SALSA-report - *a map of the Milky Way*

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Course: Modern Astrophysics (7.5 hp).

Abstract

The following work has, through an analytical and experimental approach, used the 21-cm radio wave emitted by the hydrogen atom to create a map and rotation curve of our galaxy. This has been done by remote control of the SALSA-telescopes located at the Onsala Space Observatory. The intensity of the 21-cm line at different galactic longitudes has been analyzed and this led to the creation of the rotation curve which shows the velocity $v(R)$ of the hydrogen molecular clouds at different distances from our solar system. Using simple trigonometry, the distance from the clouds to us could be determined and by so doing, a map of our galaxy was plotted.

Furthermore, the problem "distance ambiguity" has been discussed and its effects on the measurements carried out by the telescope have been analyzed. The report has come to the conclusion that it is important to examine the hydrogen clouds at different latitudes to ensure that the distance to them is correct. This is because the trigonometric formulas used to calculate the distance sometimes yield two possible solutions. Measuring at different latitudes can provide the information needed to determine the correct value and in so solving the distance ambiguity problem. Finally, the report has been able to establish that our galaxy, The Milky Way, has spiral arms. This is a common feature of spiral galaxies and shows that The Milky Way is indeed one of these.

1 Introduction

For many thousands years, men have searched answers about the universe. Where are we? How did we get here? Are we alone? What are we made of? While we may still have a lot of those questions unanswered, however, modern techniques have made it a lot easier for us to study the universe and its components. One of these (fairly) new techniques will be used and discussed in this report – radio astronomy.

Radio astronomy uses wavelengths in the radio spectrum (between 1 mm up to several kilometers) to study emission from different ingredients in our universe. These ingredients could be celestial bodies, like stars, or as in this case – atomic hydrogen.

The main task of this report is to use the SALSA-telescope located at Onsala Space Observatory to make a so-called rotation curve of the Milky Way, which in short words is a graph which plots the orbital speed of different stars or clouds in the galaxy versus their radial distance to the centre of the galaxy. Furthermore, the report also aims to map the atomic hydrogen in our galaxy, the Milky Way, while also solving the *distance ambiguity* which is a known problem when applying the technique used in this report.

2 Method

The fact that our atmosphere doesn't absorb radio waves in the same way that it absorbs other type of radiation, gives us an unique opportunity to study the universe and in particular – our galaxy. As the introduction mentioned this report will use emission of the 21-cm line to create the rotation curve $v(R)$ as well as mapping the atomic hydrogen (HI) of the Milky Way. Still, how will the 21-cm line help us achieve that? That will be explained, briefly, in this chapter.

2.1 Determination of $v(R)$

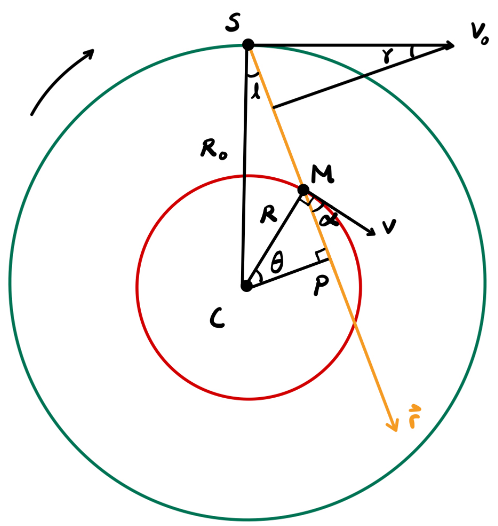


Figure 1: A simple illustration of the trigonometry and quantities used in this experiment, the galactic centre (C) with the orbit of one HI cloud (M) and our sun (S).

