as the WNM and temperatures of 8000K [5]. It is mostly photoionized although there is evidence of shock or collisional ionization high above the galactic plane. The WIM is observed by H_α emission and pulsar dispersion.

The Hot Ionized Medium (HIM) has density of ~ 0.0065 atoms cm^{-3} and temperatures of $\sim 10^6$K [5]. This gas is heated by supernovae and appears as bubbles. it is mainly observed by X-ray emission and absorption lines in the far-UV.

Gas that is in between these temperatures is not stable and can thus not be classified under any of these phases of the ISM.

1.3 Motion of Interstellar matter within the Milky Way galaxy

We need to derive an equation that will describe the motion the stars, gas and dust around the galactic center. So we have to consider the galactic coordinate system. The galactic coordinate system is a celestial coordinate system with the Sun as its center. The galactic longitude measures the angular distance positive to eastward from the galactic center and the galactic latitude measures the angular distance positive to the north. From figure 1.1 we get the equation for V_{LSR} on flat rotation disk.

$$V_{LSR} = V cos(\alpha) - V_0 sin(l)$$

where l is the galactic longitude. By replacing $cos(\alpha)$ with $R_0/R\ sin(l)$ and assuming $V = V_0$ we get

$$V_{LSR} = V_0 \left(\frac{R_0}{R} - 1 \right) sin(l)$$

But we live in three dimensional world so we need to add a term for the galactic latitude in (V_{LSR})

$$V_{LSR} = V_0 \left(\frac{R_0}{R} - 1 \right) sin(l) cos(b) \tag{1.1}$$

where b is the galactic latitude. Although this is a very simple model it gives a good idea of the motion of gas and dust within the galaxy and the results are shown on figure 1.2 where we have $V_0 = 220$ km/h and $R_0 = 8.5$ kpc [5]. The figure shows us that this is a good approximation for the motion of gas in the galaxy. If the gradient of the V_{LSR} is big then it is easy to use V_{LSR} to determine the radius of a cloud from the center of the Milky Way.

$$\frac{dV_{LSR}}{dd} = -\frac{V_0 R_0 sin(l)(d - R_0 cos(l))}{(R_0^2 - 2dR_0 cos(l) + d^2)^{3/2}} \tag{1.2}$$

The gradient is shown figure 1.3 and we can see where the gradient is low is when l is close to 0° or 180° and in the circle that traces the tangent point and in chapter 3.2 we will see what effect it will have on the results.

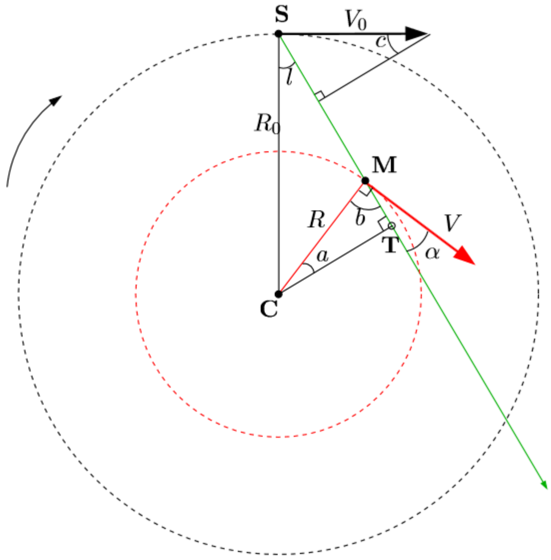


Figure 1.1: Galactic rotation. C in the Milky-Way center, S is the sun, M is the observed cloud, V is the velocity of the cloud and the green line is the line of sight

