EBERHARD KARLS UNIVERSITÄT TÜBINGEN

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT

Advanced Labwork in Astronomy and Astrophysics

Experiment Radio astronomy

Victor Doroshenko and Alejandro Guzmán

Kepler Center for Astro and Particle Physics
Institut für Astronomie und Astrophysik, Sand 1,72076 Tübingen
Stand: September 23, 2024

http://www.uni-tuebingen.de/de/4203

Contents

1 The radio sky

When we look up into the sky on a clear, cold night, our eyes can see a bright band stretching across the sky. If you observe it with a pair of binoculars or a small telescope like Galileo 1609, you will notice that this band consists of a myriad of stars. It is the Milky Way, our own galaxy, which we see from Earth in this way, containing about a hundred billion stars, of which our Sun is just one among many, and there are many others in the Universe galaxies.

Astronomers took a long time to figure out what our galaxy really looks like. It would be so much easier if one could get into a spaceship and simply look at it from the outside. Unfortunately, traveling in and around the Milky Way is because of the enormous distances that have to be set aside for it. On the other hand, observing the Galaxy from within the Solar system is complicated by the fact that some regions of the Milky Way appear darker than others they are obscured by large amounts of interstellar dust, these dark clouds obscure many stars.

Observations of external galaxies, both with optical and radio telescopes, have helped to clarify the structure of the Milky Way. Today, astronomers assume that they know exactly how stars and gas are distributed within it: our galaxy is a thin disk of stars and gas arranged in a spiral, with a larger bulge at the centre, which hosts also a supermassive black hole with mass of about three million times the mass of the Sun. The central black hole is also a strong radio source named Sagittarius A*.

In the thirties of the twentieth century, another mystery arose around the Milky Way, so called dark matter. The largest part of the mass of our galaxy seems to be invisible, and only reveals itself through gravitational interaction. Imagine a fast-dancing couple in a dark room. The man is completely dressed in black, the woman is wearing a fluorescent dress, the man is invisible, so to speak, but the movement of the woman makes it possible to conclude his presence: someone has to hold on to her, otherwise she would not be able to keep spinning. Likewise, in our Galaxy, the stars and the gas are spinning too fast to be held by gravity of observable mass, so additional massive matter must be present, but remain invisible to the human eye and all instruments built so far. This substance of yet unclear origin is called “dark matter” and is only observed indirectly.

One of the most important indication of the existence of dark matter is the measured velocities of visible matter in the outer regions of the Milky Way, and Radio observations of the kind you will do during the current lab-work have played an important role in the discovery of dark matter. In this experiment we will take a radio look at the closest star, the Sun, and the closest Galaxy, the Milky way, in order to get a first glimpse on methods and instruments specific to radio astronomy, and what we can learn from it.

1.1 A bit of history

The history of radio astronomy is closely tied with the history of physics in general. The breakthrough in understanding of electromagnetic phenomena associated with works of James Clerk Maxwell in 1960s, immidiately prompted physicists and astronomers to conclude that there must be sources of radio emission in the sky. Several unsuccessfull attempts were made to detect thermal radio emission from the Sun including experiments by Johannes Wilsing and Julius Scheiner (Germany) in 1896 and by Oliver Lodge soon after that. The technical limitations at the time made such detections extremely challenging and were the true reason for failure, although the discovery of the radio reflecting ionosphere in 1902 led physicists to conclude that the layer would bounce any astronomical radio transmission back into space, making them undetectable from Earth. Which, as we now know, and will verify in the current lab work, is not fully true.

The actual radio astronomy begun with the work of American physicist and radio engineer Karl Jansky, who was hired by his employer, Bell Laboratories of Holmdel, New Jersey, to locate the origin of the transatlantic radio telephony interference. To this end, he built a large, rotatable and vertically polarised directional antenna, which could observe at a frequency of ~ 20.5MHz, and began his observations in 1930. In 1932, he published his first results. In addition to local and more distant thunderstorms, he had identified a third source of interference, a very uniform noise of unknown origin, and in the following year he succeeded in proving that the source of this radiation was outside the Earth. Through close observation and comparison with star maps, Jansky concluded that the Milky Way, and in particular its centre, was the source of these radio waves, however, Jansky was not able to continue his work at the time due to lack of support from Bell Labs.

Several years later, American amateur astronomer Grote Reber picked up on Jansky's discoveries and built the first radio telescope dedicated to purely astronomical purposes in his garden in 1937. It was a nine-meter parabolic antenna that was swivelling but not rotatable. In 1938 he was able to verify Jansky's observation and in 1940 was the first to publish a radio astronomical work in an astronomical journal. In 1941 he began to create a map of the starry sky in the radio band. He discovered several strong radio sources, including Cygnus X−1 and Cassiopeia A. In addition, he found that the sun is a radio source whose intensity follows the 11-year rhythm of solar activity. Jansky had been observing during the period of minimum activity, which precluded him from detection of the sun as a radio source. Another important discovery of Reber's was that the radiation emitted from the center of the Galaxy did not follow Planck's law, but rather a power law. The explanation for this is found only in the 1950s when it was recognized that cosmic radio emission most often has non-thermal origin.

Radio astronomy experienced a boom after World War II, as many formerly military (radar) facilities could be used for astronomical purposes. The first detection of the Sun came somewhat later, on February 27, 1942, was also associated with that boom. James Stanley Hey, a British Army research officer, made the first detection of radio waves emitted by the Sun using military equipement. Later that year George Clark Southworth, at Bell Labs like Jansky, also detected radiowaves from the sun. Both groups were bound by wartime security surrounding radar, so were actually not the first to publish the results in due time, which allowed several people (including Reber mentioned avove) to independently discover our star in radio band.

Nobel Prize winner Martin Ryle's group also used two formerly military antennas as interferometers. In 1944, Hendrik van de Hulst suggested that atomeric hydrogen in interstellar space could produce line emission in the radio band, a theory that was proved in 1951 by Harold Ewen and Edward Purcell by observing the 21 cm hydrogen line.

In 1967, the then doctoral student Jocelyn Bell discovered the first pulsar, for which her doctoral supervisor received the Nobel Prize in 1974. The reason was that this discovery proved for the first time existence of extremely dense compact objects, neutron stars, first predicted by Landau based on fundamental physics grounds, and basically cemented achievements of particle physics of the 20th century.

As previously suggested by Grote Reber, the system consisting of the antenna and the receiver from which each radio telescope is made, performs a bolometric measurement, i.e. determines the temperature of a source. This is what Arno Penzias and Robert Wilson used in 1965 in their attempt to measure the temperature of absolutely cold space, by comparing the radio signal detected from the sky with that coming from within a cooled cavity on ground. This work led to the discovery of the 3 K cosmic microwave background radiation, which, directly or indirectly, eventually was worth several nobel prizes.

The radio astronomy made great strides ever since its birth, discovering thousands of sources of all kinds, and becoming an essential observational window for modern astrophysics. Of course, this success is largely attributed to developement of modern instrumentation, i.e. radio telescopes and interferometers. These are among most impressive constructions devoted to studies of the sky, and the largest can be hudgred of meters or even larger. The Five-hundred-meter Aperture Spherical radio Telescope (FAST)) is the largest single-dish radio telescope located in southwest China, and, as the name suggests has a diameter of half a kilometer. Radio interferometers uniting many telescopes can be even larger. The space-based radio interferometer project, *Radioastron*, for instance, allowed to have an effective antenna size comparable to that of the moon's orbit. In current experiment, however, you will move back in time, to when the radio telescopes were small and had comparatively low sensitivity. Still, you will be able to give your first look to the radio sky and observe the Sun, and our own Galaxy, the Milky Way.

Exercise: What kind of radiation is emitted by the galactic center in the form of radio waves and what is its origin? What's the origin of radio emission from the Sun?

1.2 The Sun

Only a handful of radio sources are accessible to small telescopes. In current lab work we will observe the Brightest discrete Radio source in the Sky, the Sun. Unlike the Galactic hydrogen, the Sun emits mostly continuum thermal radio emission, which has i.e. same origin as the optical light we can se with our own eyes. However, considering that the radio band corresponds to lower temperatures, this emission is produced in cooler parts of the sun, in the chromosphere and in the corona (the solar atmosphere) rather than photosphere observed in the optical band. A radio image of the Sun as observed with high-resolution radio telescope is shown in Fig. 1.1, where one can also see active regions associated with the magnetic activity of our star. These regions have somewhat different radio spectrum compared to rest of the surface, and are variable on a timescale of days to months. This variable component is most prominent at longer wavelengths and is observable with our telescope.

Unfortunately, the spatial resolution of Tübingen radio telescope is not sufficient to see the Sun as extended source, so the goal of our observations will be just to detect it as a point source, and use it to measure the angular resolution, or beam size, of our instrument. Keep in mind that it is still not a small achievement, and only happened for the first time less than a hundred years ago!