Examine figure 1 above, imagine that we measure emission from a HI cloud in the direction of $\vec{r}$, at point P. Since both the cloud and our solar system (the sun) moves relatively to each other, we measure the relative speed v_r, according to

$$v_r = v \cdot \cos(\alpha) - v_0 \cdot \sin(\gamma) \tag{1}$$

where v is the actual cloud speed, v_0 the speed of our sun and α and γ are defined as in figure 1. We can then see that $\gamma = \ell$ (ℓ is called the galactic longitude) since for a triangle, $90 - \ell + 90 + \gamma = 180$. We can also relate the angle α to ℓ, by noticing that $\theta = \alpha$ in the same way as before. Then the distance CL can be written in two ways; CL $= R \cdot \cos(\theta)$ and CL $= R_0 \cdot \sin(\ell)$. Equality between these gives

$$R \cdot \cos(\theta) = R_0 \cdot \sin(\ell) \iff \cos(\theta) = \frac{R_0}{R} \cdot \sin(\ell)$$

and since $\theta = \alpha$ we can rewrite (1) as

$$v_r = \frac{R_0}{R} \cdot v \cdot \sin(\ell) - v_0 \cdot \sin(\ell) \iff \frac{R_0}{R} \cdot v \cdot \sin(\ell) = v_r + v_0 \cdot \sin(\ell) \tag{2}$$

Nevertheless, we still need an expression of R for the rotation curve. However, the maximal velocity in a specific direction ℓ is measured from the tangent point P, since this point produces the maximal projected velocity in the $\vec{r}$-direction. At this point, we have

$$R = R_0 \cdot \sin(\ell) \tag{3}$$

which, plugged into equation (2) gives

$$v = v_{r_{max}} + v_0 \cdot \sin(\ell) \tag{4}$$

So, measuring the maximal velocity for different galactic longitudes ℓ gives the rotation curve $v(R)$. The velocity v_r can be determined with the Doppler effect, which relates the observed frequency from the cloud to its velocity as per

$$\frac{f - f_0}{f_0} = -\frac{v_r}{c} \iff v_r = -c \cdot \frac{f - f_0}{f_0} \tag{5}$$

where f is the observed frequency, $f_0 = 1420$ MHz is the rest-frequency of the 21-cm line and c is the speed of light. By use of these three equations (3, 4 and 5) and experimental values of f (and thus v_r) from the SALSA-telescope, the rotation curve can be determined. For more information about the SALSA-telescope and how to use it, see the website `https://liv.oso.chalmers.se/salsa/`.

2.2 Mapping the HI and solving the distance ambiguity

In order to map the HI in our galaxy, we simply need the distance from the measured clouds to us. In figure 1, this is the distance SM – name it r. By the result of the calculated rotation curve, we see that the rotation velocity v can be approximated to be constant, $v_c = v_0 = 220\,000\,\mathrm{m\,s^{-1}}$ (since the sun itself should have this constant velocity). This assumption, together with equation (2) gives

$$R = \frac{R_0 \cdot v_0 \cdot \sin(\ell)}{v_0 \cdot \sin(\ell) + v_r} \tag{6}$$

Now we will use the cosine theorem on the triangle SCM. This gives

$$r = R_0 \cdot \cos(\ell) \pm \sqrt{R^2 - R_0^2 \cdot \sin(\ell)}. \tag{7}$$

Then we can use figure 1 and see that $\phi = \ell - 90$, where ϕ is used in the polar coordinate system with origin at the sun. This means that we can express the position of a cloud in a (x, y) coordinate system by using

$$x = r \cdot \cos(\ell - 90) \tag{8}$$

$$y = r \cdot \sin(\ell - 90) \tag{9}$$

To get the galactic centre in the origin of the map, which was the aim of this study, the distance $R_0 \approx 8.5\,\text{kpc}$ is added to the y-coordinate. So, by studying different velocities v_r and using equations (7) – (9), we can determine the observed cloud's position and thus (by repetition for several clouds in different directions), make a map of the galaxy in MATLAB.