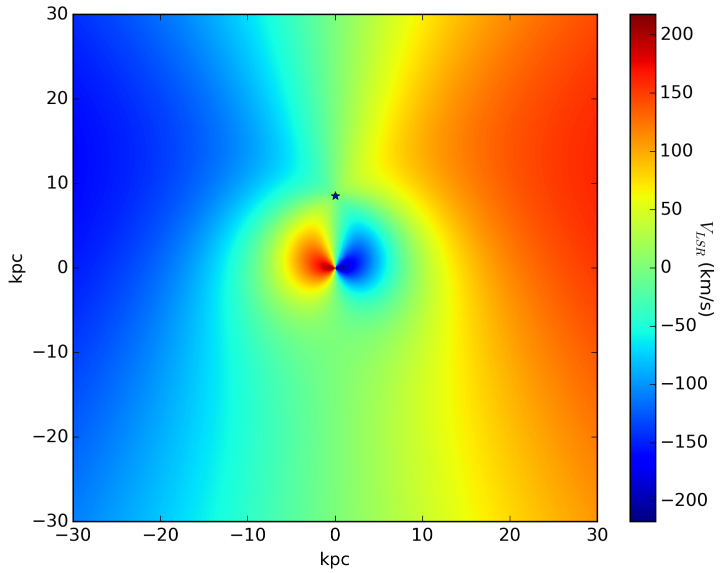


Figure 1.2: The velocity relative to the local standard of rest with clockwise rotation. The blue region of the figure is gas and dust moving towards the sun and the red region is moving away from the sun. The center point in the figure is the center of the Milky Way and the star shows where the sun is located.

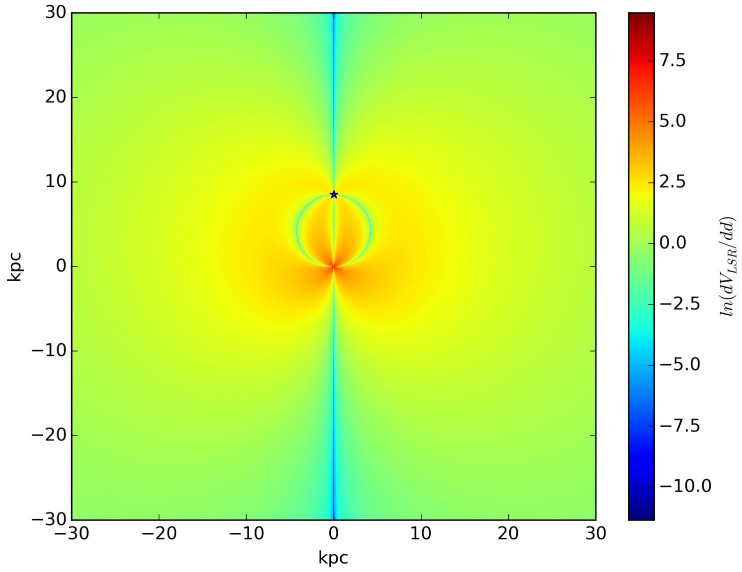


Figure 1.3: The natural logarithm of the gradient of the velocity of local standard of rest with respect to distance to observed object. The circle that forms from the sun to the center of the Milky Way traces the tangent points for different radii.

1.3.1 The Doppler effect

When we observe the 21-cm line of hydrogen gas we learn about the motion of the hydrogen clouds because of the **Doppler effect**. The Doppler effect describes the change in frequency of a moving object and can be experienced in everyday life. The frequency of the 21-cm line is related to how fast the gas is moving towards us or how fast it is moving away from us. This relation is described with

$$\frac{f - f_0}{f_0} = -\frac{v}{c} \tag{1.3}$$

where f is the observed frequency, f_0 is the frequency of the 21-cm line and v is the velocity of the gas cloud, >0 if the cloud is receding or <0 if the cloud is approaching.

2 Methods to detect and observe hydrogen gas

There are three main methods of detecting and analyzing interstellar gas, the 21-cm neutral hydrogen line, spectra lines from molecules and emission lines from hot ionized gas. Here we will discuss two methods, the emission and absorption of the 21-cm hydrogen line and how we can use the luminosity of the 2.6mm CO spectra line to find H_2 density.

2.1 The 21-cm line

The 21-cm line was first predicted by Dr Hendrik van de Hulst in 1944. He predicted that neutral hydrogen could produce radiation at a frequency of 1420.4058MHz and wavelength of 21.1 cm [4]. This is due to the hyperfine structure of the ground state of hydrogen. Neutral hydrogen has one electron and the hyperfine structure is due to the relative spin of the electron to the proton. Parallel spin (higher energy state) and the anti-parallel spin (lower energy state). When the hydrogen is in the higher energy state and the spin of the electron flips, the energy of the hydrogen drops to the lower energy state and the hydrogen emits radiation at the before mentioned frequency and wavelength. The emission is in the radio part of the spectrum and passes easily through interstellar gas and dust but can be absorbed by hydrogen in the CNM.