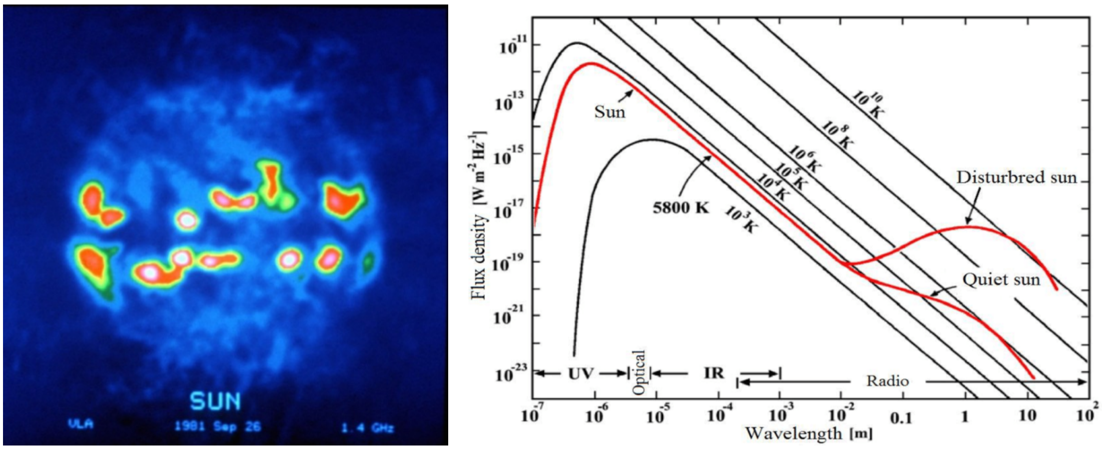

Figure 1.1: The radio Sun: radio image of the Sun recorded by very large array (VLA) radio interferometer. The brightest regions are part of corona nearby but beyond sunspots (left), and the spectral energy distribution of the Sun (Right). Images courtesy (NRAO/AUI)

Exercise: Calculate the expected angular resolution of 2.3 m radio telescope operating at GHz frequencies and compare it with the angular size of the Sun. Is the assumption mentioned above justified?

1.3 The Milky Way

Location of all celestial objects can be specified in a number of ways or, equivalently, "coordinate systems". Considering that most astronomical objects are very far away, it is often sufficient to specify their location on the celestial sphere, which is typically done by definition of two angles, much like the longitude and lattitude for coordinates on Earth. Of course, this is only true when we are not interested or can not recover the three-dimensional relation between individual objects and Earth! The choice of a reference point from where the two angles are measured depends on a particular problem one faces, i.e. serves our own convinience. Some commonly used coordinate systems, also useful in context of our experiment include Alt-azimuthal, Equatorial, Ecliptic, and Galactic coordinates. The Alt-azimuthal coordinate system is connected to a given point on Earth's surface, and location of the celestial objects is defined by their altitude above the horizon (or displacement from Zenith), and their Azimuth, i.e. angle between the direction to the object and Earth's north pole. The problem here is of course, rotation of the Earth, which makes all coordinates time-dependent. To overcome this issue, several coordinate systems tied to the sky itself rather than Earth have been introduced.

In Equatorial coordinates the plane of the horizon is substituted with Earth's equatorial plane, and the direction to the north with the angle between March equinox point (intersetion of equatorial and Ecliptic planes), and the object. This angle is called "right ascention" or α, and can be measured either in degrees or time units (remember, the Earth rotates, so angle between the equinox and an object can be measured also as difference of their rise times, i.e. from 0 to 24 h). The second angle is measured from the celestial equator, and is called declination δ, and is usually measured in degrees (from -90° to 90°). Coordinates of a given star in this coordinate system remain constant (ignoring precession of Earth), and thus are suitable to specify position of objects in catalogues. Moreover, rotation only changes right ascention, so this coordinate system is particularly suitable for tracking objects in the sky as the Earth rotates. This is by far the most often used coordinate system, and will be used during the experiment to point the telescope to and track the Sun in the sky. Ecliptic coordinate system is similar, but uses ecliptic plane (i.e. projection of the solar system equatorial plane on the celestial sphere), and is more suitable for specifications of the positions of solar system objects. In fact, this would be your coordinate system of choice for Sun observations if our telescope supported! (why?).

Finally, the Galactic coordinate system uses the Galactic equator as fundamental plane, and is useful to understand where a given star is located within the Galaxy. Here the relevant angles are the Galactic latitude b (measured from the Galactic plane), and the Galactic longitude l measured from the Galactic centre. The relation between different coordinate systems is illustrated in Fig. 1.2.

The Sun is located in the "outer" regions of the Galaxy, approximately 8.5 kpc (or $\sim$ 25000 light-years) away from the Galactic center. Similarly to most stars and gas, the Sun resides in a thin disc and orbits around the common centre of mass with orbital period of about 240 million years. The Sun thus moves with $\sim$ 220 km/s. As already mentioned, to describe the position of a star or a gas cloud in the Galaxy, the use of the galactic coordinates (l, b) is appropriate. l is the galactic longitude, and measures the angular distance of an object eastward along the galactic equator from the galactic center. b is the galactic lattitude (Fig. 1.3), and thus measures the angle of an object north or south of the galactic equator (or Galactic plane) as viewed from Earth. In this coordinate system the Galactic center has coordinates $(0, 0)$.

For further orientation, the Galaxy is divided into four quadrants, which (unlike in Star Trek) are denoted by Roman numerals (Fig. 1.4):

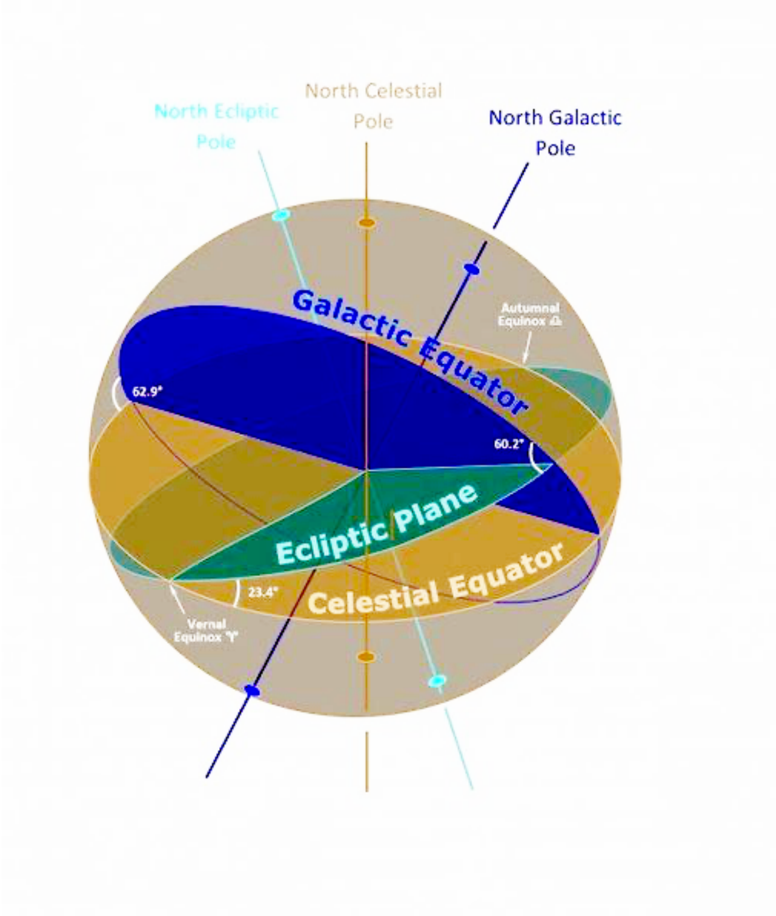

Figure 1.2: Reference planes of commonly used celestial coordinate systems. The Alt-azimuthal coordinate system also uses two angles, but is connected to point on Earth and thus is not shown.

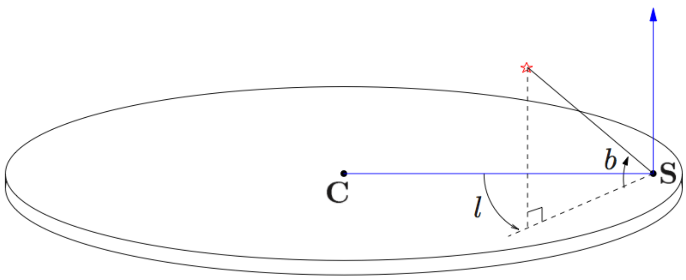

Figure 1.3: The galactic coordinate system with the coordinates l and b. C denotes the center of the Galaxy, S the position of the Sun.

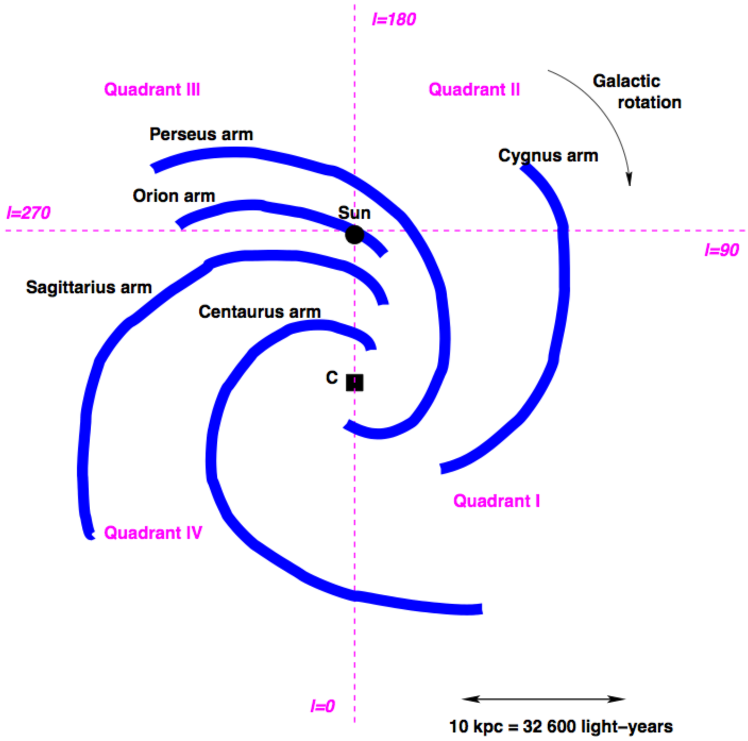

Figure 1.4: Schematic representation of the spiral arm structure of the Galaxy. *C* is again the center of the galaxy, the location of each arm is indicated. In addition, the division into quadrants is outlined.

Quadrant I:	$0° < l < 90°$
Quadrant II:	$90° < l < 180°$
Quadrant III:	$180° < l < 270°$
Quadrant IV:	$270° < l < 360°$

The quadrants II and III mainly contain matter in orbits around the galactic center with a radius greater than that of the Sun. Quadrants I and IV mostly cover the inner parts of the Milky Way.

