Important Instructions

1. Download the DDM Event Files linked in the email (will be sent at 9:45 AM), and extract it in a particular folder.
2. Press `ctrl + alt + T` to open the terminal run the following commands one by one:

    - `pip install numpy scipy pandas matplotlib --upgrade`
    - `pip install scienceplots`

3. Be seated with a notebook and a pen. Hope you will have fun ! We will begin at 10:00 AM sharp .

13 800 000 000
years ago

12 799 999 999

12 799 999 998


ONE MILLION, ZILLION, JILLION, DILLION, COTILLION TIMES LATER...

4

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-1

Oops 😐

DETECTING DARK MATTER

DETECTING DARK MATTER

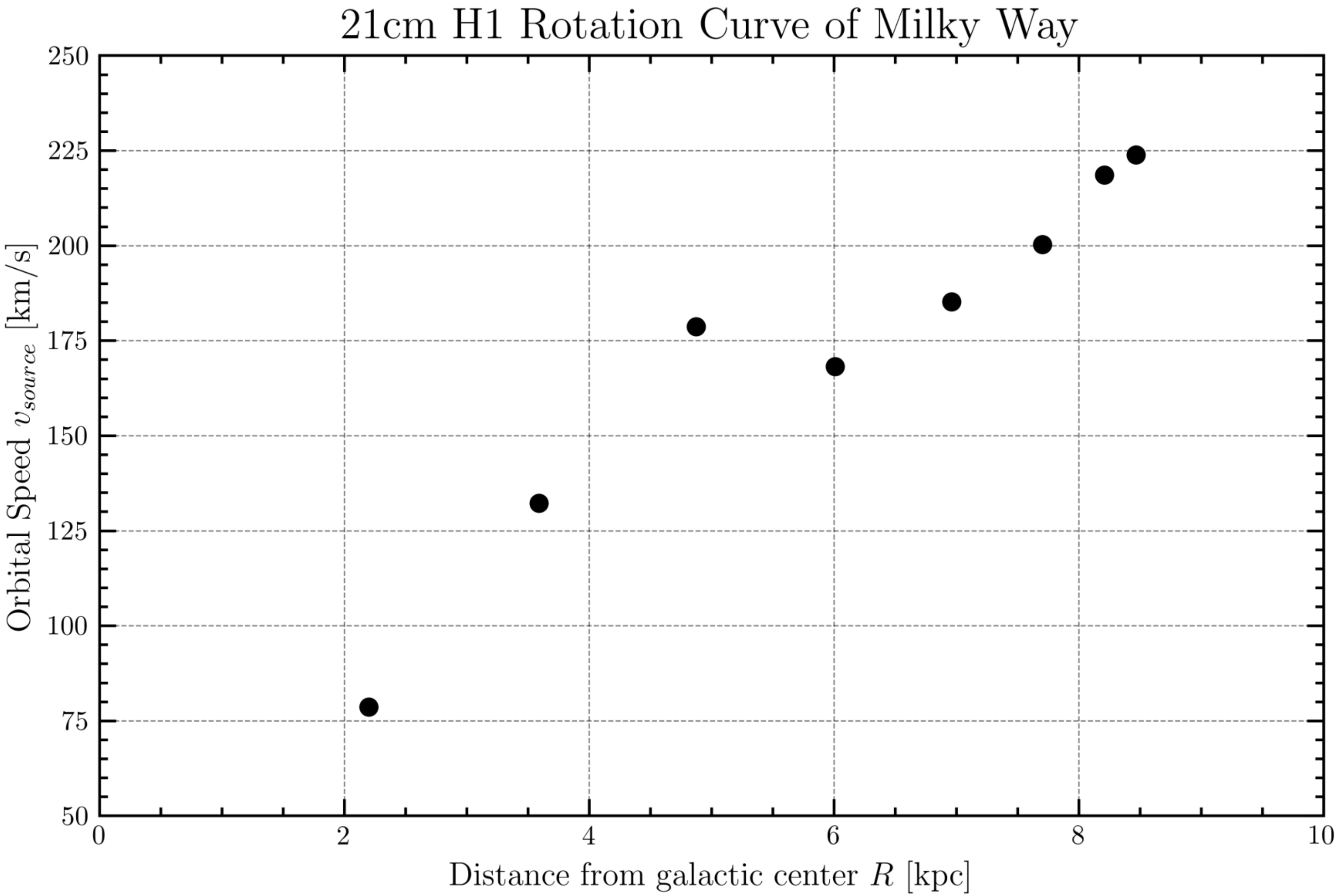
!