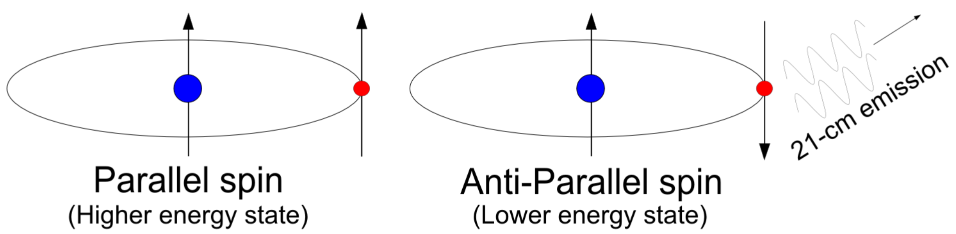


Figure 2.1: The spin flip from the higher energy state to the lower energy state in the neutral hydrogen atom emitting the 21-cm radiation.

2.2 The CO luminosity to H_2 mass conversion factor X_{CO}

Molecular hydrogen (H_2) in cold molecular clouds can not be observed directly. Fortunately molecular clouds are not pure H_2 but also contain helium and heavier elements such as carbon and oxygen. Carbon and oxygen are the most abundant and under certain circumstances, which are present in molecular clouds, they combine to form CO. CO is easily excited due to it is weak permanent dipole moment and a ground rotational transition with low excitation energy. With wavelength of $\lambda =$ 2.6mm the transition $J = 1 \rightarrow 0$ is easily observed [1].

There are three independent calibration techniques used to determined the conversion factor. The first technique uses the optically thin ^{13}CO intensities and measurements of optical extinction along the line of sight through the molecular cloud. The calibration for ^{12}CO then obtained from observed average ratio of $I(^{13}\mathrm{CO})$ to $I(^{12}\mathrm{CO})$. The second technique uses γ-rays from cosmic ray interaction with hydrogen gas and compares the γ-ray flux to the CO flux. The third technique measure the virial mass for molecular clouds in the galactic plane [1, 9].

The relation between molecular hydrogen and the intensity of CO is described by

$$N(H_2) = X_{CO} W(\mathrm{CO}) \tag{2.1}$$

where the column density is in cm^{-2} and $W(\mathrm{CO})$ is the integrated line intensity. This corresponds to a molecular mass to CO luminosity ratio

$$M_{mol} = \alpha_{CO} L_{CO}. \tag{2.2}$$

Where α_{CO} is mass-to-light ratio and L_{CO} is CO luminosity. X_{CO} has found to be 2×10^{20} cm^{-2}(K km s^{-1})$^{-1}$ and with corresponding $\alpha_{CO} = 4.3$ M$_{\odot}$(K km s^{-1} pc^2)$^{-1}$ [1].

3 Calculation of observed 21-cm line data

This paper uses the LAB survey data of the 21-cm line [6]. The Leiden Argentine Bonn (LAB) survey is the final data release of observations of 21-cm emission from neutral hydrogen over the entire sky combined from the Leiden/Dwingeloo survey (LDS) and Instituto Argentino de Radioastonomía survey (IAS). The LAB survey is the most sensitive survey of the 21-cm H I emission of the whole Milky Way galaxy to date. The data is released as brightness temperature as function of longitude, latitude and velocity of local standard of rest [6]. The measurement itself is intensity, I, but in radio spectroscopy I is often replaced with brightness temperature. The brightness temperature is defined at low frequency and high temperatures with the Rayleigh-Jeans law

$$T_b = \frac{2\nu^2 kT}{c^2} \tag{3.1}$$

where ν is the frequency, k is the Boltzmann constant, T is the kinetic temperature of the cloud and c is the speed of light [10].

3.1 Deriving the total column density of H I

The 21-cm line of H I has an opacity at the line center of

$$\tau = 5.2 \times 10^{-15} \frac{N_H}{\Delta v T_s} \tag{3.2}$$

where T_s is the spin temperature, N_H is the column density and Δv is the full width at half-maximum in km/s [4]. Spin temperature describes the ratio between the number of H I atoms in the higher energy state (E_2) and the number of H I atoms in the lower energy state (E_1). This can be expressed with the Boltzmann factor

$$\frac{N_{E_2}}{N_{E_1}} = \frac{g_2}{g_1} exp\Big(-\frac{\Delta E}{kT_s}\Big)$$

where g_2/g_1 is the statistical weight ratio for hyperfine transition. The spin temperature is generally not known so we have to select our own for our calculations. To simplify we assume that the spin temperature is a constant throughout the galaxy. The brightness temperature is a mix of emission and absorption at a velocity v. We assume the spin temperature is a constant throughout the galaxy we can define the brightness temperature as