A few more quantities are useful for description of the Galaxy and movement of its components during your work on the experiment (Fig. 1.5):

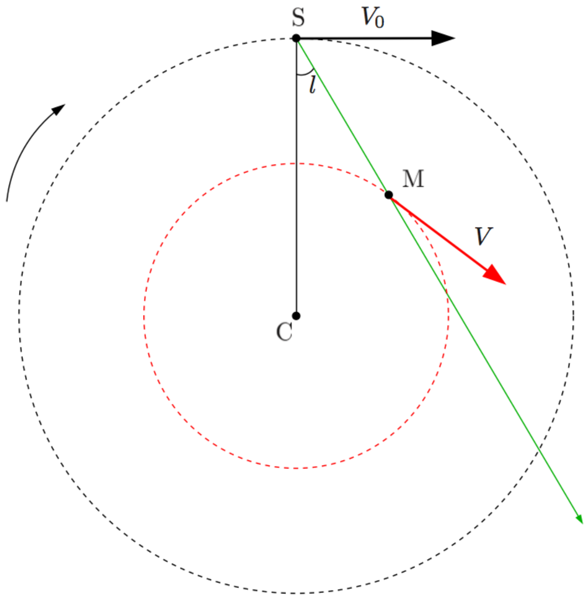

Figure 1.5: Explanation of the magnitudes used C denotes the galactic centre, S the position of the sun and M the position of a gas cloud.

V_0	The speed with which the sun moves around the galactic centre ($220\,\mathrm{km\,s^{-1}}$)
R_0	Distance of the sun from the centre of the galaxy(8,5 kpc)
V	Speed of a gas cloud
R	Distance of a gas cloud to the Galactic centre
r	Distance of a gas cloud to the Sun

Exercise: Why do the two coordinates l and b suffice to describe the (three-dimensional) Milky Way? Is it always the case?

1.4 The search for hydrogen

The largest part of the gas in the Milky Way is neutral hydrogen (H). H I is the simplest of all atoms: it consists of a proton and an electron. Atomic hydrogen emits a line with a wavelength of $\lambda = 21$ centi meter, which is thus a radio line. This is the signal we want to observe! The corresponding frequency can be calculated as

$$\lambda = 21\,\mathrm{cm} \Rightarrow f = c/\lambda = 1420\,\mathrm{MHz} \tag{1.1}$$

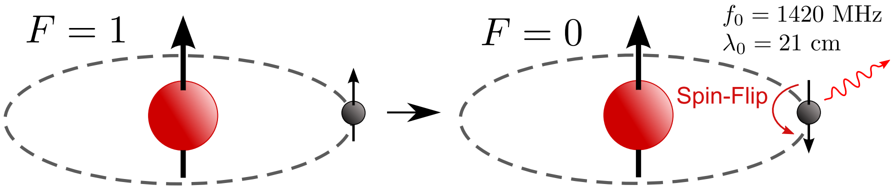

Figure 1.6: Schematic representation of the hyperfine structure transition of neutral hydrogen from $F = 1$ to $F = 0$ Source: Wikimedia Commons, in the public domain

The 21 cm line is associated with the hyper-fine structure transition in neutral hydrogen, the energy released when the spin of the electron jumps from antiparallel to the nuclear spin parallel to the nuclear spin ("spin-flip"), $\sim 5.9 \times 10^{-6}$ eV, which is another way to say 21 cm. The probability for this transition is very small (approximately once every 10 million years per atom), however, the large amount of neutral hydrogen in the Milky Way makes it one of the most prominent features in radio sky.

Exercise: what kind of observable signal does neutral hydrogen produce? Why is it easy to observe? Can you think of other tracers which can be used for similar purposes?

2 Theory basics

2.1 The Sun

Sun is the brightest discrete object in radio Sky, and is observed as a point source with our small telescope. Indeed, difraction-limited angular resolution, or beam width of a telescope in radians is given by $\sim \lambda/D$ where $\lambda \sim 20\,\mathrm{cm}$ is the wavelength of the observed emission (in GHz band), and $D = 2.3\,\mathrm{m}$ is the characteristic size of the antenna. This implies beam width of $\sim 5°$, i.e. by factor of 10 larger than angular diameter of the Sun. One can verify this conclusion directly by pointing the telescope at slightly offset angle with respect to the position of the Sun, and measuring the respective intensity. Alternatively, one can use this approach to locate objects in the Sky. To do that, one can scan the sky by moving the telescope axis around and measuring the intensity. In this way a radio map of the sky can be obtained, which is, in fact, how most of the currently operating radio telescopes work.

In our experiment we will do both using the observations of the Sun (assuming that it is a point source). In particular, the goal of the excercise is to scan over (known) position of the Sun in two perpendicular directions, and measure the observed intensity as function of respective coordinate. The observed intensity will obviously be maximal when pointing directly at the sun and lower as the angle between it and the pointing direction of the telescope increases as illustrated in Fig. 4.2. Considering that the sky and the sun constantly move due to the rotation of the Earth, for this experiment it is convinient to use the equatorial coordinate system, and scan along the right assention and declination by adjusting one coordinate at a time. As a result, two curves similar to that in Fig. 4.2 will be obtained, which can be used to determine the position of the Sun (i.e. its coordinates), and width of the telescope beam. To do that, one needs simply fit the observed lightcurve with a gaussian function (plus some constant to account for astrophysical and instrumental background)

Exercise: Why equatorial coordinate system is preferred for this excercise? How many points would you need to accomplish the excercise (for a single scan)? What

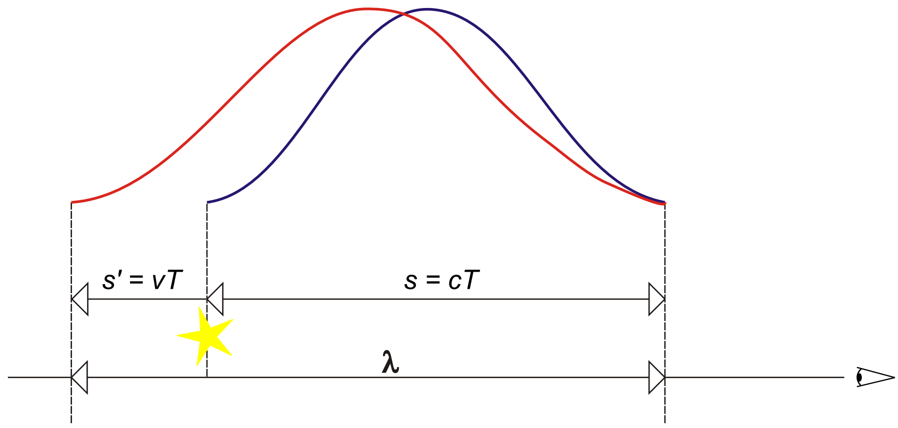

Figure 2.1: Illustration of the Doppler effect. Source: Wikimedia Commons, Bartek444, GFDL / CC-BY-SA-3.0, modified

would be corresponding step size expressed in degrees, and hours, minutes, seconds (for right assention)?.

2.2 The Doppler effect

By observing the 21 cm hydrogen line, we can learn a lot about the movement of gas in our galaxy. In particular, thanks to the Doppler effect, named after the Austrian physicist Christian Johann Doppler (1803-1853), we can directly measure velocity of the gas.

For the derivation we consider Fig. 2.1. The source of the radiation, in this case a star, emits electromagnetic waves with the period T. In the time T the radiation moves with the speed of light c by the distance $s = cT$ to the observer (left in the figure). At the same time, the source moves at speed v relative to the observer by the distance $s' = vT$. Here, $v > 0$ f for a moving object (redshift) and $v < 0$ f for an approaching object (blue shift), so for a complete period, the wavelength will be

$$\lambda = s + s' = cT + vT \quad . \tag{2.1}$$

The wavelength for emission from a stationary source is

$$\lambda_0 = cT \quad . \tag{2.2}$$

The movement of the source thus leads to a change in the wavelength

$$\Delta\lambda = \lambda - \lambda_0 = cT + vT - cT = vT \tag{2.3}$$

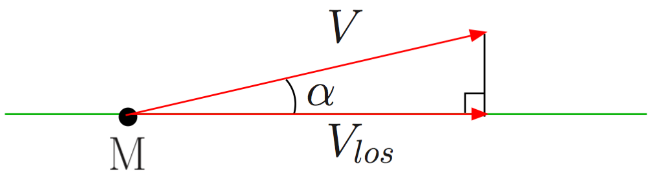

Figure 2.2: The speed of the cloud is projected onto the line of sight.

or relative change

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c} \quad . \tag{2.4}$$

This only applies to $v\ llc$. The result is > 0 for a redshift. Converted into frequencies, the relationship is

$$\frac{\Delta f}{f} = -\frac{v}{c} \quad . \tag{2.5}$$

In this notation, the result is < 0 f for a redshift.

Rotation of the Galactic disc implies that there is always some movement of its components with respect to each other, so frequency of emitted 21 cm line at Earth will deviate from 1420MHz. Measuring this deviation allows us thus to map velocity of the gas clouds and thus the rotation of the Milky way as a whole

Exercise: Derive equation 2.5 from equation 2.4.

