Mapping parts of the outer spiral arms of the Milky Way using radio astronomy

by Martin Mueller – The Open University, December 12, 2022

Introduction

On average, once every 10 million years, a neutral hydrogen atom emits electromagnetic radiation when the spin of its electron changes from parallel to anti-parallel in relation to the spin of the proton. The electron thereby transitions to a lower hyperfine energy level and the released energy is carried away as an electromagnetic wave (The Open University, 2022a). Since this is a quantum event, the resulting frequency is very precisely defined at about 1.4 GHz and at least 12 decimal places to this unit (Hellwig et al., 1970). Conversely, according to the Planck equation the wavelength of such radiation is determined at about 21 cm with the same accuracy.

Small frequency variations in this radiation could be explained by Doppler shifts and thus could enable the determination of radial velocities, speeds and ultimately the positions of hydrogen clouds in the galactic plane. Since, according to the galactic model of the Milky Way, the clouds should rotate around the galactic centre, the position of the clouds should reveal patterns and their arrangement should make it possible to map the outer spiral arms of the Milky Way (The Open University, 2022b).

The question to be answered is therefore: Can frequency shifts to the very precisely defined frequency of the electromagnetic waves emitted by the hydrogen-electron spin flip be detected with a radio telescope so that the positions of large hydrogen clouds in the galactic plane of the Milky Way can be determined and finally parts of its spiral arms be drawn in accordance with the galactic model?

Methods and results

The whole experiment was conducted under the guidance of the Open University study material and can be divided into 5 consecutive main steps with corresponding intermediate results after their completion. The first activity was a team effort by three students, namely Eric Monkman, David McLean and the author of this report, Martin Mueller.

Step 1: Creating an observation plan and carrying out the observation in a team of three students

The key instrument used in the experiment was the ARROW radio telescope on the campus of the Open University in Milton Keynes, United Kingdom. With its 3-metre dish and internal electronics, it can sample a range of frequencies in 5-kHz steps between -0.800 MHz and +1.200 MHz, centred on the rest frequency of atomic hydrogen (1420.406 MHz). It can be slewed remotely and thus is suitable for team work of students at different locations (The Open University, 2022c).

The team created a detailed observation plan using Stellarium and Python Astropy. The originally planned observation had to be postponed by two weeks due to a technical defect of the telescope. On the day of the observation, the team was also informed that the slewing would be unusually slow and that the track target functionality would not work. The observation could finally be executed on 15 November 2022 between 15:30 and 17:30 UTC without interruptions and delivered 31 .csv files with data of the 3 scans per galactic longitude of 20°, 30°, 40°, 50°, 60°, 70°, 80° and 10 scans for the reachable background target, the north ecliptic pole (NEP). High and suspicious noise was detected by all team members during the scanning process.

Step 2: Analyzing the raw data of the observations, calibrating and converting the archive data and plotting

Initially, the raw data was visualized for verification using Python Matplotlib by plotting intensities against frequencies for each galactic longitude and for the background as depicted in Figure 1. As exemplified in Figure 1 using the 3 scans for the galactic longitude of 50° and the 10 background scans for the NEP, there was high noise. In addition, the background scans mostly had higher intensities than the target scans, which in principle should not be the case.