$$\Delta T_b(v) = [T_s - T_0][1 - e^{-\tau(v)}] \tag{3.3}$$

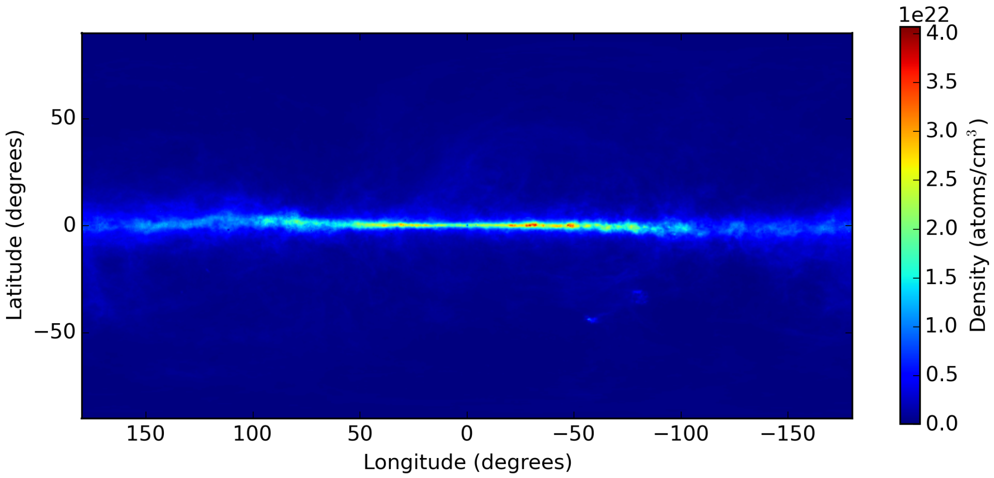
where T_0 is the background temperature. If $T_b << T_s$ then we can define the total column density of H I is given by a velocity integral under the profile (in K km/s)

$$N_H = 1.823 \times 10^{15} \int T_b \, dv \tag{3.4}$$

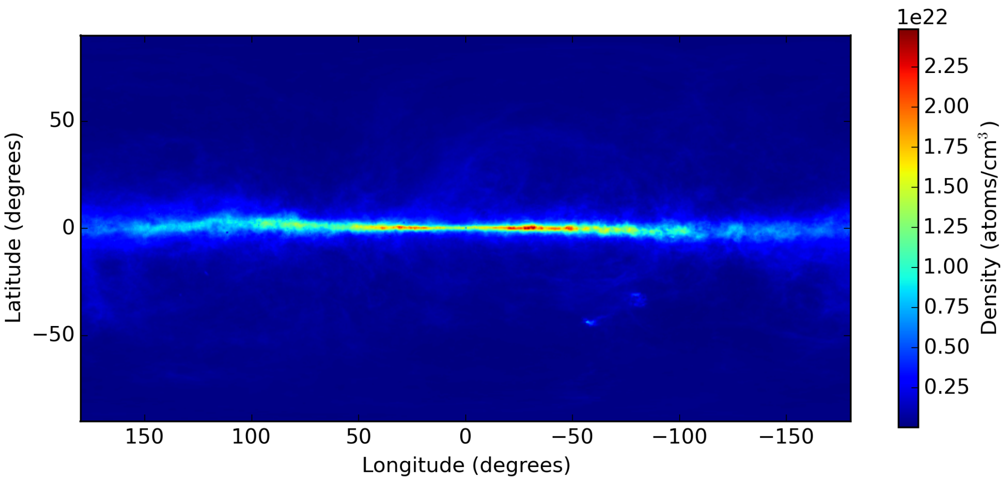
Now to fully derive the equation for the total column density of H I we combine equations (3.2), (3.3) and (3.4) and then assume everything under the integral is constant we get

$$N_H = -1.823 \times 10^{15} ln\Big(1 - \frac{T_b}{T_s - T_0}\Big) T_s \Delta v \tag{3.5}$$