2.3 The Milky Way

2.3.1 Geometry for preparation

Imagine, we look with our radio telescope towards a gas cloud somewhere in the galaxy. In Fig.2.2 and 2.3 it can be seen that the actual velocity V of a cloud is at an angle with the line of sight, so we can only measure the projection of the velocity of the cloud onto the line of sight, V_{los}. The observed velocity is usually referred to as the radial velocity V_{r}, i.e. the projection of V minus the velocity of the sun on the line of sight. One obtains from Fig. 2.3

$$V_{\mathrm{r}} = V \cos\alpha - V_0 \sin c \quad . \tag{2.6}$$

In the upper triangle you can see that

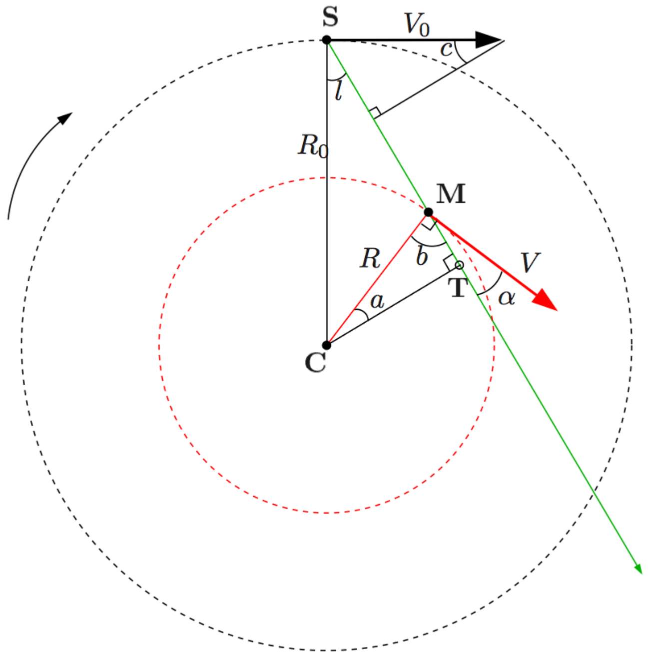

Figure 2.3: Geometry of the Galaxy and definition of angles used in tangent point method.

$$(90 - l) + 90 + c = 180 \Rightarrow c = l \quad . \tag{2.7}$$

The angle α between V and the line of sight can be calculated from the triangle **CMT**, here

$$a + b + 90 = 180 \Rightarrow b = 90 - a \quad . \tag{2.8}$$

The path **CM** forms a right angle with V. If one uses the expression just calculated for the angle b (not to be confused with the galactic height!), One obtains

$$b + \alpha = 90 \Rightarrow \alpha = 90 - b = 90 - (90 - a) = a \Rightarrow \alpha = a \quad . \tag{2.9}$$

Thus, equation 2.6 can be rewritten as

$$V_\mathrm{r} = V \cos\alpha - V_0 \sin l \quad . \tag{2.10}$$

Now α should be replaced by other variables. Looking at the triangles **CST** and **CMT**, we notice that the distance of the galactic centre **C** from the tangent point **T** can be expressed in two ways:

$$CT = R_0 \sin l = R \cos\alpha \quad . \tag{2.11}$$

Substituting $\cos\alpha$ from this expression in equation 2.10 one gets

$$V_r = V\frac{R_0}{R}\sin l - V_0 \sin l \quad . \tag{2.12}$$

2.3.2 How does the gas rotate?

To describe the rotation in a disk, so-called rotation curves are used. They indicate the orbital velocity as a function of the radius, and at this point three different types of rotation curves can be discussed. These are shown in Fig.2.4.

Solid body rotation: This rotation can be applied, for instance to describe rotation of a CD which spins at a constant angular velocity $\Omega = \frac{V}{R} = \text{const}$:

$$V \propto R \quad . \tag{2.13}$$

Keplerian rotation: The most prominent example of this is the solar system, which has a negligible mass compared to the sun. Thus, the center of gravity of the solar system is very close to the centre of the sun. The centrifugal acceleration of the planetary orbits is equal to the gravitational acceleration:

$$\frac{V^2}{R} = \frac{GM}{R^2} \quad , \tag{2.14}$$

where M is the total mass of the system and G is the gravitational constant. The rotation curve is then called Keplerian and the web speeds decrease with increasing radius:

$$V_{\text{Kepler}}(R) = \sqrt{\frac{GM}{R}} \quad . \tag{2.15}$$

Differential rotation: The rotation curve of a galaxy shows the orbital velocity as a function of the galactic radius not described as Keplerian rotation. Unlike a system with a large central mass, most galaxies have more or less uniformly distributed mass, which of course changes the expression for angular velocity given above. In particular, flat rotation curves, $V(R)$ are often observed at larger radii.

$$V_{\text{Galaxie}}(R) = \text{const} \quad . \tag{2.16}$$

The angular velocity then goes with $\Omega\ propto 1/R$. The mass, which is closer to the center, rotates at a higher angular velocity than the mass further out. At large radii the velocities are significantly greater than in the case of Kepler rotation even if all visible mass is taken into the account. As mentioned above, this indicates the

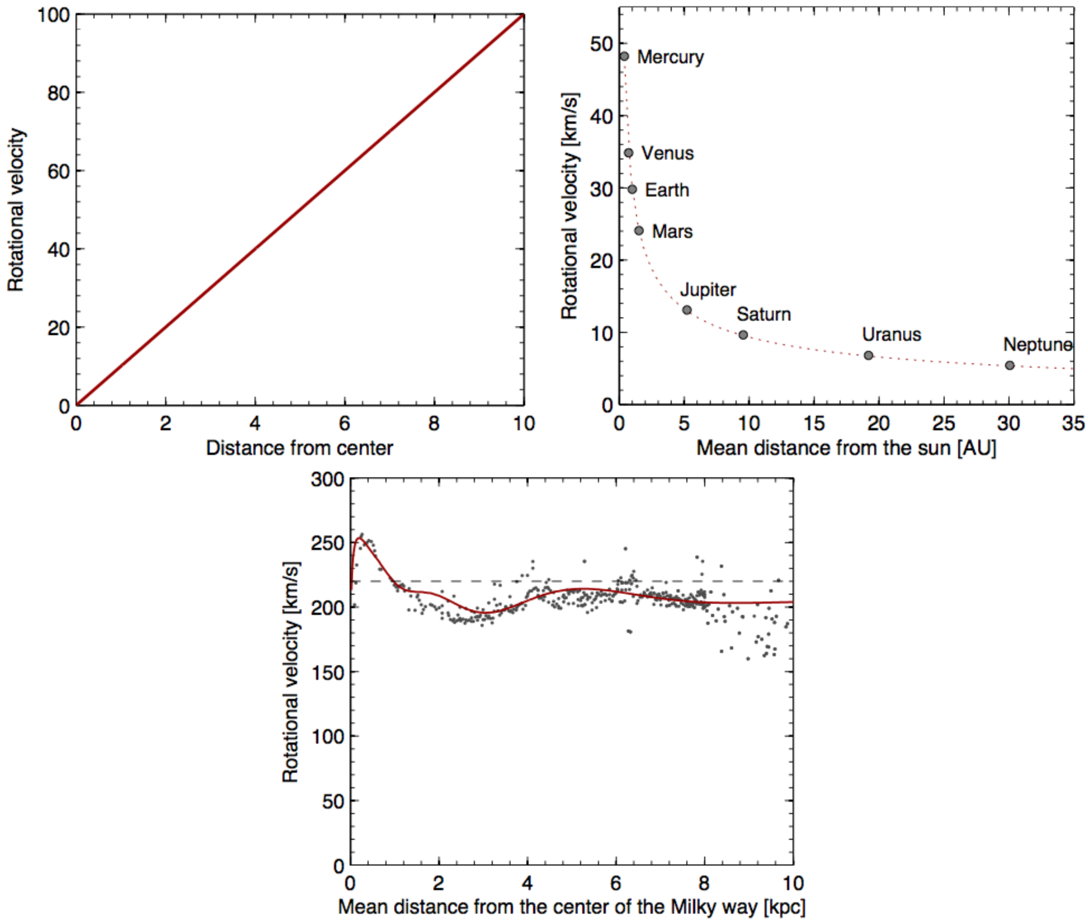

Figure 2.4: Rotational curves of different types of rotation: solid body rotation (top left), Keplerian rotation (top right), and differential rotation (bottom).

existence of additional “dark” matter at large radii, and represents a strong (but not the only) argument in favour of “dark” matter existence.

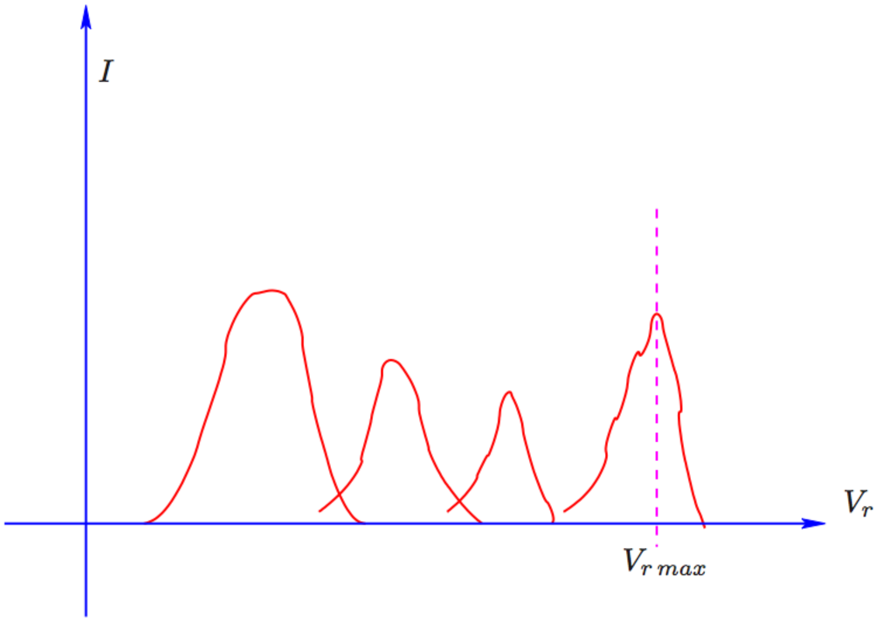

Figure 2.5: Different velocity components in the observed spectrum at a fixed position l.