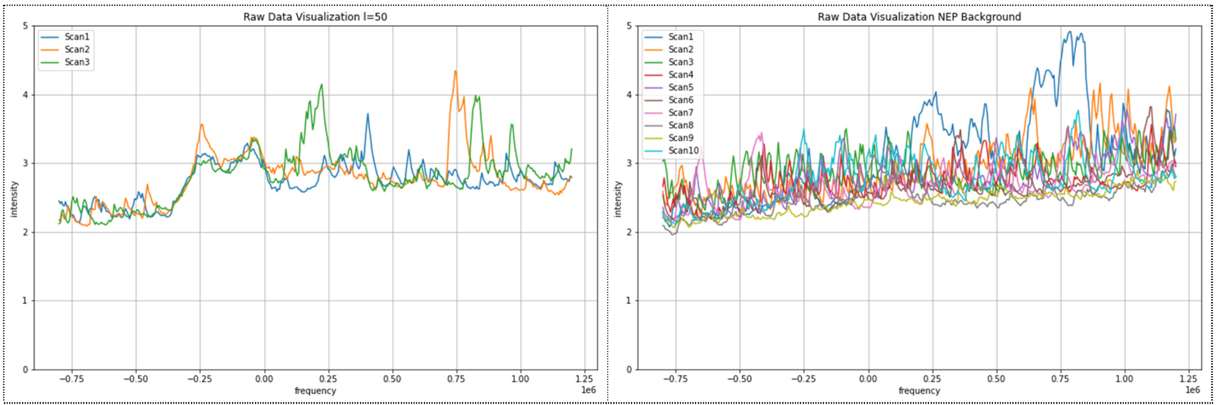

Figure 1: Two examples of raw data visualizations of the own observation session

Because of the irregularities found in the data, and after consultation with the ARROW specialist in the student forum, the decision was made to use the Open University archive data for further processing instead.

The received archive data, dated 22 October 2019, 13:30 - 15:00 UTC, was then subjected to three data operations executed by Python:

- Averaging the background spectra
- Substracting the averaged background intensity from each spectrum
- Converting the frequencies to radial velocities using the Doppler shift equation

The results were finally printed using Python Bakoh and are shown as red graphs in Figure 2 where *S* are the spectra and *l* the appropriate galactic longitudes. To compare the data quality and justify the switch to the archive data, the same operations were applied to the data from the own observation (in addition, the spectra of the targets are averaged over the three scans per target) and are shown as blue graphs.