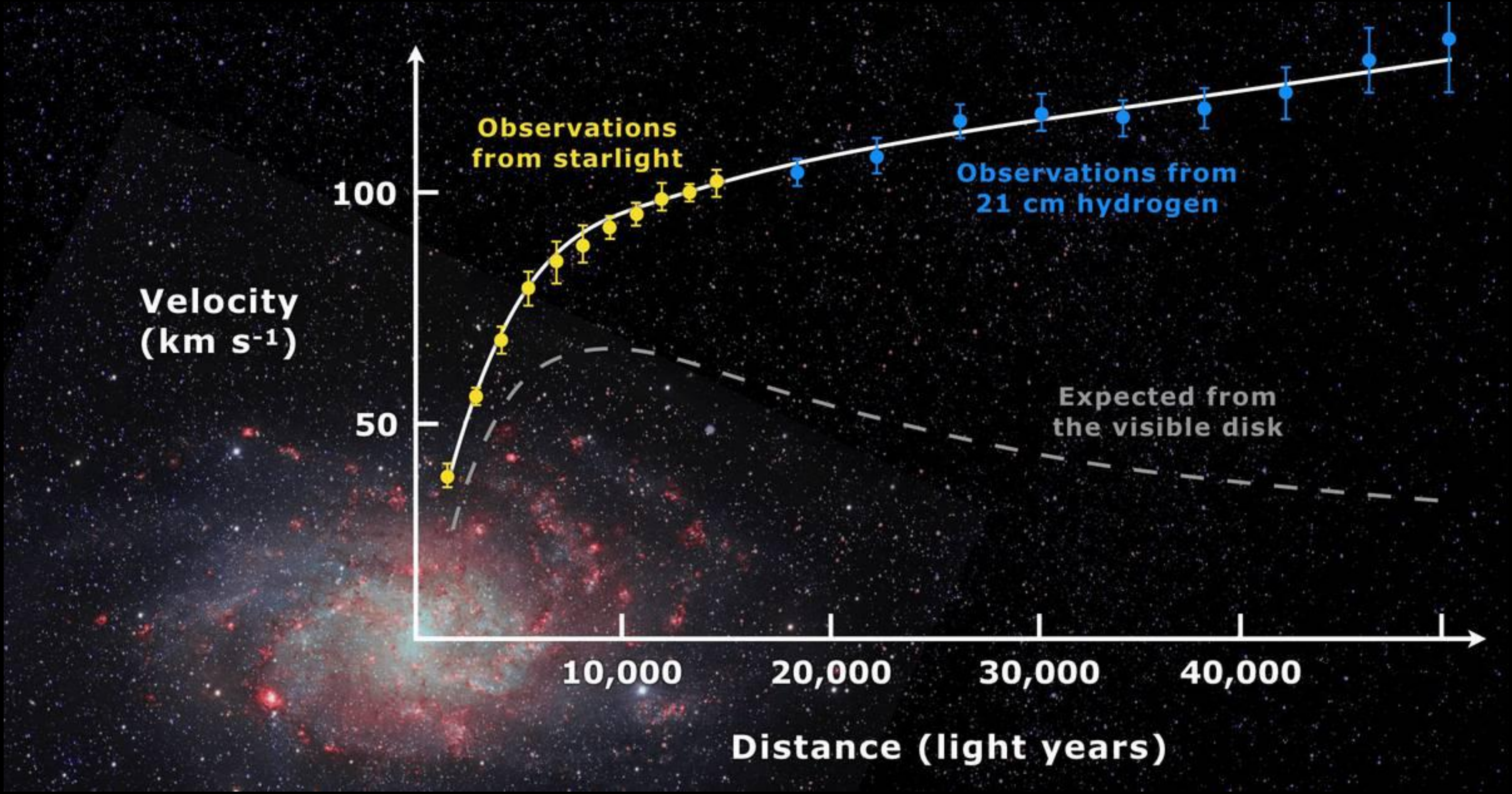
DETECTING DARK MATTER

!

Host: Susnata Chattopadhyay (22MS)
Date: Mar 22, 2025
Time: 10:00 AM – 1:00 PM
Venue: CC1, AAC 1st Floor

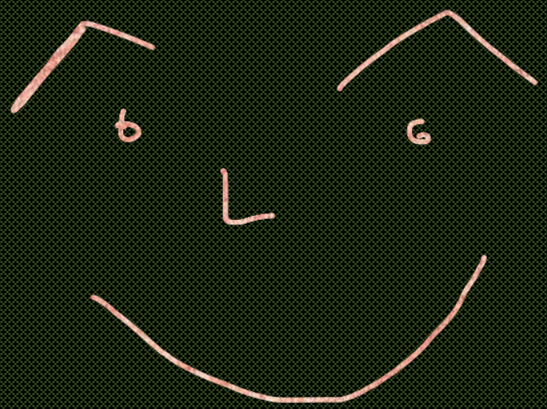
TARGET


21cm H1 Rotation Curve of Milky Way
250
225
200
175
150
125
100
75
50
0
2
4
6
8
10
Orbital Speed v_{source} [km/s]
Distance from galactic center R [kpc]


Observations
from starlight
Observations from
21 cm hydrogen
100
50
Velocity
(km s-1)
Expected from
the visible disk
10,000
20,000
30,000
40,000
Distance (light years)

OUTLINE

- Who?
- What ?
- Where ?
- How?
- Errors ?
- Conclusion
- Assignment !



NOTE: I am not a radio astronomy / dark matter expert !

Vera Rubin

Pioneering Observations: Vera Rubin's meticulous observations of galactic rotation curves revealed that stars at the outer edges of galaxies were moving at speeds that couldn't be explained by the visible matter alone. This discrepancy provided compelling evidence for the existence of unseen "dark matter."

Overcoming Barriers: Despite facing significant gender discrimination in the field of astronomy, Rubin persevered, becoming a highly influential figure. Her work at the Carnegie Institution of Washington, in collaboration with Kent Ford, was crucial to her groundbreaking discoveries.

Legacy and Impact: Rubin's work revolutionized our understanding of the universe, establishing dark matter as a fundamental component. Her legacy extends beyond her scientific contributions, as she also served as a strong advocate for women in science. Her name is now honored by the Vera C. Rubin Observatory, highlighting the lasting impact of her research.

The Rotation of Spiral Galaxies
Vera C. Rubin

Science, **220** (4604), .
DOI: 10.1126/science.220.4604.1339

The Rotation of Spiral Galaxies

Vera C. Rubin

Historians of astronomy may some day call the mid-20th century the era of galaxies. During those years, astronomers made significant progress in understanding the structure, formation, and evolution of galaxies. In this article, I will discuss a few selected early steps in determining the internal dynamics of galaxies, as well as current research concerning the rotation and mass distribution within galaxies. These studies con-

um, Scheiner correctly concluded that the nucleus of M31 was a stellar system composed of stars like the sun, rather than a gaseous object.

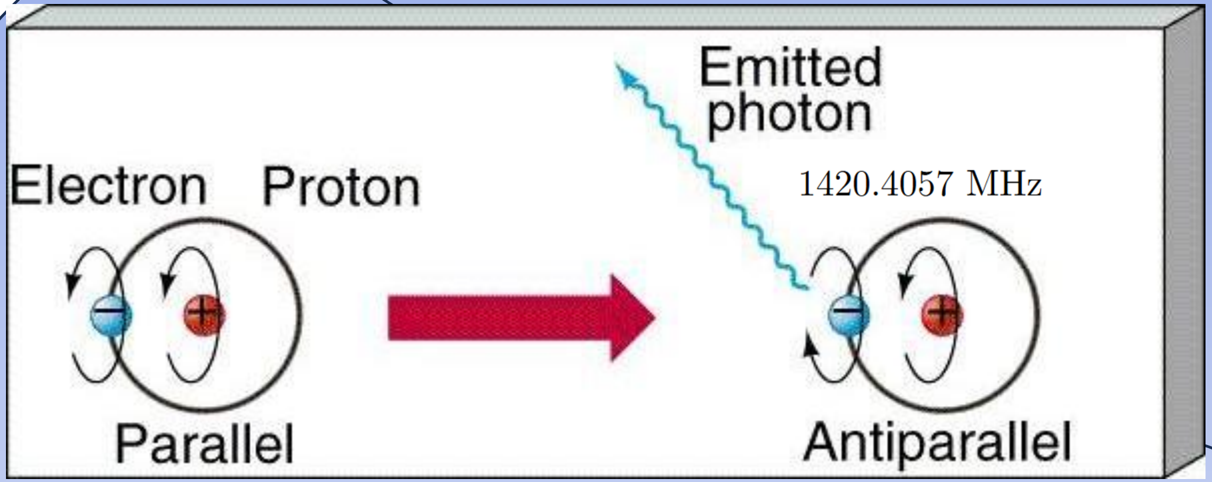
Even earlier, Lord and Lady Huggins (*4*) had attempted at their private observatory to obtain a spectrum of M31, but their labors were fraught with disaster. Exposure times were so long that each fall when M31 was overhead they would expose consecutively on one plate dur-

the galaxy carries the stars toward the observer, spectral lines are shifted toward the blue region of the spectrum with respect to the central velocity. On the opposite side, where rotation carries the stars away from the observer, lines are shifted toward the red spectral region.