In this experiment we want to use the gas clouds to determine the rotation curve $V(R)$ in the first quadrant (0 deg $\leq l \leq 90$ deg). Since several gas clouds can lie along arbitrary line of sight, one usually observes several different spectral components, i.e. several doppler-shifted lines corresponding to different velocities as shown in Fig.2.5. For a gas cloud in the *tangent point* **T**, the velocity vector **V** lies exactly on the line of sight, so the projection of its velocity is largest, and the cloud has the maximum observed velocity $V_{r\max}$ relative to us (see 2.3). For **T**

$$R_T = R_0 \sin l \tag{2.17}$$

$$V_T = V_{r,\max} + V_0 \sin l \quad . \tag{2.18}$$

By observing at different galactic longitudes l, several values of $V_{r,\,\max}$ can be measured for respective tangent points. For each point we can then calculate R and V, and thus construct a rotation curve.
To summarise, the sequence can be as follows: We have

- H I is observed at different galactic longitudes l in the first quadrant.
- the maximum velocity component $V_{r,\,\max}$ is measured for every l.

- assumed that the corresponding gas is at the point of tangency.

- assumed we know R_0 and V_0.

From this we can determine the rotational curve $V(R)$ of the Milky Way. **Exercise:** Where (in terms of l) the method is applicable? Why?

2.3.3 Where is the gas?

So far, we've only used the maximum velocity component, assuming it comes from the tangent point. To determine the location of the H I gas in the galaxy, all velocity components of the observed spectrum can be used. Indeed, this can be done once we assume that rotation curve $V(R)$ is known (for example from the previous section). As in the previous section, we measure V_r at different l in the Galaxy and assume that we know R_0 and V_0. Again, equation 2.10 is used. However, on the basis of the measured rotation curve, we can now say that we know that the gas in the Milky Way is differentially rotating, that is, $V(R) \simeq \text{const} = V_0$, so that from equation 2.10

$$V_r = V_0 \sin l \left(\frac{R_0}{R} - 1 \right) \tag{2.19}$$

and R can be expressed as a function of known variables:

$$R = \frac{R_0 V_0 \sin l}{V_0 \sin l + V_r} \quad . \tag{2.20}$$

Now we can make a map of the Milky Way and plot the positions of the gas clouds we have discovered, using the measurements of the radial velocity V_r and Equation 2.20 to estimate the distance of the individual clouds from the galactic center. We also know the direction in which we observed it (the galactic longitude). If now we go back to Fig.2.3, it becomes clear that:

- If we have observed I or IV quadrants, there are two possible positions of a cloud for given values of l and R: Closer than the tangle point **T** (in the figure with **M**) or farther away, at the intersection of the inner circle with the path **ST**.

- If we have observed in quadrant II or III, the position is univocally determinable.

This can also be shown mathematically: If one plots the position **M** of the cloud with respect to the Sun **S** in polar coordinates (r, l) with the distance from the sun r and the galactic longitude l, for the triangle **CSM** we have

$$R^2 = R_0^2 + r^2 - 2R_0 r \cos l \quad . \tag{2.21}$$

This is a quadratic equation for r with two possible solutions, $r = r_+$ and $r = r_-$:

$$r_\pm = \pm\sqrt{R^2 - R_0^2 \sin^2 l} + R_0 \cos l \quad , \tag{2.22}$$

therefore,

- If $\cos l < 0$ (in quadrants II and III), one can show that there is only one positive solution r_+, which is still positive, since $R > R_0$
- In the other two quadrants two positive solutions are possible.

Negative values of r are not physically meaningful. In the case of two positive solutions for given l, we can observe at slightly different b which is likely to make the further situated cloud invisible. Alternatively, the solution can be selected manually on the basis of the overall structure of the Galaxy if it is known at least approximately.

In real life the situation is a bit more complex. Emission from material located at different distances is mixed together, so detailed modelling is required to remap the velocity-longitude to distance longitude space, and thus the map of the Milky Way in Galaxy. In fact, despite extensive observations in radio and other bands, even the number of spiral arms of our Galaxy is still uncertain. Neverthless, the main features shown in Fig. 2.6 have been mapped.

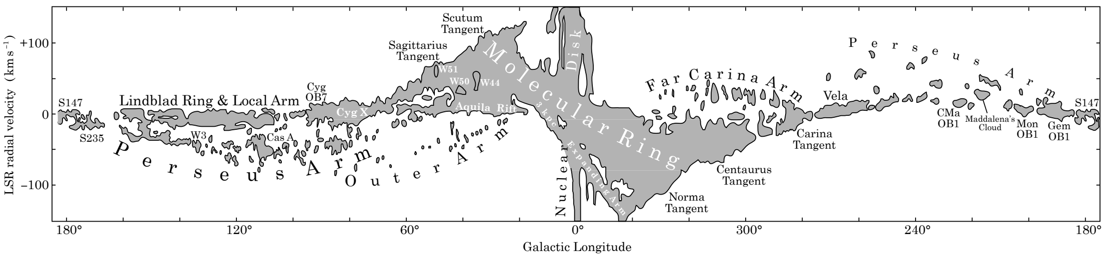

Figure 2.6: Portrait of the Milky Way in $v - l$ space. Structures located at different distances have different velocities, so it is possible to see individual spiral arms shown in Fig. 1.4 directly in such plot (Image credit: COGAL survey).

Exercise: What else (besides the rotation curve) can we say about the Galaxy using the obtained measurements? Explain the steps to do so.

2.3.4 Estimation of the mass of our Galaxy

Assuming that most of the mass of our galaxy is in a spherical structure around its centre (in the so-called dark-matter halo), its mass M within a certain radius R can be calculated. Indeed, the Jeans theorem states that in the case of a symmetric symmetric distribution, the mass outside of R does not affect the velocity at R, so we can ignore contribution of the outer parts. In addition, according to another theorem (also by Jeans), the motion of matter at the radius R, is the same as if mass was concentrated in one central point if mass distribution is spherically symmetric. As we discussed in section 4.3.2:

$$\frac{V^2}{R} = \frac{GM(< R)}{R^2} \quad , \tag{2.23}$$

therefore,

$$M(< R) = \frac{V^2 R}{G} \quad . \tag{2.24}$$

Exercise: Calculate the mass of the Galaxy within the orbit of the Solar system and give it in solar masses and kilograms. Compare the value with a literature value (source!) and explain deviations and assumptions.

3 Observations with the Tübingen Radio Telescope

3.1 The telescope

The Tübingen Radio Telescope (Fig.3.1) was designed by Are Elektronik in Sweden and was funded by the University of Tuebingen throgh student fees and a prize for pedagogical achievments awarded to Dr. T. Nagel in 2009. The telescope has a parabolic antenna with 2.3 m diameter, and stands next to the dome building of the large 80 cm telescope telescope on the Sand. It has an angular resolution of about 5° at the frequency of the 21 cm line of hydrogen (1420 MHz), and is controlled by the program *qradio* from a small Ubuntu PC out, which is located next door in a small telescope dome. The telescope can operate as a bolometer, i.e. measuring the total power of radio signal coming from the sky, or as a spectrometer. In the former case the measured signal can be compared with calibration source, the “noise diode”, situated in the middle of the dish. In the later case, the power is measured quasi-simultaneously at two frequencies corresponding to spectral line of interest (“signal”), and background (“reference”), i.e. part of the spectrum containing no line. In this way, the contribution of the human produced radio waves, emisison of the sky, and continuum emission of the source itself can be significantly supressed, and the line amplified. One can select the appropriate mode from *qradio* interface.

The telescope is equipped with Alt-Az mount, but one can specify desiring pointing position using several coordinate systems, including Galactic and Equatorial coordinates expressed either in degrees or hour minutes and seconds (for right assention). Please see the help of *qradio* for allowed coordinate formats. Be sure to control that correct coordinate system and format are used, as otherwise the telescope will be pointing in wrong direction and measurements will be meaningless! When planning and conducting the experiment please consider that targets low above the horizon are harder to observe as the power of radio interference picked by the antenna increases. Trees and other obstacles also decreas power of the signal and are best avoided. Finally, it is important to keep in mind that the control software is somewhat unstable, so be sure to save your results regularly.

Figure 3.1: The Tuebingen radio telescope

3.2 Preparation

During the experiment we will observe the Sun and the Milky Way along the galactic longitude l with $b = 0$, so in equatorial coordinates it extends according to Table 3.1. Before starting the experiment please try to answer the question: which part of the Milky Way can you actually see during the experiment? Which quadrant? Only this section can be observed with the radio telescope. Which parts of the observable part of the Milky Way would you observe in the morning and which later on? Why?

The Sun is obviously observed for most of the day, however, it makes sence to observe it when it is highest above the horizon. When is that? Please consider also that position of the Sun changes during the year, so you will need to find a way to learn where it is located at the time of observations, i.e. its coordinates. Please use software of your choices to calculate the coordinates of the Sun in advance.

Exercise: What part of the Milky Way is observable on the day of experiment (give range of l)? Use planetarium program of your choice or online planetarium such as `https://in-the-sky.org/skymap.php`.