For some ℓ however, equation (7) results in two possible solutions for r. This is called the *distance ambiguity*. For one cloud, as mentioned earlier, the distance ambiguity was solved by measuring intensity of the 21-cm line at different galactic latitudes, b. The intensity from two possible cloud locations at galactic longitude 45°, one close to us and one as far away as possible, was observed at latitudes $b = 0°$, 3° and 10°, and the intensity data showed the correct value of r. As figure 2 illustrates, the intensity of the HI-cloud will decrease significantly if the cloud is at large distance, while the intensity will stay somewhat constant if the HI-cloud is located nearer to us.

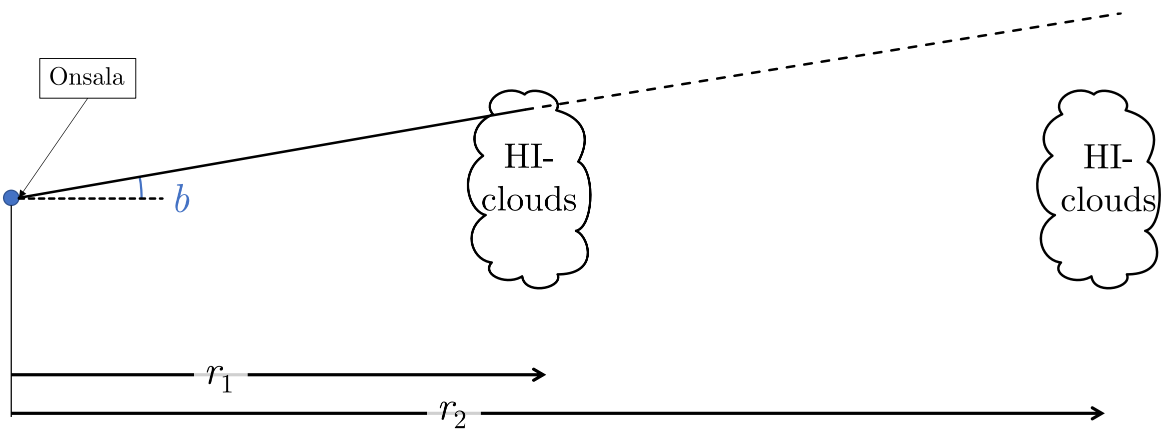


Figure 2: This sketch shows how measurements at different latitudes b was used to choose the right value of r when equation (7) yields two possible solutions, r_1 and r_2. Since the intensity from an HI-cloud at the distance r_2 will have a narrower detection span when compared to the HI-cloud at r_1, a correct value of r can be determined by varying b.

3 Results

Figure 3 presents 11 data points of the velocity and distance from the galactic centre and they make up a rotation curve of the Milky Way. The mean value for the velocity, $v_c \approx 206\,000\,\text{m}\,\text{s}^{-1}$, is also included in the plot. One of the raw-data-plots obtained from the telescope is attached in appendix A.