Several years later, Pease (*8*) convincingly illustrated that rotation *was* responsible for the inclined lines. Using the 60-inch telescope on Mount Wilson during the months of August, September, and October 1917, he patiently acquired a 79-hour exposure of the spectrum of the nuclear region of M31 with the slit aligned along the apparent major axis of the galaxy. Inclined lines appeared. A second exposure made during these 3 months in 1918, with the slit placed perpendicular to the major axis along the apparent minor axis, showed no inclination of the lines. Along the minor axis, stars move at right angles to the line-of-

The 21.11 cm Signal

Origins



High Energy

Low Energy

Neutral Hydrogen (HI or H1)

In the absence of $\vec{B}$, these 2 states are degenerate. But when $\vec{B} \neq 0$, the interaction between the magnetic moments of p^+ , e^- gives a slightly different magnetic energy for each state → **Hyperfine Splitting.** For more info visit **PH3102**

Horn Antenna

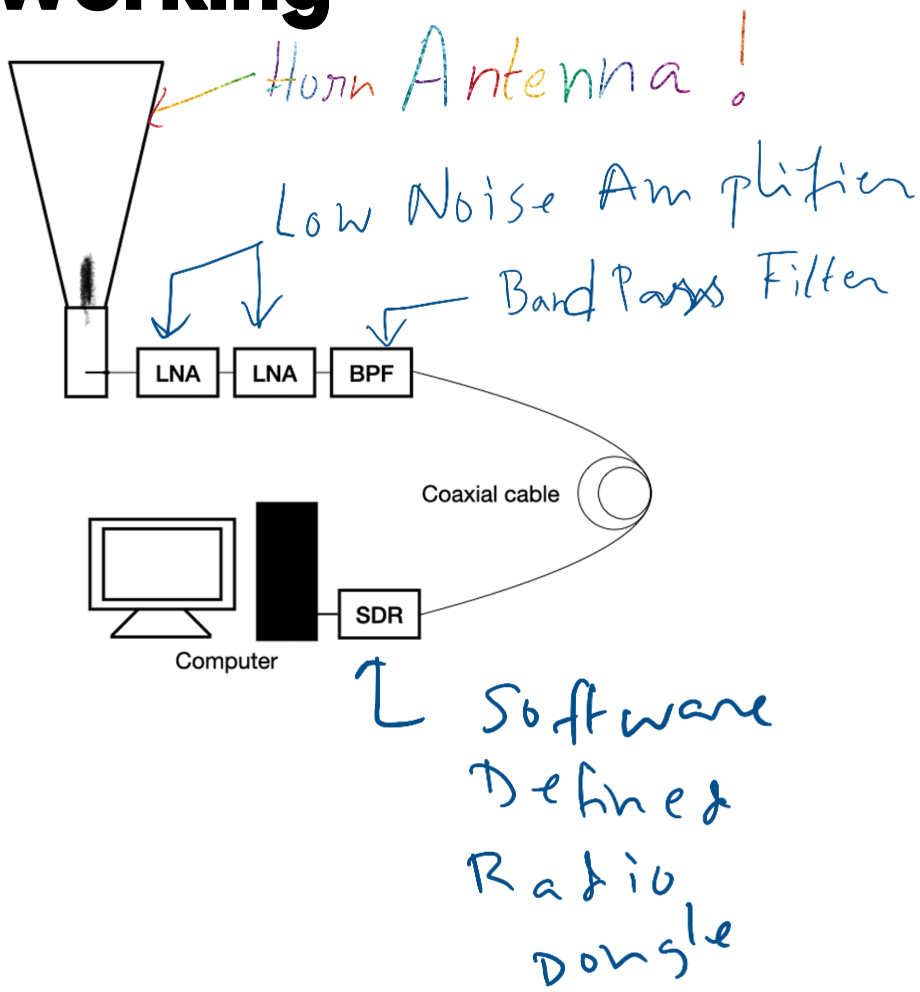
- FOV = 16°
- Integration Time = 64 s
- Bandwidth = 2.048 MHz

(1419.38 – 1421.43) MHz

- Bin Size = 4000 Hz
- Output is in **Linear scale.** (that is units proportional to W)

Note : Units of dB or dBm means **logarithmic scale**

Working



How does the data look like?

	A	B	C	D	E	F
1	Frequency (MHz)	Power (arbitrary units)	Date and Time	Bin Size Info		
2	1419.381751	46.15928695	19/12/2024 16:53	Bin Size: 4000.0 Hz		
3	1419.385759	45.59038685	19/12/2024 16:53	Bin Size: 4000.0 Hz		
4	1419.389767	47.00820126	19/12/2024 16:53	Bin Size: 4000.0 Hz		
5	1419.393774	46.64340074	19/12/2024 16:53	Bin Size: 4000.0 Hz		
6	1419.397782	44.02922605	19/12/2024 16:53	Bin Size: 4000.0 Hz		
7	1419.40179	43.5185097	19/12/2024 16:53	Bin Size: 4000.0 Hz		
8	1419.405798	43.00811131	19/12/2024 16:53	Bin Size: 4000.0 Hz		
9	1419.409806	42.77788639	19/12/2024 16:53	Bin Size: 4000.0 Hz		
10	1419.413814	42.58587691	19/12/2024 16:53	Bin Size: 4000.0 Hz		
11	1419.417821	42.159006	19/12/2024 16:53	Bin Size: 4000.0 Hz		
12	1419.421829	41.95292012	19/12/2024 16:53	Bin Size: 4000.0 Hz		
13	1419.425837	41.81141983	19/12/2024 16:53	Bin Size: 4000.0 Hz		
14	1419.429845	41.80387134	19/12/2024 16:53	Bin Size: 4000.0 Hz		

File: 25.csv

PROOF: This data is not AI Generated !
100% Authentic

Theory

TARGET :

1. To find the circular orbital speed of the source (v_{source} $[km/s]$)
2. Radial distance of the source from galactic center (R $[kpc]$)

DATA:

1. Readings across 8 different galactic longitudes in the galactic disk.

$$l = [15,25,35,45,55,65,85] \text{ deg}$$

2. Calibration Readings : Sky, Ground.

In Hand -

- Frequency
- Power (Linear scale)

?

To get -

- Velocity
- Distance

Brightness Temperature (T_b)

Naively, it is the temperature at which a **black body** would have to be- in order to duplicate the observed intensity of an object at a frequency ν .
It is used to quantify the temperature of a **non thermal source** (for ex: synchrotron radiation, pulsars, electron spin temperature, etc.) and it is very different from physical / thermometer (kinetic) temperature!