Table 3.1: Coordinates of the Milky Way

l	RA in °	DEC in °	l	RA in °	DEC in °
0	266.41	-28.94	155	66.81	48.95
10	271.94	-20.29	160	71.74	45.25
15	274.47	-15.90	165	76.06	41.35
20	276.88	-11.49	170	79.87	37.31
25	279.22	-7.05	175	83.30	33.17
30	281.52	-2.61	180	86.40	28.94
35	283.80	1.84	185	89.27	24.64
40	286.10	6.29	190	91.94	20.29
45	288.43	10.72	195	94.47	15.90
50	290.83	15.14	200	96.88	11.49
55	293.33	19.53	205	99.22	7.05
60	295.98	23.89	210	101.52	2.61
65	298.80	28.20	215	103.80	-1.84
70	301.87	32.44	220	106.10	-6.29
75	305.23	36.61	225	108.43	-10.72
80	308.97	40.66	230	110.83	-15.14
85	313.19	44.59	235	113.33	-19.53
90	318.00	48.33	240	115.98	-23.89
95	323.56	51.84	245	118.80	-28.20
100	330.00	55.05	250	121.87	-32.44
105	337.50	57.86	260	128.97	-40.66
110	346.13	60.16	270	138.00	-48.33
115	355.87	61.82	280	150.00	-55.05
120	6.45	62.73	290	166.13	-60.16
125	17.39	62.80	300	186.45	-62.73
130	28.07	62.03	310	208.07	-62.03
135	37.98	60.50	320	226.81	-58.30
140	46.81	58.30	330	241.12	-52.42
145	54.50	55.57	340	251.74	-45.25
146	55.50	56.57	350	259.87	-37.32

3.3 Conducting the observations

Restart the Ubuntu PC first (restart required). Start the program *qradio* on the Ubuntu PC. First, a window with configuration details appears (Fig. 3.2). These are fine (i.e. in line with the figure), go ahead with *accept*. Now you see the actual graphical user interface (GUI) for the telescope control (see Fig.3.3). Here you can set various parameters as required for observation. Click on the tab *Control*:

- in the box *Receiver*:
  - in the box *Mode*: select *switched* for Milky Way or *signal* for Sun observations, be sure not to confuse!
  - in the box *Switching*: select *frequency* (if this mode is used)
  - in the box *Frequency/Gain*: Adjust the gain (db * 10) so that both levels show about 30 % power. The gain should usually be set to about 40-60. This applies also to Sun observations, although only signal amplification will need to be adjusted in this case. For Sun observations be sure to conduct this adjustement when Sun *is not* in the field of view.
- in the box *Telescope* the actual position and the commanded position are displayed. To change a position, first set the desired coordinate system (in our case it is easiest to use galactic or ecliptic), and then enter the desired coordinates in the boxes next to it. The Galactic coordinates must be entered in degrees, whereas for Ecliptic coordinates both degrees and *hms* format (as provided, for isntance, by Kstars) are accepted. Be sure to provide coordinates in correct format and verify that the telescope points in correct direction (i.e. to the Sun when current Sun coordinates are entered). **Keep in mind that coordinate system selection resets upon restart so you need to set it to correct value again!**
- If you now click on *Track*, the telescope will move to the required position, the target coordinates will be displayed in *commanded* field. To stop the telescope, click on *Stop*. Has the telescope reached its target position, the values in the *commanded* and *actual* fields should match. Remember that these are indicated in Altitude/Azimuth coordinate system, regardless on which coordinate system was used to specify desired position. After the telescope reached commanded position wait a bit before it fully settles and begins tracking.
- To record a spectrum (that is to perform a measurement), first set the integration time (below right), 10-20 s should be sufficient. Then start

the integration by pressing *Observe* button. In the left column a file name appears (eg B.00001c.fits) once the integration is finished. At this point the interface screen blinks and the number of recorded spectra in the left panel increases. Be sure not to click stop before this happens as otherwise result may not be recorded. To inspect the result, click on the file name, the display changes from *Control* to *Spectrum* (Fig. 3.4). You can choose if the x axis represents frequency or velocity (assuming zero velocity corresponds to the observing frequency). You can also restrict the displayed value range. Note that spectrum will not be displayed for Sun observations as you only measure intensity!

- To start a new recording, switch back to *Control* again. Click *Stop* to stop tracking, and then enter new coordinates. Drive the telescope to new position with *Track*, and once the pointing is settled you can record a new spectrum.

- For Sun observations start with entering current position of the object, and verify that the telescope indeed points in the correct direction. If the weather allows, you can check the accuracy of the pointing visually by pointing to the Sun itself and checking whether the secondary mirror shadow is centered on the main dish. After that, you have two options on how to proceed with the experiment:

  – conduct scans in $\pm 10°$ interval along DEC with RA fixed to known Sun position. Please repeat measurement at least twice for each angle, starting from -10 and going to 10 degree offset, and then back. This is to get an idea of true uncertainty of measured intensities and flux variability. Take continuum spectrum at each location and store for further analysis. Once done, fix DEC to known Sun position and alter RA to scan along this direction. If you enter coordinates in hms format, be sure to use correct step size. Keep in mind that 24h correspond to 360°. Alternatively, you can just convert Sun position to degrees.

  – alternatively, you can do a raster scan with $10° \times 10° \times$ to $20° \times 20° \times$ size of the region around the Sun (scan along one coordinate, then make a small step in other and repeat the scan, and so on). That is, to make a proper image of this region. Here you can balance the size of the region, resolution, and time it takes to complete the imaging. Of course, this implies that more measurements have to be taken than in the first option, but reward is that you can really see the Sun in your picture! To speed things a bit, you can avoid taking spectra and just read out intensity values from user interface for each pixel. That's slightly less accurate, but faster to measure and does not require extra analysis steps afterwards, so including analysis both options are actually comparable.

- For Milky way observations, start the observations with part of the sky which is closest to setting at the start of experiment (i.e. with altitude of $\sim 15°$ in the west), and continue along the Galactic plane in eastern direction. As you traverse the observable part of the Milky Way, note the galactic coordinates and corresponding file name for each exposure (obviously b is kept fixed to 0). Alternatively you can re-name the file after each exposure so that coordinates can be read directly from file name. Save each shot immediately as a precautionary measure, *qradio* tends to crash spontaneously, so any unsaved exposures will be lost.

- It may also be a good idea to take a "background" spectrum to aid identification of the spectral lines coming from the gas concentrated in the Galactic plane. In order to do so, you must point the telescope at $|b| > 10°$ for a given l in addition to the main exposure taken at $b = 0$. The lines only appearing in the later but not in the former spectrum, are what you are looking for. You are done with the measurements please stop tracking and park the telescope by clicking *Reset*. Wait until the telescope reaches parking position before quitting *qradio* and switching off power of the telescope.

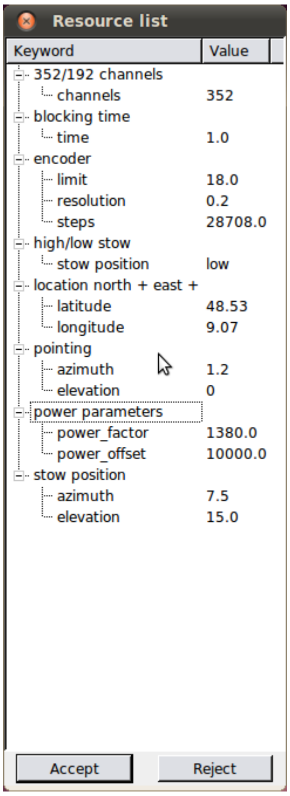

Figure 3.2: Configuration window for *qradio*. Adjust to match the figure if there are any discrepancies

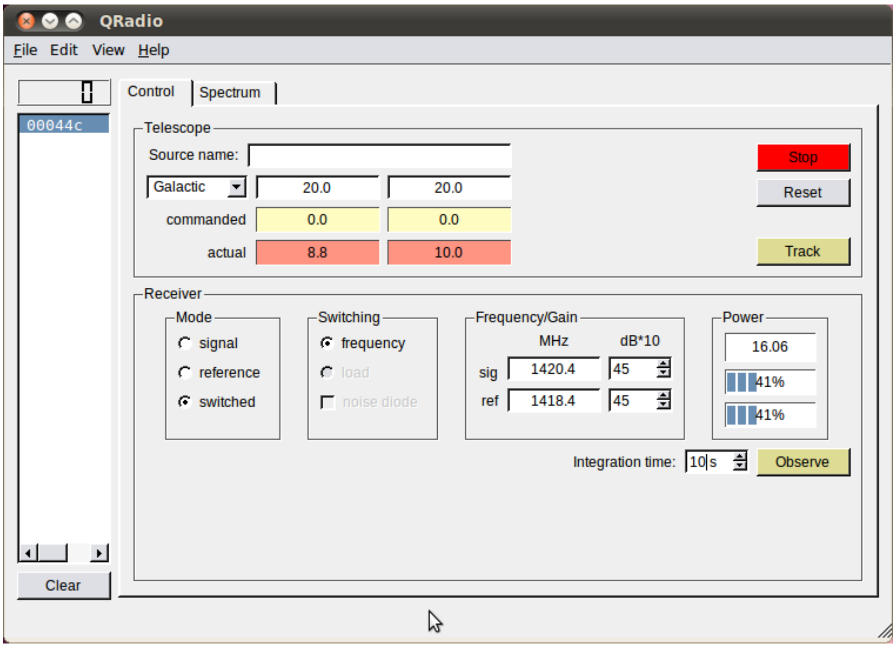

Figure 3.3: User interface of the *qradio* control software.