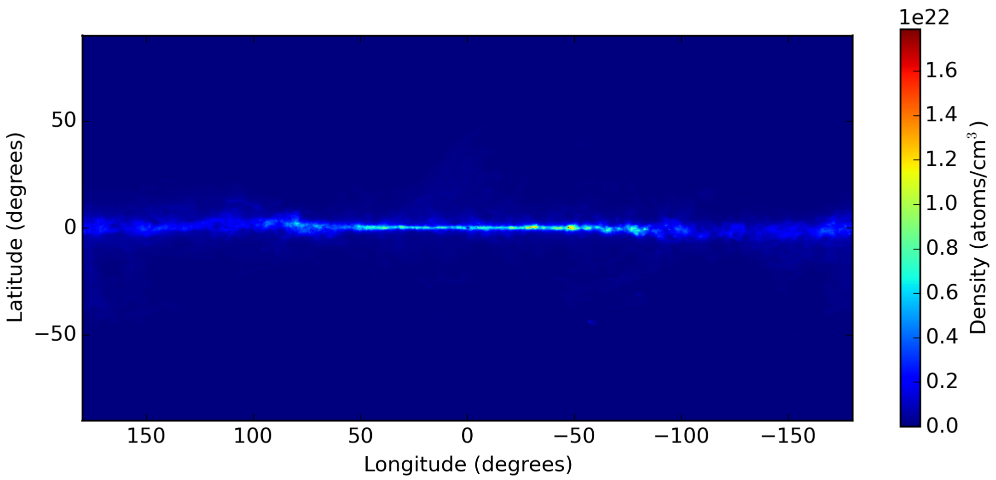
We can apply this to the LAB data and manually select the T_s. The results can be seen on figure 3.1. Because the value of T_s is not generally known and as can be seen on figure 3.1 choosing the value of T_s can greatly affect the results of the column density of H I. By choosing T_s = 160K we get almost two times higher column density then choosing T_s = 5000K, we could be over-, underestimating or be lucky and choosing the right value for T_s.



(a)



(b)



(c)

Figure 3.1: Results of the 21-cm data. (a) shows the column density of H I *in the Milky Way using* $T_S = 160K$*, (b) shows the column density of* H I *in the Milky Way using* $T_S = 5000K$ *and (c) shows the difference in the column density between the two values.*

3.2 Column density of annular distribution

By using (1.1) we can derive an equation for the radius as function of V_{LSR}.

$$R(V_{LSR}) = \frac{V_0 R_0 sin(l) cos(b)}{V_{LSR} + V_0 sin(l) cos(b)} \tag{3.6}$$

Because T_b is a function of velocity in the LAB survey and we have equation for the radius at a given velocity we can find how far from the center of the Milky Way a cloud is with some $T_s(v)$. By doing this we can find the column density as a function of radius. The results are shown on figure 3.2.

Our model for the motion of gas is rather simple, for example we are ignoring the turbulence of the gas, we assume the gas to have perfect circular motion around the galactic center and that the velocity of the observed gas is constant, $V(R) = V_0$. This results in anomalies in the column density of annular distribution. The rotation curve we use is proportionate to $R(V)^{-1}$ but the rotation curve of the Milky Way is far from it [3]. Also in figure 1.3 where $ln(dV_{LSR}/dd)$ is small, like when $l = 0°$ or $l = 180°$ and in the trace of the tangent point, it is harder to determine $R(V)$ than when $ln(dV_{LSR}/dd)$ is big. On figure 3.2 we can see how the distribution of the gas is mostly concentrated close to the galactic plane and as we move out the gas distributes more above and below the plane. Figure 3.2(g) shows us that the galactic plane warps at the outer edges of the Milky Way.