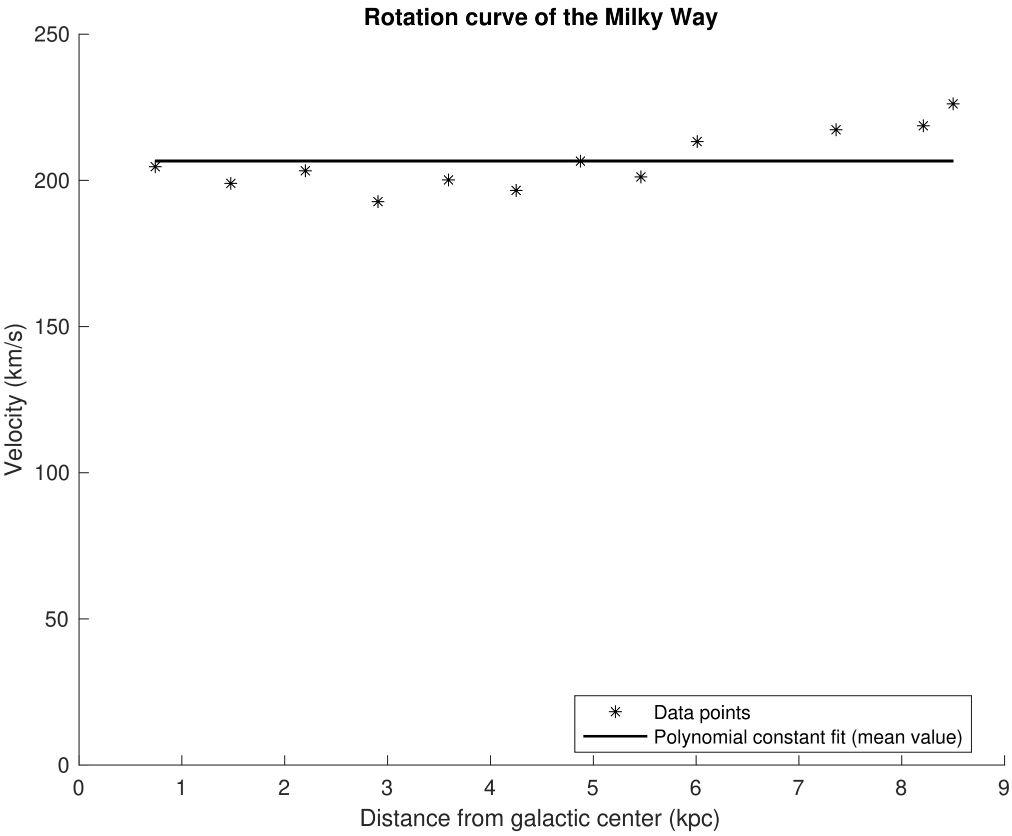


Figure 3: The rotation curve of the Milky Way produced with data obtained from the SALSA radio-telescope at Onsala Observatory.

Figure 4 shows a total of 45 possible HI cloud positions. Green points are definite points which corresponds to a single solution to equation (7) Red and blue points are theoretical positions, corresponding to two possible solutions to equation (7). The black spirals represent some of the real spiral arms of the Milky Way, drawn using [1].

The blue points represent two possible positions for a cloud in the 45°-direction. Which of these two points that represent the real position was found to be the closest one to the sun.