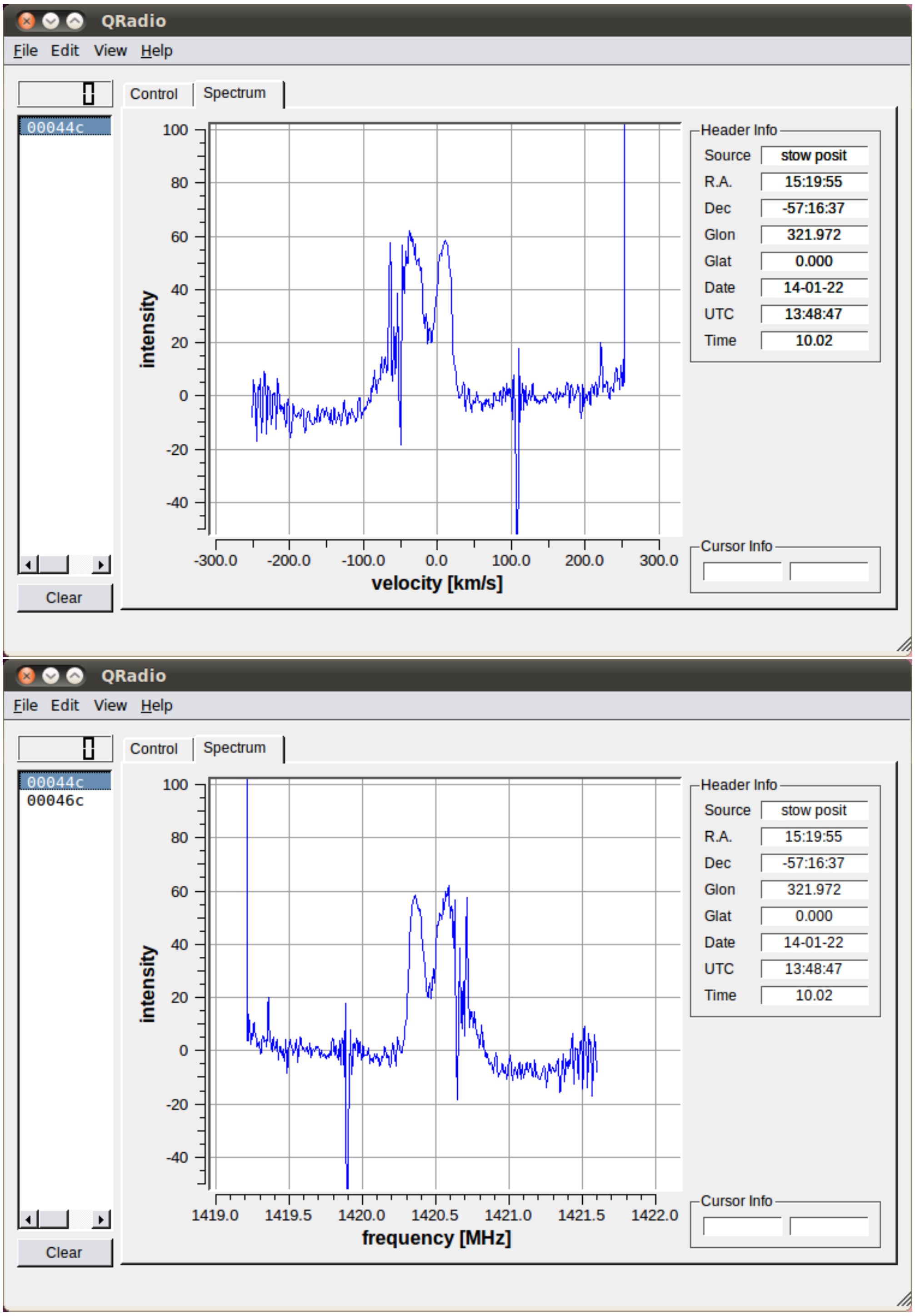

Figure 3.4: Presentation of the observed spectrum in *qradio*, in frequency and velocity spaces

4 Data analysis

4.1 Software

The recorded data can be analysed with various computer programs, including *SalsaJ*, a software of the Hand-on Universe Europe project, which is available on the EU-HOU website for all operating systems, and simply by can be downloaded there. *SalsaJ* is also installed on the computers in the Astro library where you are suggested to conduct the evaluation of your results. If you have a laptop, bring it with you, preferable with *SalsaJ* installed already. This will make it easier to finish evaluation at home if you run out of time. The operation of *SalsaJ* is not complicated, however you need to use “open Radio spectrum” rather than simply “open” to ensure that the velocity information is read correctly. In addition, you will need to use a spreadsheet program (i.e. Excel or alternative) to perform calculations and make plots. Alternatively, you can use software/programming language of your choice, but in all cases please hand over your code/spreadsheet together with the protocol, so the calculations are reproducible by the tutor.

4.2 Data reduction and measurement

1. Inspect the data.
SalsaJ can be used for this. Attempt to display the spectrum, so read the appropriate FITS file as a spectrum and display it in the program window. Set the speed as the unit for the x-axis. Now you should see a spectrum. Some (if not all) of your spectra will show a relatively sharp peaks, which is not the signal from the Milky Way but rather terrestrial interference, and can be ignored.

2. Measure the intensities.
For observations of the Sun we are only interested in the observed intensity, not the spectrum shape. You will notice, however, that the observed spectra are not flat (as expected), but rather exhibits low and high frequency roll overs. These are associated with the response of the instrument, and not the sun itself! Furthermore,

radiointerference (RFI) peaks may be observed. A representative spectrum is shown in Fig. 4.1. To estimate the intensity, pick a region in the middle of the spectrum which is free from RFI, and read out several representative values from this band with *SalsaJ*. Use the same channel/velocity range for all spectra! For each solar spectrum note the average of measured intensity values and RA/DEC coordinates of the pointing expressed in units of degrees. To convert from *hms* units to degrees you may note that Earth completes one full roation (360 degrees) in 24 hours.

3. Measure the velocities.
Same procedure can be used to read spectra of the Mikly Way. Here we are interested, however, in velocities of observed spectral lines. An example of such spectrum in *qradio* interface was shown above and is shown in Fig. 4.1 as it appears in *SalsaJ*. Note that several velocity components may be present each spectrum. If that is the case, please read all of them one by one by moving the cursor to middle points of respective peaks in the spectrum. It's best to put these directly into a table with the galactic length of each observation in the first column and the measured velocity in the second column to keep track of the measurements. Ignore the sharp peaks mentioned above. If in doubt, compare the spectrum with the "background" spectrum you took away from the Galactic plane which shall contain similar features. Examine each spectrum and use the cursor to read the velocities, zoom if more accurate values are required. Please consider that realistic accuracy of your measurements is quite low, so it is sufficient to round measured values to integrer number of kilometers/s.

If a spectrum has several velocity components, each must be measured and assigned to the same galactic length, for example:

l	v in km/s
50	48
50	12
50	25
70	-90
70	-22
70	2

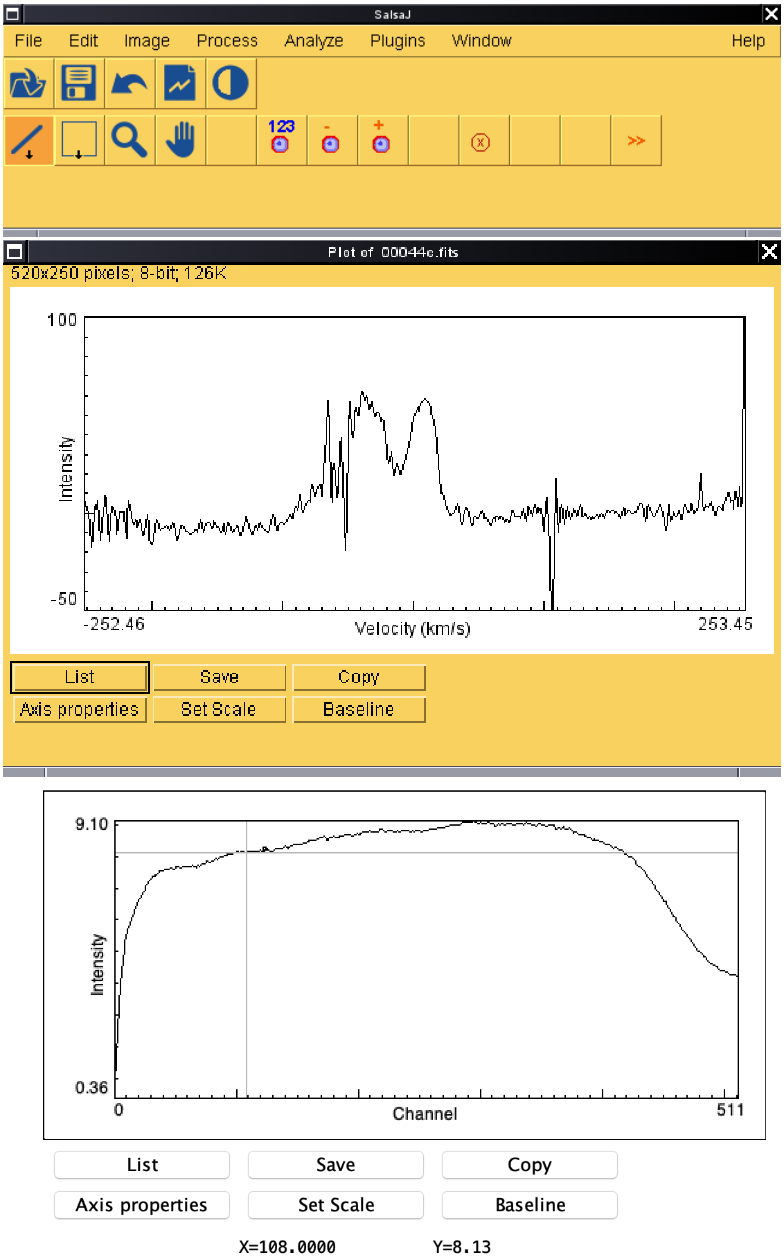

Figure 4.1: User interface of the *SalsaJ* program showing examples of spectra measured from the Milky Way and the Sun.

4.3 Data analysis

4.3.1 Position of the Sun and angular resolution of the telescope

For scans along RA/DEC directions plot two curves similar to Fig. 4.2. In each curve you shall be able to see increase of intensity corresponding to position of the sun. To estimate the respective coordinates, you may fit the peak with a Gaussian function combined with a constant to account for background using software of your choice. Please give some details on the procedure you use in the report. The center location and width of the gaussian will give you respective coordinates and width of the beam, i.e. angular resolution of the telescope.