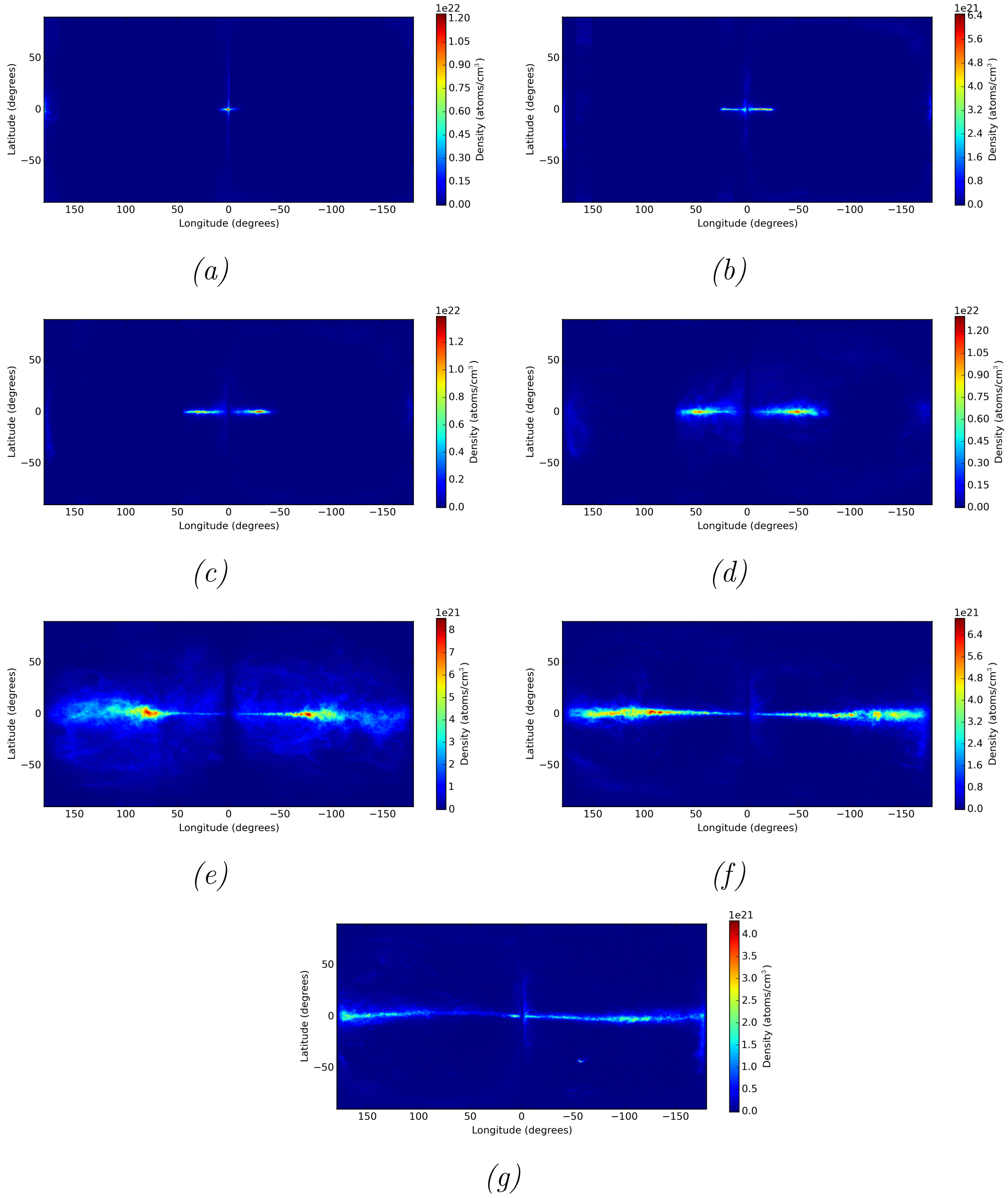


Figure 3.2: Column density of H I *gas in annular distribution. (a) having R in the range 0 - 2 kpc, (b) having R in the range 2 - 4 kpc, (c) having R in the range 4 - 6 kpc, (d) having R in the range 6 - 8 kpc, (e) having R in the range 8 - 10 kpc, (f) having R in the range 10 - 15 kpc and (g) having R > 15 kpc.*

4 Conclusions

We derived an expression for velocity relative to local standard of rest to model the motion of interstellar matter within the Milky Way galaxy. Although this model is simple, by ignoring turbulence of the gas and the gas travels in a perfect circular path around the galactic center, we can use it to find the radius of a cloud from the galactic center.

We have reviewed different methods of detecting hydrogen gas in the Milky Way galaxy. The three calibration techniques have shown that there is a linear connection between W(CO) and N(H_2) and thus we can use CO to evaluate H_2 mass. The 21-cm line of neutral hydrogen that is produced by the hyperfine structure of the ground state of the neutral hydrogen has proven a useful tool to map the distribution of hydrogen throughout the galaxy.

Using the equation we derived for the motion of the gas in the galaxy and applying it to the LAB data of the 21-cm neutral hydrogen line we have mapped the distribution of the neutral hydrogen gas. By calculating the column density of the neutral hydrogen we see how important it is how we choose the spin temperature. We compared the two values we choose for the spin temperature and we see the column density can differ as can be seen on figure 3.1(c). It has shown us that the neutral hydrogen distribution is mainly in the galactic plane and distributes out from plane as we move out from the galactic center. We also find that the galactic disk warps in the outer edges of the Milky Way.

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