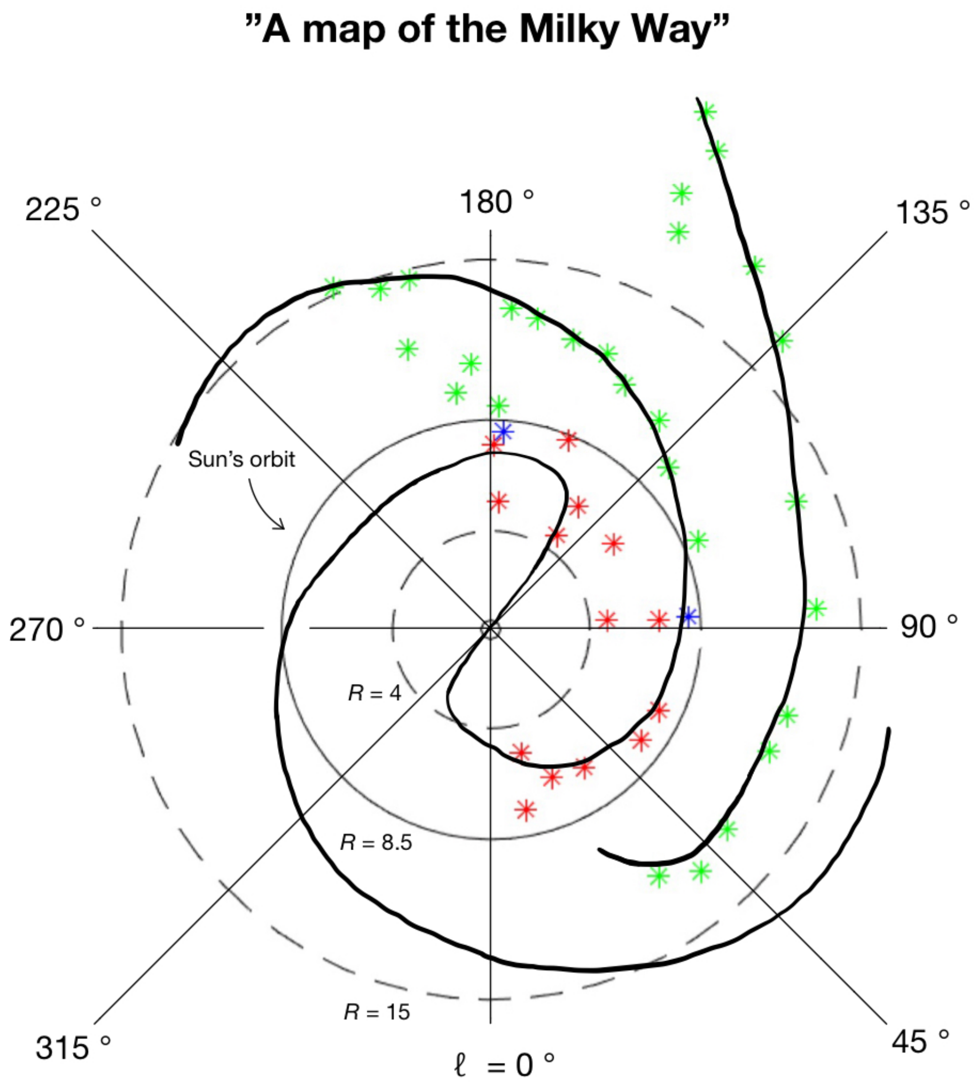
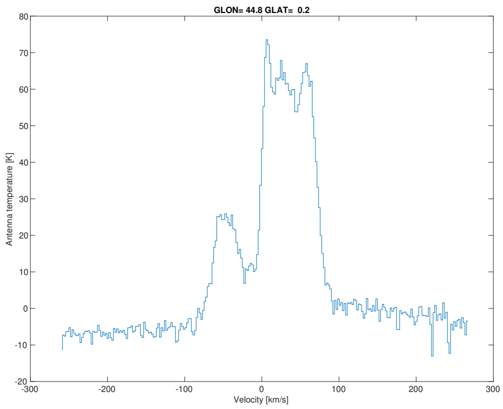
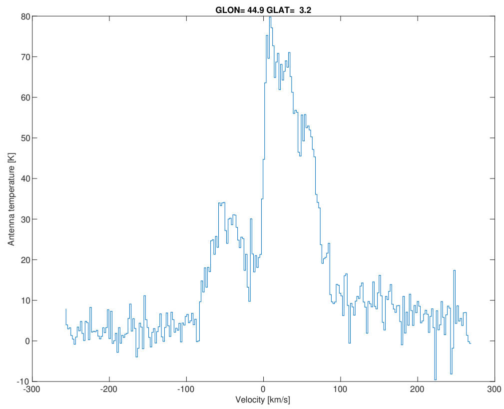


Figure 4: Possible HI-cloud positions; green points are definite positions (one solution to equation (7)), whereas red and blue illustrate non-definite positions (two solutions to equation (7). Note the black lines, which are a estimate of where our galaxy's real spiral arms are positioned.