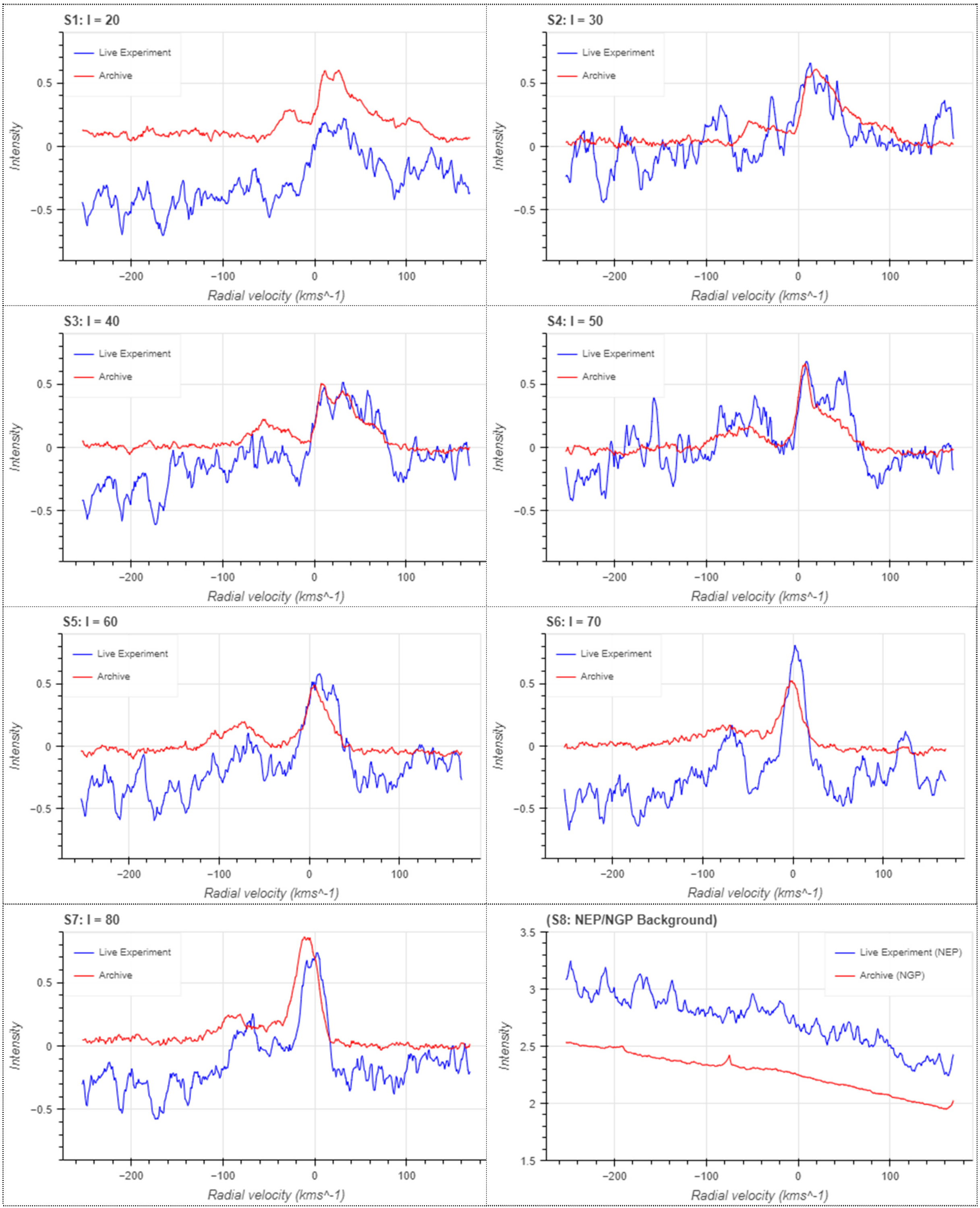

Figure 2: Calibrated and converted spectra from the Open University archive data (red graphs) and from the own observation (blue graphs)

Step 3: Identifying the clouds, correcting their radial velocities to a suitable frame of reference and exchanging the results with other students

Using the Python Bakoh Hover Tool and the naked eye, each spectrum in Figure 2 was examined for possible clouds by inspecting characteristic, i.e. broad, intensity peaks. Once identified, their mean observed radial velocities (V_{obs} /km s^{-1}) were noted along with estimated uncertainties (Err (+/-) /km s^{-1}), as shown in Table 1. No statistical or mathematical methods were used to identify both the peaks and the errors.

Since all objects in the universe are subject to different forces, movements that distort the observed motions must be eliminated. The Open University has provided an online calculator to convert the data to the appropriate reference system, the Local Standard of Rest (LSR) (The Open University, 2022d/e). The corrected values of the radial velocities V_{obs} are listed in Table 1 in column V_{obs_lsr}, which were shared with other students to fill gaps in their observations. Conversely, Table 1 was supplemented with data for longitudes 10°, 90°, 100° provided by student Jonathan Chow and for 80°, 110°-140° by student Robert Arthur.

Gal. long. /°	V_{obs} /km s^{-1}	V_{obs_lsr} /km s^{-1}	Err (+/-) /km s^{-1}	R_gc /kpc	R_sun /kpc
10	28	22	2	6.1	14
20	103	95	1	4.3	11
20	26	18	1	7.8	15
20	11	3	1	9.3	17
20	-27	-35	1	18	26
30	84	75	3	5.7	11
30	20	11	4	8.8	15
30	-53	-62	6	22	29
40	60	50	1	7.1	11
40	31	21	2	8.4	13
40	7	-3	2	9.9	15
40	-56	-66	1	18	24
50	42	31	5	8.2	10
50	7	-4	1	9.9	13
50	-53	-64	4	16	20
50	-75	-86	1	20	24
60	5	-6	1	10	11
60	-71	-82	2	17	20
60	-104	-115	1	24	27
70	-1	-12	1	10	9.3
70	-70	-81	4	16	17
80	-78	-89	10	16	16
80	-47	-58	12	13	12
80	-4	-15	8	10	7.6
90	-89	-99	2	18	15
90	-19	-29	2	11	7.2
100	-80	-90	2	17	13
100	-15	-25	2	11	5.5
110	-109	-118	7	23	18
110	-68	-78	10	16	10
110	-17	-26	6	11	4.7
120	-116	-124	7	28	22
120	-77	-85	7	17	12
120	-23	-31	6	12	4.6
130	-100	-106	7	26	20
130	-68	-74	7	17	10
130	-22	-28	8	12	4.1
140	-93	-97	7	31	24
140	-59	-63	7	17	10
140	-24	-27	9	12	4.1

Table 1: Observed radial velocities (V_{obs}, V_{obs_lsr}) of detected clouds for the galactic longitudes (Gal. long.) considered in this experiment as obtained in step 3 and distances of the clouds from the galactic centre (R_gc) and the sun (R_sun) as obtained in step 5

Step 4: Determining the maximum radial velocities for different lines of sight from high quality archive data and using a galactic model and trigonometry to calculate the maximum cloud speeds

Using a model of the galactic rotation and basic trigonometry it can be shown that the maximum radial velocity *V* of a cloud for a certain line of sight (i.e. its rotational speed) can be calculated as follows:

$$V = V_{obs\_lsr\_max} + V_0 \times \sin(l) \qquad (1)$$

where $V_{obs\_lsr\_max}$ is the observed LSR-corrected maximum radial velocity, V_0 is the rotational speed of the Sun around the galactic centre known from other experiments and *l* is the galactic longitude (The Open University, 2022f). To determine *V*, The Open University provided high quality LSR corrected spectra which were plotted using Python Bokeh (Figure 3).