For a black body, Planck's Law gives,

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_BT}} - 1}$$

where I_ν is called the **spectral brightness** and it is a quantity which is proportional to the power (luminosity).
For radio wavelength $h\nu << k_BT$,

HW1

$$I_\nu = \frac{2\nu^2 k_B}{c^2}T \implies I_\nu \propto T$$

Now, let us say the measured brightness of the region (where the antenna points) in a particular frequency band $\nu + \mathrm{d}\nu$ is B_ν.
We define **brightness temperature** T_b as

$$B_\nu \equiv \frac{2\nu^2 k_B}{c^2}T_b \implies P = GT_b$$

The surface containing $d\sigma$ can be any surface, real or imaginary; that is, it could be the physical surface of the detector, the source, or an imaginary surface anywhere along the ray. If energy dE from within the solid angle $d\Omega$ flows through the projected area $\cos\theta\, d\sigma$ in time dt and in a narrow frequency band of width $d\nu$, then

$$dE = I_\nu \cos\theta\, d\sigma\, d\Omega\, dt\, d\nu. \tag{2.1}$$

Power is defined as the flow of energy per unit time, so the corresponding power dP is

$$\underset{(\mathrm{watts})}{dP = \frac{dE}{dt}} = I_\nu \underset{(\mathrm{m}^2 \ \ \mathrm{sr} \ \ \mathrm{Hz})}{(\cos\theta\, d\sigma\, d\Omega\, d\nu)}\,.$$

Thus the quantitative definition of **specific intensity** or **spectral brightness** is

$$\boxed{I_\nu \equiv \frac{dP}{(\cos\theta\, d\sigma)\ \ d\nu\, d\Omega}} \tag{2.2}$$

and the MKS units of I_ν are $\mathrm{W\ m^{-2}\ \ Hz^{-1}\ \ sr^{-1}}$.

15/12/2024

Fundamental Equation of 21cm galactic structure Analysis.

Assumptions (till 1st order)

- circular velocity of gas
- $\Omega(R)$ is a decreasing function
- Differential Galactic Rotation.
- We are looking at the plane of Galaxy ($b = 0°$)
- SUN is observer.
- Axisymmetric Galaxy

Notation

l – Galactic longitude

θ – Galacto centric Azimuth

b = Galactic Latitude.

R – Distance from Galactic center

$R_\odot$ – Distance of Sun from galactic center (~ b/w 7.4 – 8.7 Kpc)

(SUN!)

r – Line of sight (LOS) distance of observer to the emitting concentration of hydrogen.

Ω_0 – Angular velocity of SUN about galactic center.

v_{obs}

$v \equiv$ Radial velocity which is measured. ~ Doppler shifted velocity of gas along LOS.

convention: + → emitting gas is moving away from obs. (SUN).

Differential rotation → $v(R)$ is constant. But $\Omega(R)$ is varying

What we want

$$v = \left(\text{component of } \Theta \; (= \Omega(R)\cdot R) \text{ along } r \text{ (LOS)}\right) - \left(\text{component of } v_\odot \text{ along } r\right)$$

$$= \Omega R\left(\cos\left(\pi/2 - l - \theta\right)\right) - \Omega_\odot R_\odot \cos\left(\pi/2 - l\right)$$

$$= \Omega R \sin(l+\theta) - \Omega_\odot R_\odot \sin l$$

$$= \Omega R\left(\sin l \cos\theta - \cos l \sin\theta\right) - \Omega_\odot R_\odot \sin l$$

subst.

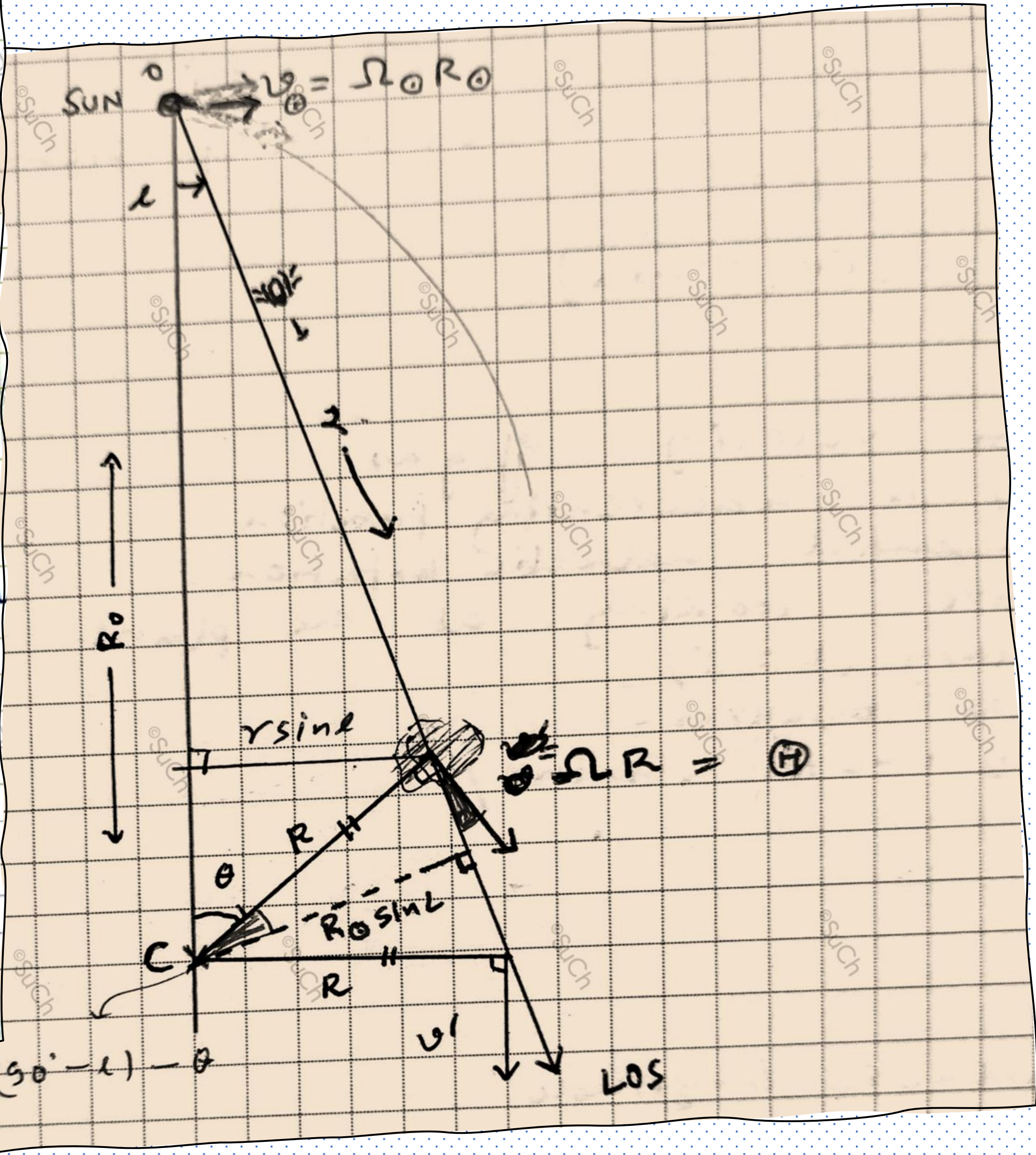
$$\boxed{\begin{aligned} r \sin l &= R \sin\theta \\ R\cos\theta &= R_\odot - r\cos l \end{aligned}}$$

$R = ?$ unknown → Elimina

1. $v = \Omega \sin l \,(R\cos\theta) + \Omega \cos l \,(R\sin\theta) - \ldots$

$$= \Omega \sin l\, R_\odot - \cancel{r\,\Omega \sin l \cos l} + \cancel{r\,\Omega \sin l \cos l} - \Omega_\odot R_\odot \sin l$$