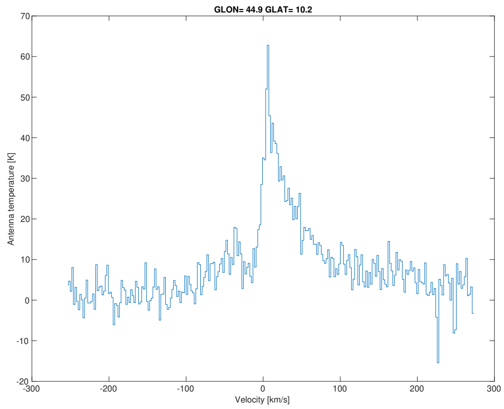
Figure 5 below shows the intensity of the 21-cm line at galactic longitude $\ell = 45°$ and different galactic latitudes b. One cloud was observed at distance 0.5 kpc and one at 11.5 kpc. Since the velocity-peak (the one closest to 0 in figure 5 below) that belongs to these possible distances is still present at latitude $b = 10°$, this implies that the correct position of the HI cloud is the nearest one, i.e. the cloud at distance 0.5 kpc, as the theory-chapter (sec. 2.2) explains.



(a)



(b)



(c)

Figure 5: Intensity of the 21-cm line at galactic longitude $\ell = 45°$ and latitude $b = 0°$ (a), $b = 3°$ (b) and $b = 10°$ (c) respectively. Notice how the first peak at $\approx 8500\,\mathrm{m\,s^{-1}}$ doesn't disappear as the latitude increases, unlike the other peaks.

4 Discussion

The resulting rotation curve in figure 3 is not what might be expected when analysing the rotational velocity, v, of an object in orbit at a distance r. A theoretical expression for the rotational velocity can be obtained considering an equilibrium between the centrifugal force and the gravitational force. Assuming a circular orbit and that most of the galaxy's mass, M, is concentrated at the centre, the rotational velocity is predicted to be

$$\frac{v^2}{r} = \frac{GM}{r^2} \Longrightarrow v = \sqrt{\frac{GM}{r}},$$

where $G = 6.67 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$. The theoretical expression for v is, however, not consistent with the observed data in figure 3, which instead shows a flat rotation curve. This inconsistency suggests that the Milky Way has an alternative mass distribution that does not emit EM-radiation and where $M \propto r$. In conclusion, the measured rotation curve gives evidence that dark matter are largely present in our galaxy.

The measured HI-cloud positions in figure 4 gives evidence that the Milky Way has spiral arms, a characteristic of a spiral galaxy. Due to the location of Onsala, we can not measure the 21-cm line emission in every direction (galactic longitude), therefore the map only contains observed points from $\ell \approx 0°$ to $\ell \approx 230°$. However, in this plot, the galactic centre is at the origin, whereas we observed the HI clouds with respect to a coordinate system with origin in Onsala (= the sun's orbit). Thus, the value of ℓ in which we observed a specific HI cloud is not the same as the value of ℓ for that specific cloud in this plot.

5 Summary

To summarize, this report has discussed the existence of the 21-cm long radio wave emitted by the hydrogen atom. A so-called rotation curve has been created from the observational data and the existence of the hydrogen atom in our galaxy the Milky Way has been mapped in the form of spiral arms. The intensity of the 21-cm line at different galactic longitudes has been analyzed and this has led to the creation of the rotation curve which shows the velocity of the hydrogen molecule clouds at different distances from our solar system. Further use of simple trigonometry made it possible to determine the cloud positions and map them in a simple plot.

Secondly, the problem "distance ambiguity" has been discussed and its effects on the measurements carried out by the telescope have been analyzed. The report has come to the conclusion that it is important to examine the hydrogen clouds at different latitudes to ensure that the distance to them is correct. This is because the trigonometric formulas used to calculate the distance sometimes yield two possible solutions. Measuring at different latitudes can provide the information needed to determine the correct value and in so solving the distance ambiguity problem.

Thirdly, it has been found that the resulting rotation curve is not what might be expected when analyzing an object in orbit. The theoretical expression for the rotational velocity, obtained from considering an equilibrium between the centrifugal force and the gravitational force, does not correspond to the observed data which shows a flat rotation curve. This suggests that the Milky Way has an alternative mass distribution that does not emit EM-radiation and where $M \propto r$. Finally, the report has been able to establish that our galaxy, The Milky Way, has spiral arms. This is a common feature of Spiral galaxies and shows that The Milky Way is one of them.