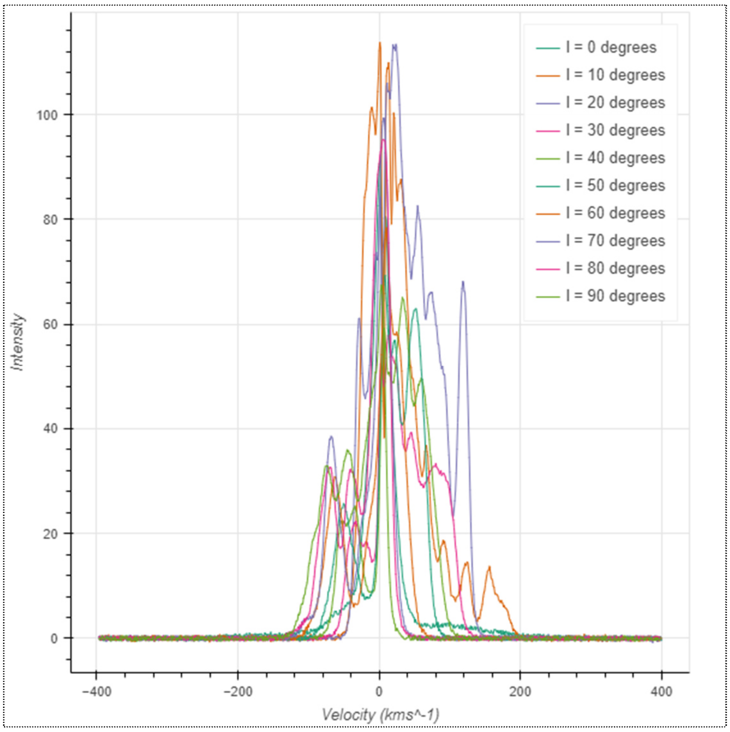

Figure 3: Spectra for different lines of sight from high quality archive data

The maximum observed radial velocitiy $V_{obs\_lsr\_max}$ per line of sight *l* could then be read with the naked eye by hovering over the rightmost elevations in Figure 3 and were noted together with their uncertainties.

Further, $R_{obs\_lsr\_max}$, the distances of such specific clouds to the galactic centre, were calculated using Python by equation:

$$R_{obs\_lsr\_max} = R_0 \times \sin(l) \qquad (2)$$

where R_0 is the distance of the Sun to the galactic centre known from other experiments (The Open University, 2022f).

Finally, the results were written to Table 2.

Gal. Long. /°	$V_{obs\_max\_lsr}$ /km s^{-1}	Error (+/-) /km s^{-1}	$R_{obs\_max\_lsr}$ /kpc	V /km s^{-1}
0	52	2	0.00	52
10	196	1	1.48	234
20	147	2	2.91	222
30	132	1	4.25	242
40	111	6	5.46	252
50	92	2	6.51	261
60	66	1	7.36	257
70	45	2	7.99	252
80	42	1	8.37	259
90	30	1	8.50	250

Table 2: $V_{obs\_max\_lsr}$ and their errors as read from plotted high quality spectra and $R_{obs\_max\_lsr}$ and V as calculated by equations 2 and 1 respectively

Plotting V against $R_{obs\_max\_lsr}$ revealed a remarkable by-product, namely that the speeds of the rotating hydrogen clouds in the Milky Way are almost the same (about 250 km s^{-1}), contrary to what Kepler's rotation curve predicts. According to Kepler, based on Newton's law of gravitation, the speed of the clouds would have to decrease with distance R from the galactic centre if all mass were concentrated there. However, the rotation curve shown in Figure 4 shows constant speeds for a wide range of distances, which could be caused, for example, by (as yet) undetectable dark matter (The Open University, 2022g).