2) $$v = R_\odot\left[\Omega(R) - \Omega_\odot\right]\sin l$$ ✓



Ref: Pg- 308, Galactic and Extragalactic Radio Astronomy , Springer (1988)

We get,

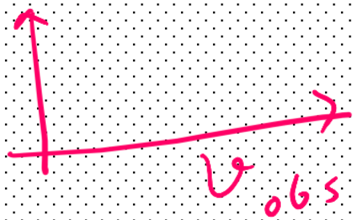
$$v_{obs} = \Omega(R)\, R \cos(\pi/2 - \theta - l) - v_{\odot} \sin l$$

Maximum when $\cos(\,) = 1$

i.e. $\frac{\pi}{2} = \theta + l$

$$R = R_{\perp} = R_{\odot} \sin l$$

Rightmost Peak in T_b



$$\therefore v_{obs} = v_{s0} - v_{\odot} \sin l$$

$$\Rightarrow v_{source} = v_{obs} + v_{\odot} \sin l$$

Must be corrected for LSR

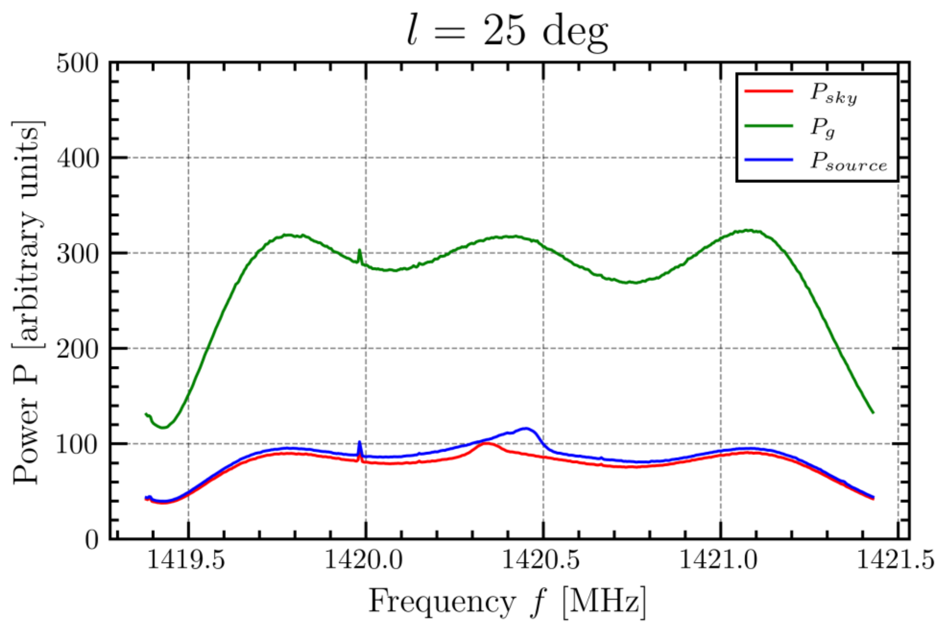
Steps

1. Plot Power v/s Frequency for a given longitude.

2. Convert Power axis to Brightness Temperature (T_b)

$$P = G(T + T_{\text{receiver}})$$

2.1 Calculate T_{receiver}



$$P_{\text{ground}} = G(T_{\text{ground}} + T_{\text{receiver}})$$

$$P_{\text{sky}} = G(T_{\text{sky}} + T_{\text{receiver}})$$

To calibrate the temperature of the antenna, we select two sources with known temperatures – namely ground and sky . Use $T_{sky} = 5\ \text{K}$, $T_{ground} = 300\ \text{K}$

$$T_{\text{receiver}} = \frac{T_{\text{sky}}\left(\frac{P_{\text{ground}}}{P_{\text{sky}}}\right) - T_{\text{ground}}}{1 - \frac{P_{\text{ground}}}{P_{\text{sky}}}}$$

Because, at this wavelength we can approximate earth as a blackbody. So, it's brightness temp = blackbody temperature.

$$P_{\text{ground}} = G(T_{\text{ground}} + T_{\text{receiver}})$$

$$P_{\text{sky}} = G(T_{\text{sky}} + T_{\text{receiver}})$$

Before Calibration

$$P_{\text{ground}} = G(T_{\text{ground}} + \cancel{T_{\text{receiver}}}^{T_{fit}})$$

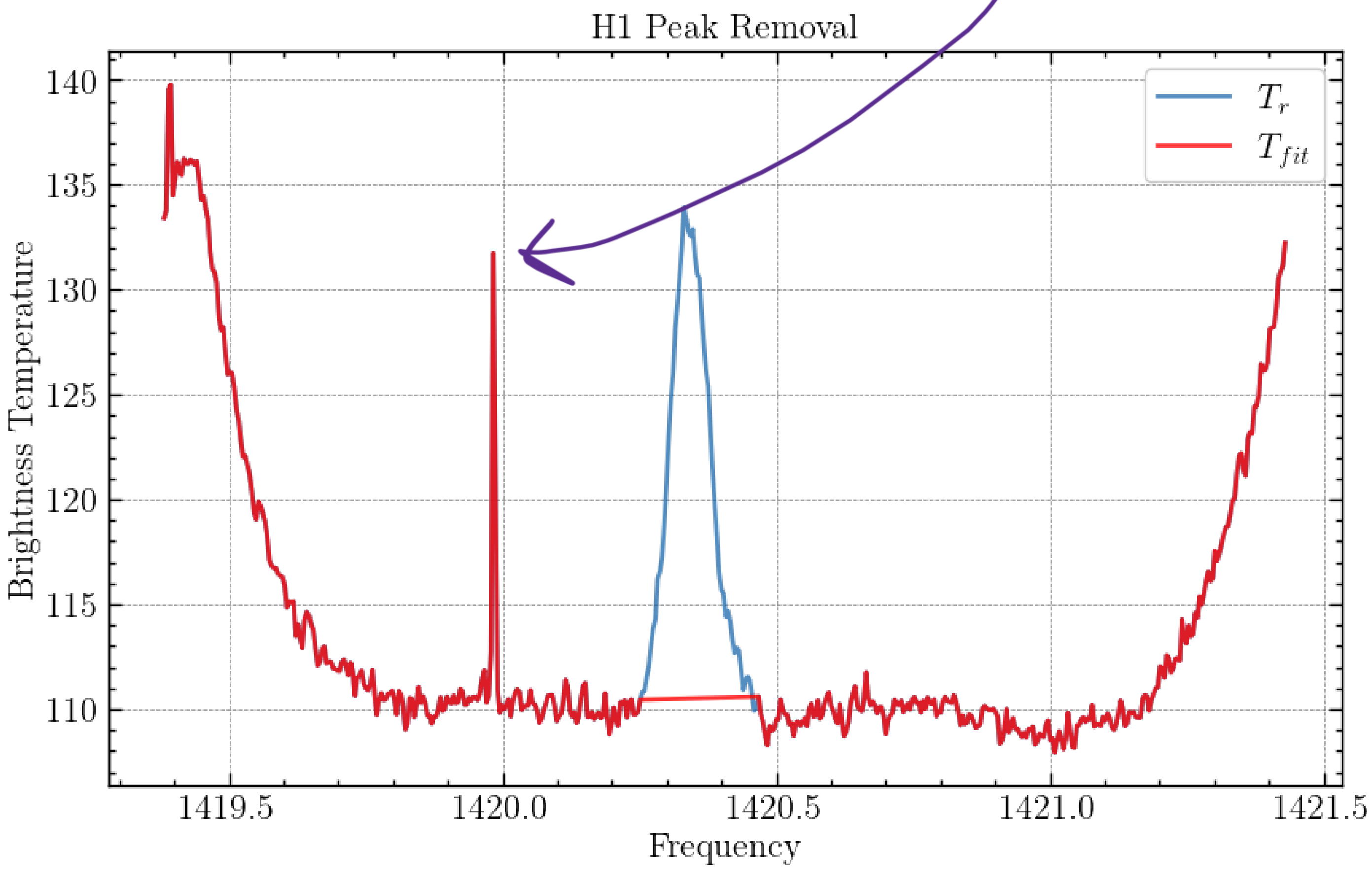
$$P_{\text{sky}} = G(T_{\text{sky}} + \cancel{T_{\text{receiver}}}_{T_{fit}})$$