References

[1] R. Hurt (NASA), "Milky Way and Our Location," 2012. [Elektronic picture]. Available: `https://www.nasa.gov/mission_pages/sunearth/news/gallery/galaxy-location.html`, downloaded 2022-12-01.

A Example of telescope data

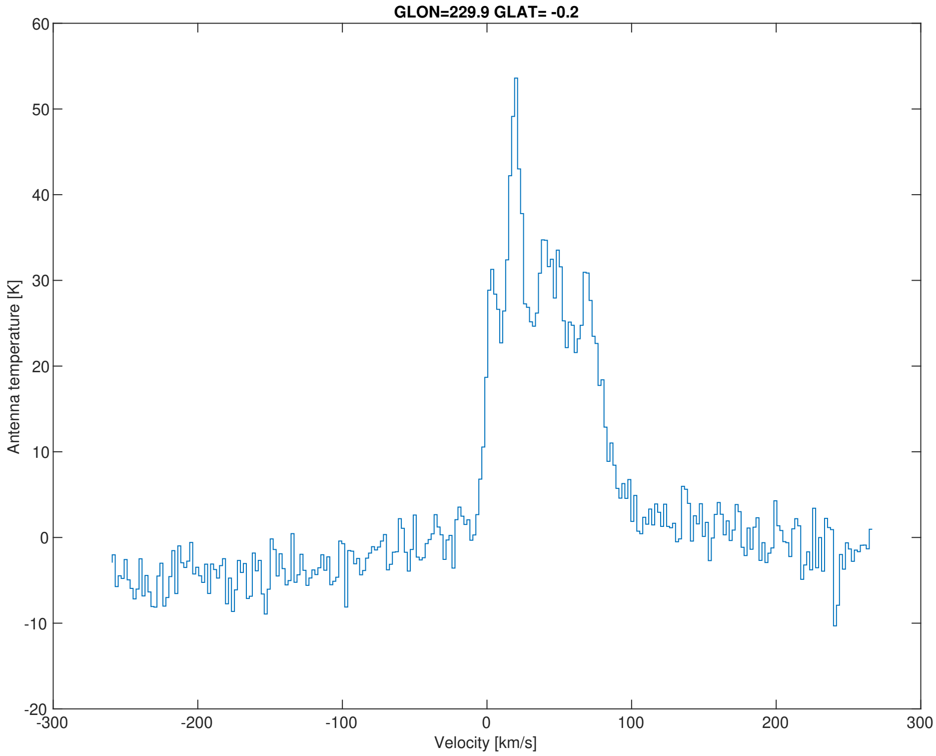


Figure 6: One typical result of an observation from the telescope; different intensity peaks of the 21-cm line at different velocities.

B Calculated r at different ℓ

Table 1 shows the calculated distance r from the sun to a HI cloud at a galactic longitude ℓ. A value followed by a value in a parentheses means that those two values are both probable distances to a cloud, i.e. they are both solutions to equation (7). Also remember that there can be several clouds in one specific direction. Note that only a handful of these values of r is to be seen in figure 4, since some of them result in close-by (x, y)-coordinates.

Galactic longitude $\ell(^\circ)$	Calculated r (kpc)
5	8.8(8.2), 13.7(3.2), 16.0(1.0)
10	9.1(7.7), 14.8(1.9)
15	9.1(7.3), 14.7(1.8)
20	9.6(6.4), 19.4
25	9.3(6.1), 9.9(5.5), 14.4(1.0), 19.7
30	9.5(5.2), 13.7(1.1), 18.7
35	8.7(5.2)
40	8.9(4.1), 10.7(2.3), 17.2
45	7.5(4.5), 11.5(0.5), 16.6
60	5.4(3.1), 14.7
75	3.1(1.3), 3.3(1.1), 12.2
90	9.7, 6.5
105	0.08, 5.2, 11.1
120	0.5, 5.0, 11.0
135	4.3, 9.5
140	0.3, 4.2, 12.3
145	13.0
150	0.5, 4.0
155	0.7, 4.1
160	2.4
170	4.2
190	2.1
200	2.2
210	1.2, 5.9
220	1.6, 6.3
230	0.3, 1.6, 4.1, 7.5