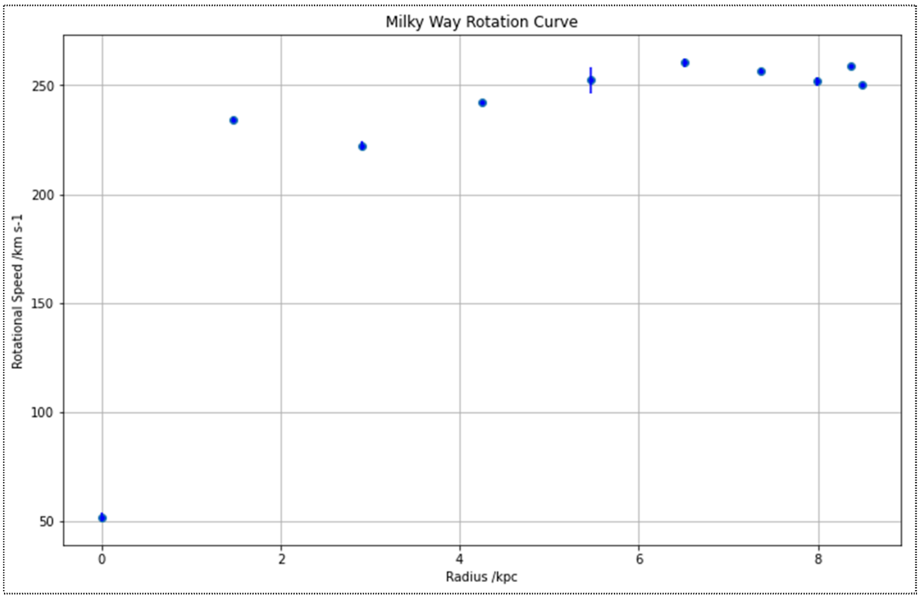

Figure 4: Milky Way rotation curve based on values of Table 2

Step 5: Applying trigonometry to finally calculate the distance of the clouds from the galactic centre using the previously gathered and processed data, plotting the results and identifying possible spiral arms based on the cloud positions

Using again the model of the galactic rotation and trigonometry it can be shown that the distance *R* of a cloud from the galactic centre can be calculated as follows:

$$R = V \times R_0 / \left[V_0 + V_{obs\_lsr} / \sin(l) \right] \qquad (3)$$

where *V* was calculated in the preceding step (Table 2) and can be assumed to be constant at about 250 km s^{-1} for the radii under consideration and V_{obs_lsr} and *l* have been obtained from the observation (here: archive data) (The Open University, 2022h).

The results of these calculations with Python were written to the *R_gc* column in Table 1. With these values, the positions of the clouds could be drawn in using a ruler, compass, pencil and paper. Plotting the cloud positions with the Python utility polar plot required the calculation of the distance of the clouds from the sun (R_{sun}, also written to Table 1) by applying the following equations based on basic trigonometry:

$$R_{sun} = R_{gc} \times \frac{\sin(\theta)}{\sin(l)} \qquad (4)$$

where

$$\theta = \pi - \delta - l \qquad (5)$$

where

$$\delta = \sin^{-1}\left(R_0 \times \frac{\sin(l)}{R_{gc}} \right) \qquad (6)$$

The final result of the experiment is shown in Figure 5.