After Calibration

This peak is a characteristic of the receiver only!

2.2 Calibrate T_{receiver} by removing the H1 artefact.

This artefact is present in measurements in any direction of the sky because H1 is present everywhere. We subtract it as we want our calibration sources to be blackbody (H1 signal is NOT blackbody)



3 . Calculate the antenna temperature (T_a)

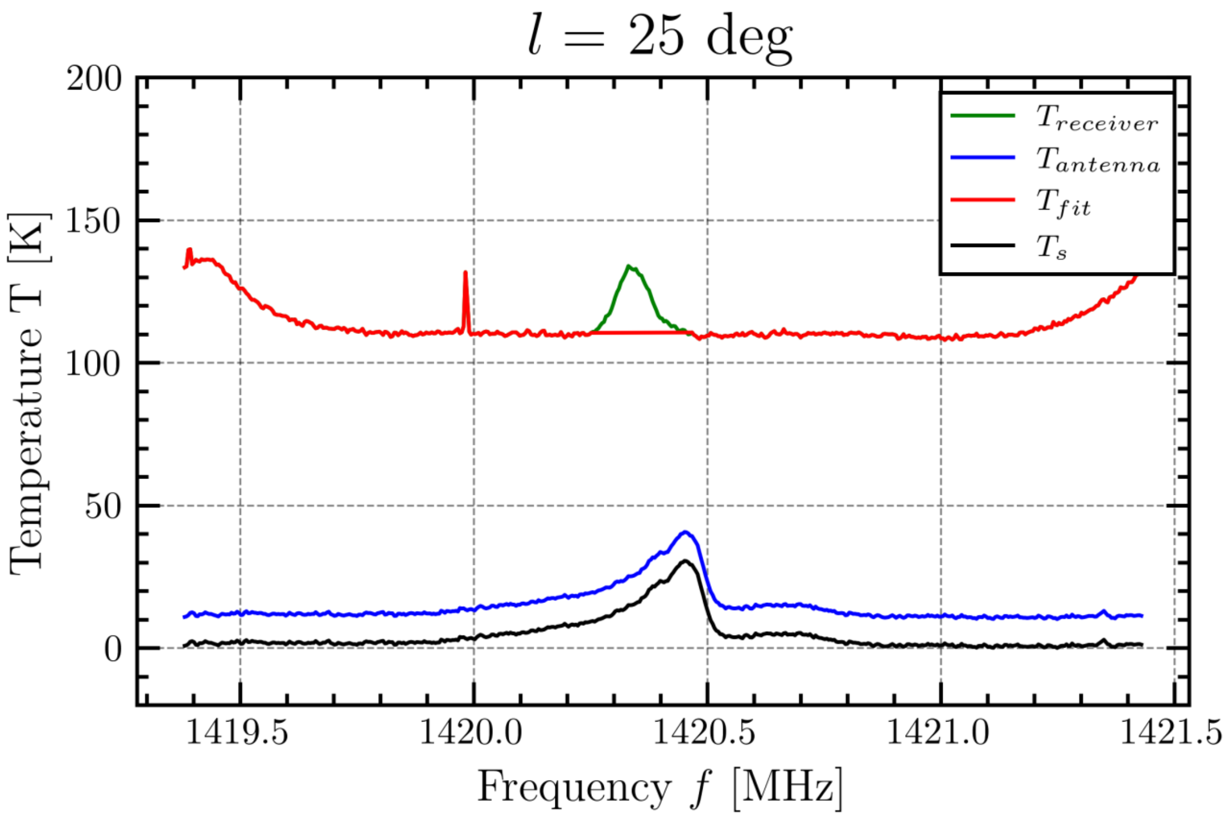
$$P_a = G(T_a + T_{fit})$$
$$P_{\text{ground}} = G(T_{\text{ground}} + T_{fit})$$

$$T_a = \frac{T_{\text{ground}} + T_{fit}}{(P_{\text{ground}}/P_a)} - T_{fit}$$

4 . Shift baseline of T_a to 0, to get T_s (brightness temperature of our H1 signal)

5. Plot'em!

T_a contains information from anything the antenna is looking at. It comprises H1, atmosphere, CMB, extragalactic sources etc. Our **desired H1 signal** lies above this *continuum background* which we are subtracting!



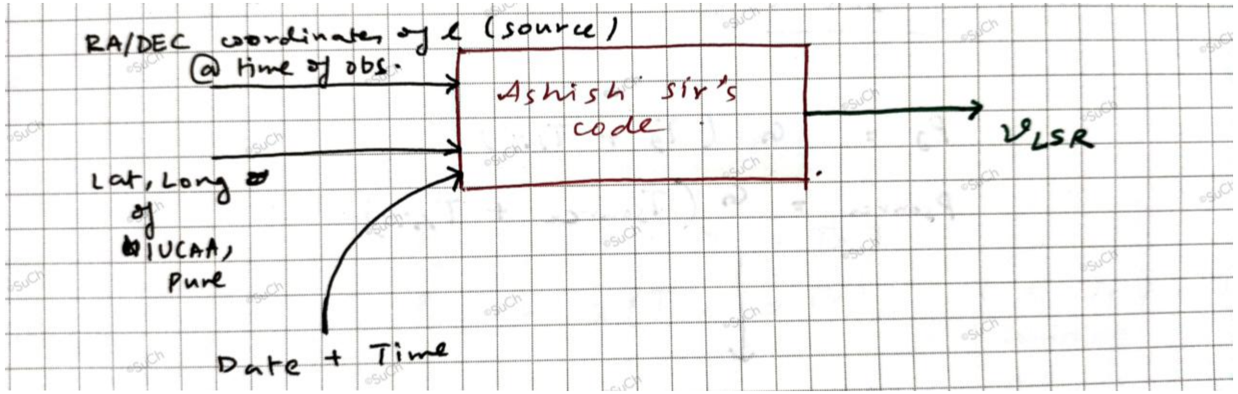
6. Change frequency to velocity

$$v = c\left(1 - \frac{f}{f_0}\right)$$

```
f0 = 1420.405751 #MHz
c = 299792.458 #km/s
```