Table 1: Calculated values of r at different galactic longitudes ℓ. Note that several clouds were detected (see parenthesis values) at every value of ℓ, though not all of them is shown in figure 4

C Matlab-code

```
spec = SalsaSpectrum('230.fits');
grid on, grid minor, format long
plot(spec,'vel')

range = 128:140;
A = spec.data(range);
[value, index]= max(A);
org_index= range(index);
freq_max = spec.freq(org_index);
v_max = -2.998e8*(freq_max-1420.4e6)/(1420.4e6);

v_r = 220000*sind(45) + v_max;
%%
xvec = [];
for l = [5 10 15 20 25 30 35 40 45 60 75 90]
    xvec = [xvec, 8.5.*sind(l)];
```

```
end
vel = 0.001.*[204683, 198977, 203286, 192733, 200159, 196571, 206573, ...
    201188, 213277, 217321, 218687, 226184];

hold on
plot(xvec,vel, 'k*')

p = polyfit(xvec,vel,0);
plot(xvec,p.*ones(length(xvec)),'k','Linewidth',1.2)
hold off
axis([0 9 0 250])
xlabel('Distance from galactic center (kpc)')
ylabel('Velocity (km/s)')

title('Rotation curve of the Milky Way')

legend('Data points','Polynomial constant fit (mean value)', ...
    'Location','best')
%%
l = 105;
v_r = -97000;
p = 220e3;
R = 8.5.*p*sind(l)/(p*sind(l)+v_r)

r = sqrt(R^2-8.5^2*sind(l)^2) + 8.5*cosd(l)
x = r*cosd(l-90)
y = 8.5 + r*sind(l-90)

%%
xvec = [1.9,0.3,0.8,4.7,5.4,-0.8,-3.3,-4.5,-1.4,-3.4,-6.4,11.8,10.7,7.6,...
    3.3,8.7,6.8,6.8,12.4,13.2,12.0,11.3,9.6,6.8,7.7,8.5,9.2,7.2,8.4];

xvec2 = [3.1,3.5,5,6.8,3.8,2.5,6.8,1.2,0.3,1.4,0.1,6.1,4.7,2.7];

yvec = [12.6, 9.1, 13.0, 11.2, 9.9,10.8,...
    14.2,13.8,9.6,11.4,13.9,11.7,14.7,16.1,11.8,21.0,8.5,8.5,5.2,0.86,...
    -3.5,-4.9,-8.1,-10,17.7,-9.8,19.4,6.6,3.6];

yvec2 = [7.7,5.0,3.5,-3.3,-5.6,-6.0,0.4,-5.0,5.2,-7.3,7.5,-4.5,0.4,3.8];

da_x = [8.0,0.5];
da_y = [0.5,8.0];

hold on
angle = 0:0.1:2*pi;
x = 8.5*cos(angle);
y = 8.5*sin(angle);
x_1 = 4*cos(angle);
y_1 = 4*sin(angle);
x_2 = 15*cos(angle);
y_2 = 15*sin(angle);
plot(x,y,'k-')
plot(x_1,y_1,'k--')
plot(x_2,y_2,'k--')

plot(0,0,'ko')
plot(xvec,yvec,'g*')
plot(xvec2,yvec2,'r*')
plot(da_x,da_y,'b*')
hold off

axis([-15 20 -20 25])
axis equal
xlabel('Distance from galactic center in the x-direction (kpc)')
ylabel('Distance from galactic center in the y-direction (kpc)')

title('Rotation curve of the Milky Way')
```