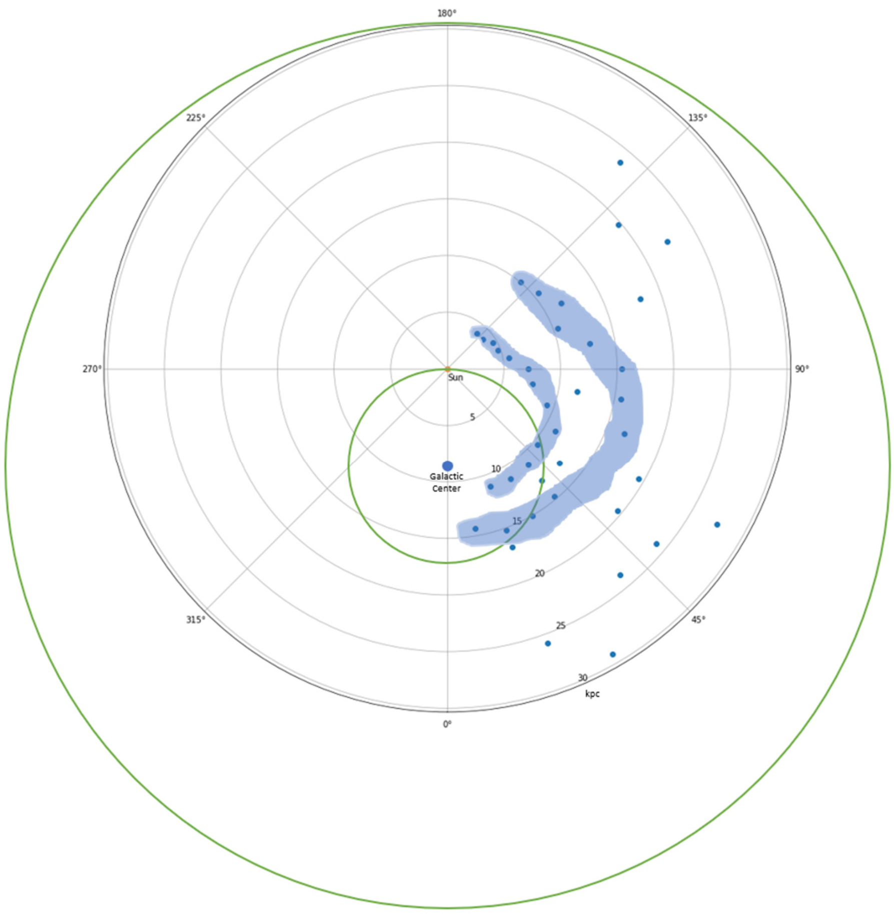

Figure 5: Plot of the cloud positions based on the values (R_{sun}) shown in Table 1. The small blue dots represent cloud positions at a radial distance from the Sun along the lines of sight studied: 10° - 140° in 10° steps relative to the axis Sun - Galactic centre. The small green circle around the galactic centre has a radius of 8.5 kpc (distance between the Sun and the galactic centre), the large green circle has a radius of about 38.5 kpc and can roughly be considered the galactic plane. The transparent blue figures were drawn by hand using MS Powerpoint and connect cloud clusters and could represent two spiral arm fragments.

Discussion and interpretation

Figure 5 is the result of a series of tool-based and manual activities. Both types of activity could be sources of errors in the experiment.

In the own observation, even when averaging three scans per target, the data showed enormous noise, possibly caused by radio frequency interference (RFI) or malfunction of the telescope. For this reason, it was decided to use Open University archive data instead. But even this data was not unambiguous, since it consisted only of single scans per spectrum. The data was then interpreted with the naked eye. This could have led to over- or misinterpretations. Each peak, especially if it was broad, could have been a summation of smaller peaks in the vicinity. The centre of such a peak could therefore not have represented a cloud, but a point between two or more nearby clouds. A more precise interpretation of the peaks, also with statistical and mathematical methods, could have prevented possible errors here.

The rotation curve provided a decisive quantity for the calculation of the individual cloud positions, namely the rotation speeds of the clouds for each line of sight. However, only a few clouds were analyzed and that only with the naked eye. More data and a more methodical analysis could have strengthened confidence in the critical value of rotation speed V.

For the drawing of the clouds and spiral arms, consideration of the intensities of the 21-cm radio waves would have provided further insights. Firstly, it would have been possible to better determine whether the clouds were located before or after the maximum of the rotational velocity in each line of sight. Second, cloud sizes could have assisted in drawing the spiral arms later. Thirdly, very small clouds could have been excluded from the overall view, thus avoiding over-interpretation.

The cloud velocities were subject to uncertainties (see Table 1), but these were not considered when calculating the cloud positions. A test of the maximum error (+/- 6 km s^{-1}) resulted in an error range of 17 % (5 kpc of 30 kpc) related to the considered scale. When drawing the spiral arms, applying the full error might have resulted in a completely different picture.

Finally, although many of the cloud locations identified seem to show structures, drawing the spiral arms by hand, as done in Figure 5, is highly speculative and requires further data and justification.

Conclusions

The methods used in this experiment, i.e. the scanning of the frequency shifts to the wavelength emitted by the hydrogen-electron spin flip with the help of a radio telescope, the data processing and the application of trigonometry to a galactic model, seem to be suitable for localizing clouds and mapping parts of the spiral arms of the Milky Way. The results finally obtained make it possible to draw spiral arms that roughly correspond to the known maps produced by more sophisticated experiments.

However, the map obtained is far from precise and serves more to confirm the methods than to exactly locate the spiral arms. Nevertheless, the work can be a starting point for further improvements of the methods, the interpretations and ultimately the results.

References and acknowledgements

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