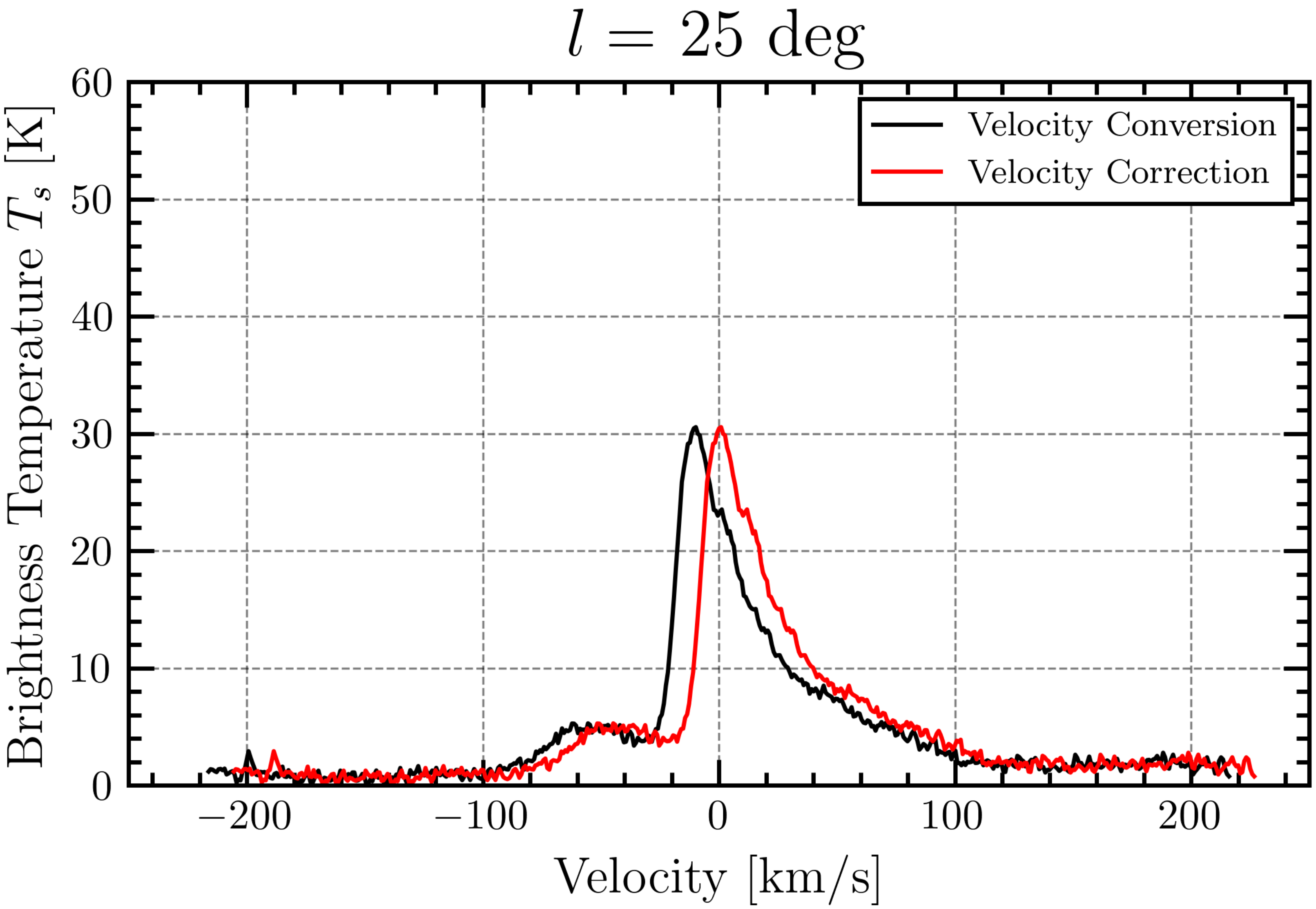
7. Do LSR (local standard of rest) correction

l (deg)	V_{LSR} (km/s)
15	-11.1622
25	-10.6882
35	-9.5282
45	-8.0994
55	-6.48644
65	-4.93495
75	-2.94176
85	-1.174827



$$V_{corr} = v - V_{LSR}$$

8. **Plot T_s v/s V_{corr}**



9. Save this data in .csv format. Time for Multipeak Gaussian Fitting ! Open SciDavis.

$$AN(\mu, \sigma^2) \equiv A \times \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}$$

$A \equiv$ Amplitude

$\mu \equiv$ Mean

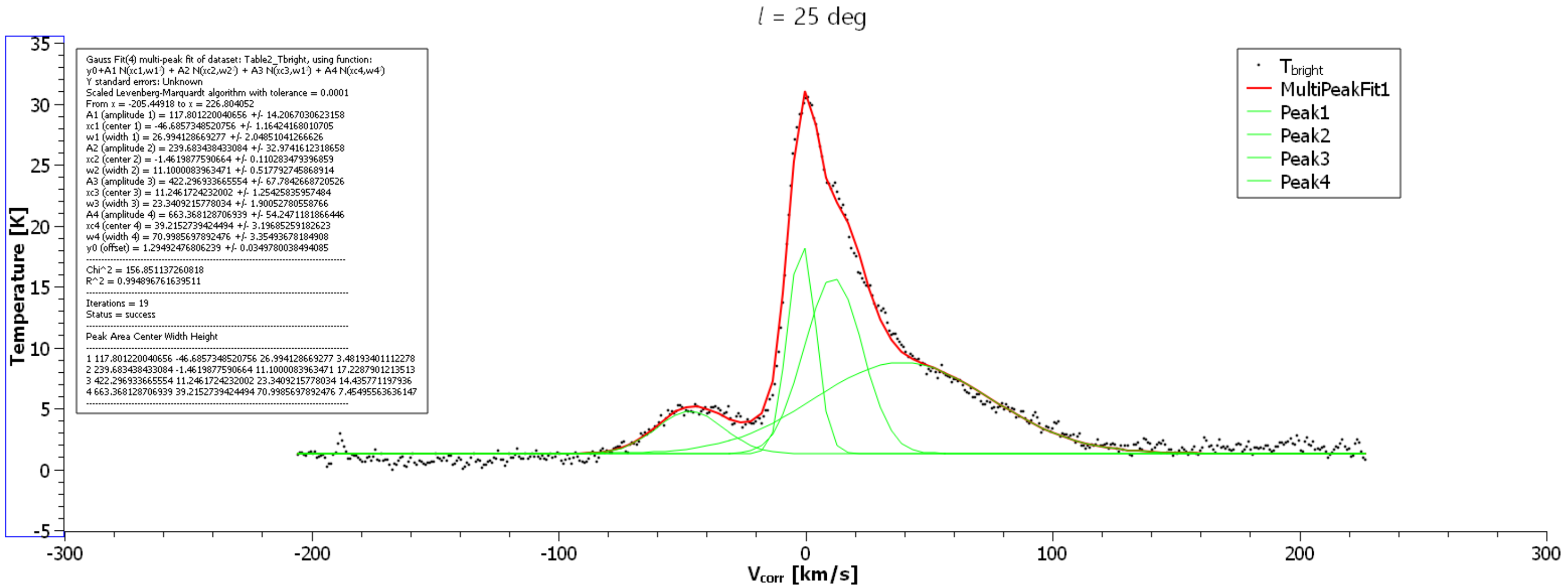
$\sigma \equiv$ Standard Deviation

Multipeak Fitting is just, fit by

$$f(x) = \sum_{i=1}^{n} A_i N(\mu_i, \sigma_i^2)(x) + y_0$$

$\in \mathbb{R}$

offset !