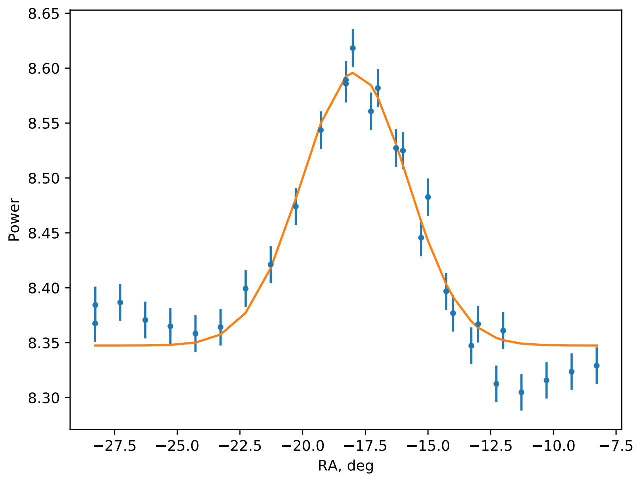

Figure 4.2: Observed intensity from the direction of the Sun as function of declination (in equatorial coordinate system). The location of the peak gives the position of the Sun, and its width corresponds to the telescopes angular resolution.

Alternatively, you may estimate both quantities by eye. Keep in mind that the width of the peak must be at measured at half of its peak value. To do that, you need, however, to subtract background intensity first. Estimate it by eye, and subtract from the observed intensities so that only source emission remains. Plot it and estimate center position and width at half maximum by eye. In any case, please indicate estimated or best-fit values in the plot. Compare results with known position of the sun at the time of observation, and with theoretical estimate of the telescope resolution. The report shall thus include plots for both scans similar to Fig. 4.2, estimated sun position, and offset from the true position.

4.3.2 Rotation curve

Now we want to construct a rotation curve from the individual data points. In chapter 2 it was shown that for gas observed at the tangential point, the distance from the centre of the Milky Way can be univocally determined. Likewise, the speed of the corresponding cloud can be calculated. In this section, only the highest velocity from each spectrum is of interest, since this corresponds to the gas cloud at the tangential point. Keep in mind that the tangential point method only is applicable for certain part of the Milky Way (which?). To create the rotation curve using the OpenOffice Spreadsheet software, follow the steps below:

- Create one column each for l and $V_{r,\max}$ and enter the corresponding values.
- Since we need V_0 and R_0, it is useful to define them as constants by putting the value of the constant (in kpc km/s) in any field. Then go to *Insert* ⇒ *Names* ⇒ *Define*. In the box that opens, the name (ie `R0` or `V0`) can be entered. Click in the box below and then on the cell in the spreadsheet with the appropriate value. The field now contains the name of the cell. Click *Add* and repeat with the second constant. Now the values can be used directly via their names in formulas.
- Now let's use the equations 2.17 and 2.18 to calculate R and V. Add a new column by typing the formula in the top box:

  `= R0 * SIN (X1 * PI () / 180)`. Here we convert degrees to Radian. X1 must be the name of the topmost cell of the l column. Complete the calculation for all rows by clicking on the top cell and dragging down the bottom left corner. Now we have calculated all values of R at the tangent point for each l.[1ex]
- In the next column V should be calculated, something like this:
  `=X2+V0*SIN(X1*PI()/180)`

  (see equation 2.18). Again, this column must be completed for all values of l.

We would like now to plot the results:

- Mark the entire third and fourth column (i.e. containing the variables you'd like to plot). Go to *Insert* ⇒ *Chart*, and select $xy - chart$ (*Scatter*), then click *create* and the graph will be generated. You should see a nearly constant rotation curve.
- By right-clicking on the diagram, the axes can now be labeled.

- save the diagram as a pdf-file: select it and go to *File* $\Rightarrow$ *Export as PDF* $\Rightarrow$ *Range: Selection* $\Rightarrow$ *Export*.

4.3.3 Map of the Milky Way

To construct a map of the Milky Way, we need all the measured speeds. Here we proceed as described in section 2.3.3.

- Go to the table where you stored all measured velocities for all Galactic longitudes.
- Calculate the distance from the centre of the galaxy R to equation 2.20 (Caution: The result from section 4.3.2 cannot be reused!). Use the functions `SIN ()` and `PI ()`.
- Calculate r, i.e. distance from a molecular cloud to the Sun using equation 2.22. As discussed above, you can have two solutions here $r_{\pm}$, it's easiest to store them in two separate columns. The following functions can be used.
  - `POWER(<cell>,Exponent)`
  - `SIN()`
  - `COS()`
  - `PI()`
  - `SQRT()`

  As already mentioned in section 2.3.3, there may be two positive solutions (in the first and fourth quadrants). A follow-up observation in the course of this experiment is not possible for reasons of time, so consider using both data points, and once the map is ready you should try to exclude one of the solutions (please provide justification in the protocol!). In case of two negative values for $r_{\ pm}$ the data point can be ignored ,
- The next step is to calculate the xy coordinates of the data points to produce the map. The following relationship should be known:

$$x = r\cos\theta \tag{4.1}$$

$$y = r\sin\theta \tag{4.2}$$

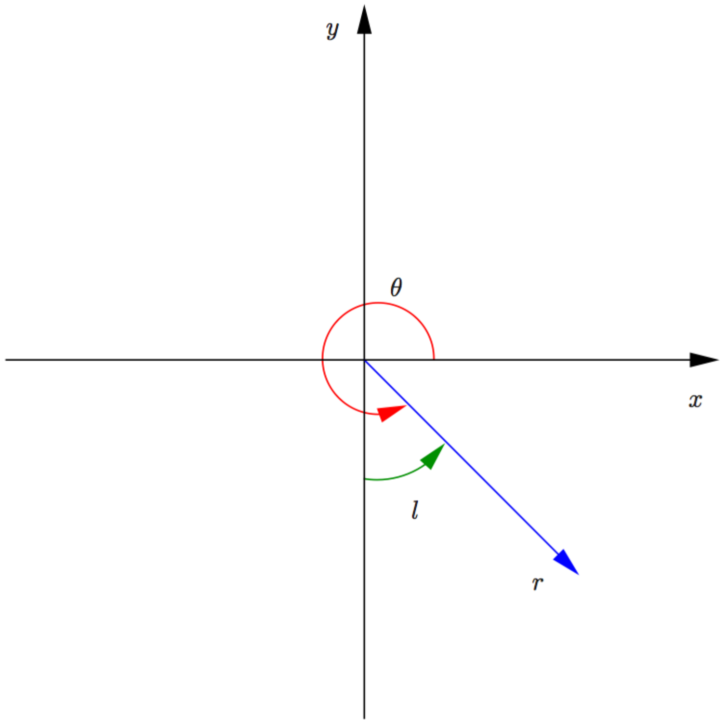

Figure 4.3: Galactic coordinates are polar coordinates, so can be converted to cartesian coordinates as usual. The important point is that the origin of the coordinate system is at the position of the Sun, and $l = 0$,$b = 0$ correspond to Galactic centre.

To use these for coordinate conversion, take a look at 4.3. It shall be clear then that $\theta = 270° + l$ bzw. $\theta = l - 90°$. With the help of the equations 4.1 and 4.2 the coordinates can now be computed, adding R_0 to the y-coordinate if the origin $(0, 0)$ should be in the galactic centre.

- Finally, the calculated coordinates can be displayed in a plot (see previous section on how to produce one). You shall be able to see the spiral structure of the Galaxy now. Please compare you're results with those pictured in Fig. 2.6. It makes sense to illustrate the position of the Sun and the Milky Way radius (source!).

4.4 Questions

Exercise: What kind of radiation is emitted by the galactic center in the form of radio waves and what is its origin? What's the origin of radio emission from the Sun?

Exercise: Calculate the expected angular resolution of 2.3 m radio telescope operating at GHz frequencies and compare it with the angular size of the Sun. Is the assumption mentioned above justified?

Exercise: Why do the two coordinates l and b suffice to describe the (three-dimensional) Milky Way? Is it always the case?

Exercise: what kind of observable signal does neutral hydrogen produce? Why is it easy to observe? Can you think of other tracers which can be used for similar purposes?

Exercise: Why equatorial coordinate system is preferred for this excercise? How many points would you need to accomplish the excercise (for a single scan)? What would be corresponding step size expressed in degrees, and hours, minutes, seconds (for right assention)?.

Exercise: Derive equation 2.5 from equation 2.4.

Exercise: Where (in terms of l) the tangent point method is applicable? Why?

Exercise: What else (besides the rotation curve) can we say about the Galaxy using the obtained measurements? Explain the steps to do so.

Exercise: Calculate the mass of the Galaxy within the orbit of the Solar system and give it in solar masses and kilograms. Compare the value with a literature value (source!) and explain deviations and assumptions.

Exercise: What part of the Milky Way is observable on the day of experiment (give range of l)? Use planetarium program of your choice or online planetarium such as `https://in-the-sky.org/skymap.php`.

Links

- Website of Tuebingen radiotelescope: http://www.physik.uni-tuebingen.de/institute/astronomie-astrophysik/institut/astronomie/80cm-teleskop/radioteleskop.html
- Website of F-Praktikums http://www.physik.uni-tuebingen.de/institute/astronomie-astrophysik/institut/astronomie/studium/f-praktikum.html
- Official web-site of the european project (EU-HOU) Hand-On Universe: http://www.euhou.net/
- Web-site of SALSA radio telescope: http://brage.oso.chalmers.se/salsa/
- Official OpenOffice Website: http://www.openoffice.org/

Literature

- *The incorrect rotation curve of the Milky Way*: L. Chemin, F. Renaud, C. Soubiran: `https://arxiv.org/abs/1504.01507`
- *The new cosmos*, A. Uns"old, B. Baschek, 7. Edition
- Chapter 5.2 *Radio telescopes*
- Chapter 10.2 *Neutral interstellar medium*, Focus on 21 cm line
- Chapter 11 *Origin and dynamics of the Milky Way*
- *Fundamental Astronomy*, H. Karttunen, themes from the list above
- other introductionary books covering the themes above