9. The value of V_{corr} corresponding to the rightmost peak (i.e maximum velocity) is our V_{obs} (km/s)

10. Correct V_{obs} (km/s) to get rid of the heliocentric frame, to get the actual orbital velocity of the source v_{source} (km/s) as deduced earlier

!! Yay!

$$\boxed{v_{\text{source}} = V_{obs} + V_{\text{sun}} \sin l}$$

$$\boxed{R = R_{sun} \sin l}$$

!!

```
Rsun = 8.5 #kpc Distance of sun from galactic center
Vsun = 220 #km/s circular velocity of sun about galactic centre

vSource = v_obs + Vsun*np.sin(np.deg2rad(GalLong))

R = Rsun*np.sin(np.deg2rad(GalLong))
```

Similarly, proceed for other longitudes to get the GRC!

HW-2

Errors

Try to find what can be the possible sources of error in your analysis/ experimentation . This can be due some assumptions which you made – which might be very approximate

Why can't we work with $l = 115^{\circ}, 135^{\circ}$ data to plot the curve ?

HW-3

Assignment Submissions!

All the participants who successfully completes the solutions to the exercises/questions posed in the session namely HW 1, 2, 3 [within 5 DAYS of the session] will get an exclusive signed **Certificate of Appreciation from Singularity!** (you can flex in your CV)

DEADLINE :

27 March, 11:59:59 PM

Please upload a .PDF of your solutions. Clearly mention your Name and Roll No. on the top and mention the questions along with your answers/workouts.

Also give your feedback here

https://forms.gle/NqhiFiUuuqiyWdgcA

Conclusion

- We derived a rotation curve from **doppler spectroscopy** performed on 21-cm H1 emissions and found it to be *non-Keplerian* in nature, indicating some misalignment between the expected gravitational effects due to visible matter and the actual dynamics of our galaxy.

- We offered the existence of a dark matter halo as a possible explanation of this phenomenon, supported by our experimental results.

- Additional analysis of the 21-cm spectra can also be performed in various directions in the galactic plane to indicate the presence of 2 possible spiral arms. ← Try to explore!

- Due to the large uncertainties in this particular analysis the results are interesting but inconclusive and definitely warrants further investigation.

- In the end, we believe we have demonstrated the 21-cm neutral hydrogen line to be a powerful tool for exploring our galaxy and beyond.

6.7. Spiral Arms of the Milky Way

Revisiting our 21cm spectra we notice that there is more information contained within the peaks than the simple maximal recessional velocity which we used in the previous few sections to derive the rotational curve of the galaxy. In order to extract information about galactic structure, we turn to the relative intensities at different redshifts. Extrapolating between the data points on our rotation curve, we plot the locations of the maximas, assuming these to be the regions of highest H1 concentration, along our line of sight in each direction l. Trigonometry is helpful in deriving these relations.

We determine geometrically radius r and angle θ of these maxima given the corresponding v_{rec} and l. We interpolate the given v_{rec} in the following function for r:

$$v_{rec}(r) = F(r, v(r)) = sin(l)\left[\frac{r_\odot}{r}v(r) - v_{LSR}\right] \qquad (7)$$

From r, we can now find the angle θ:

$$\theta(r) = G(r) = \pi - \left(l + sin^{-1}\left[\frac{r_\odot}{r}sin(l)\right]\right) \qquad (8)$$

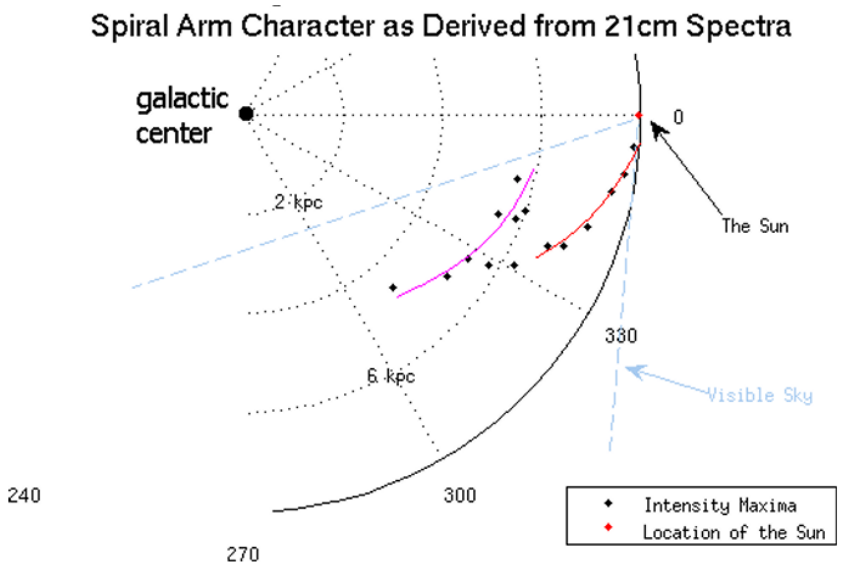


FIG. 10: Plot of the sources of maximum intensity 21 cm emission between $30 < l < 80$. We see possible evidence of two distinct density waves (spiral arms) of high H1 concentration.

Performing this analysis for each redshifted peak along $30 < l < 80$, we obtain the following polar plot showing the locations of highest H1 density in the viewable portion of the galactic plane (Figure 10). There is evidence of some spiral structure as indicated by two possible arms of high density H1 gas, whose locations are approximated by superimposed curves to aid viewing. The outer curve is likely the Orion arm, of which the solar system is a part, and the inner may be a short portion of the Saggitarius Arm.

ACKNOWLEDGEMENTS

I would like to thank

- Singularity : The Astronomy Club (hehe :D)
- CC Office , Suman Chakraborty sir
- The organizers of RAWS-2024 & Ashish Mhaske Sir
- last but not the least, my family, friends, and comrades

This work has made the use of:

- Python - Numpy, Pandas, Scipy
- Stellarium
- SciDavis
- Lots of sources from Internet

ধন্যবাদ

धन्यवाद

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நன்றி

ధన్యవాదాలు

ಧನ್ಯವಾದಗಳು

આભાર

شکریہ

Thank You

🙏

Any questions? ☺