Galaxies and Observational Cosmology: Assignment 2

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1.0 Generating a Rotation Curve

1.1 Introduction

A rotation curve for the Milky Way was calculated using radio data provided by the University of Sydney. The data was generated by the university's Small Radio Telescope (SRT) which observes the neutral HI 21cm wavelength corresponding to the hyperfine spin-flip transition of cold interstellar hydrogen. Whilst an exceedingly rare transition on an atomic scale (with a transition rate of once every ≈10,000,000 years), for radio astronomers it is a critical spectral feature for cosmology, as it is does not experience extinction by interstellar matter and can be observed to very high redshifts (Griffiths, 1982).

Initially, functions and a script were developed that read the HI radio data from a single galactic longitude l as the first step of the data reduction process. This data was used to calculate rotation curves by plotting intensity I vs. frequency f (which is directly related to channel number N), and then converting the frequencies into Doppler velocities. Intensity/velocity values were then calibrated using T_{sys} to remove the contribution of noise to the signal. For each frequency, the average intensity was found, and the most negative velocities and their uncertainties were estimated. Once the rotational velocity V_{rot} had been calculated for the appropriate distance from galactic centre R (corresponding to l), the program iterated to the next longitude data file and calculated the next V_{rot}. Upon parsing and solving each data file, the results were compiled and plotted into a final galactic rotation curve of rotational velocity versus distance from the galactic centre.

The program used to calculate the curves was written using Python, and the appropriate script has been submitted as a Jupyter notebook titled *Galaxies Assignment 2 AKusmirek.ipynb*. Hand calculations were used to ensure the script calculated appropriate values, and an Excel results spreadsheet was used to record and manage the results for easier investigation by the analyst.

1.2 Method

To begin the data analysis, the script opens a data file to parse, and plots the first graphs in the data reduction process (I vs. v). This involves plotting the first column of data [0] from the data file on the x-axis versus the second column [1] on the y-axis. However, the data only contains the signal frequency as a channel number, and so the frequency values are converted to radial velocities using Equation 1 (taken from Sydney, 2017) – this equation is described in the script by the *"f_to_v"* function. These raw data values are then calibrated using T_{sys} which is calculated using Equation 2 (equation 3 from Garcia Lopez, 2021), and the resulting data plots are shown in Figure 1. An issue which was faced in early iterations of the script was that the most extreme values plotted by the graphs were inconsistent, but these portions of the signal spectrum are not relevant to the 1420MHz HI line (even when red or blue-shifted) and can therefore be filtered out by the script.

Signal frequency *f* to radial velocity *v*:

$$v = \frac{(1420.406 - f)c}{1420.406} - v_{LSR} \qquad \textit{Equation 1}$$

Where: c = speed of light in vacuum (299792kms^{-1}); v_{LSR} = velocity along the line of sight relative to the Local Standard of Rest calculated by the SRT (kms^{-1})

System temperature for calibration T_{sys}:

$$T_{sys} = \frac{\sum s_{offline}}{\sum(s_{calibration} - s_{offline})} - * \; T_{cal} \qquad \textit{Equation 2}$$

Where: T_{cal} = calibration temperature (20K); $s_{offline}$ = offline signal (MHz); $s_{calibration}$ = calibration signal (MHz)

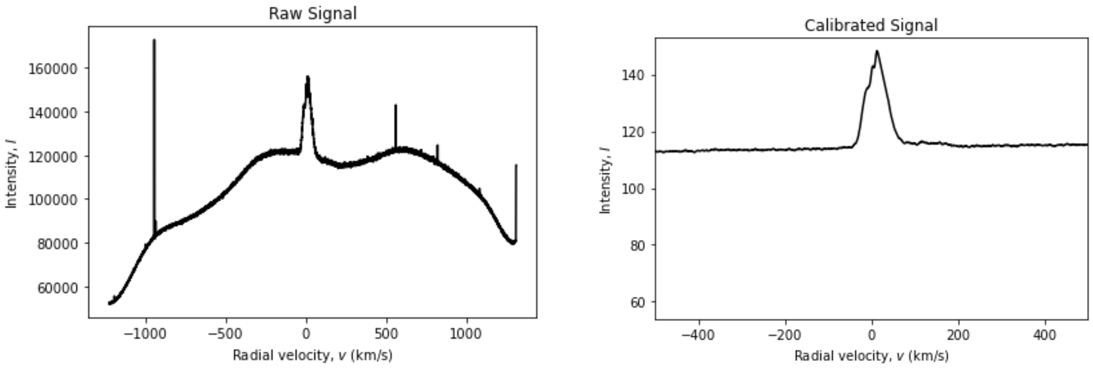

Figure 1: Data reduction plots of the raw and calibrated and filtered signals for galactic longitude l = 10°. Signals have been converted from frequencies (MHz) into radial velocities (kms^{-1}) on the x-axis.

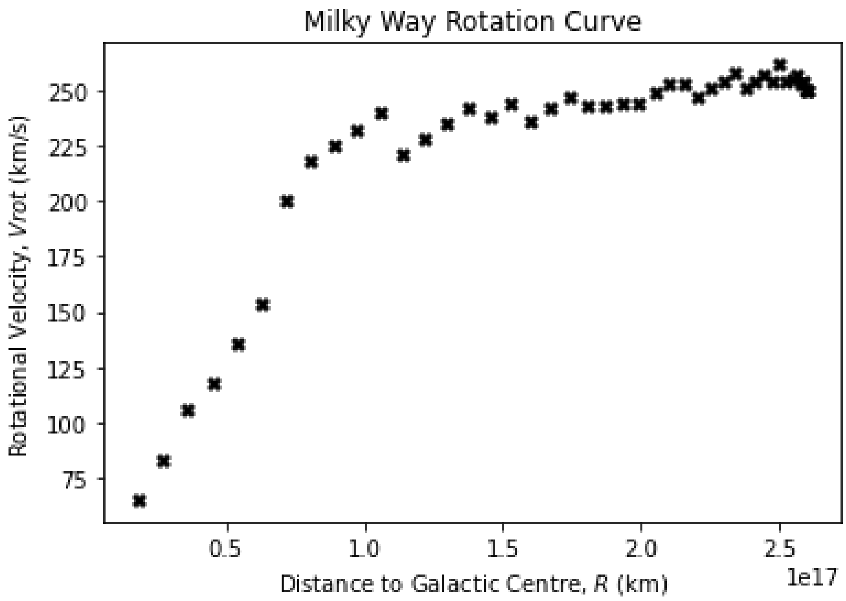

Figure 2: The calculated rotation curve for the first quadrant of the Milky Way (up to R = 8kpc), with rotational velocity V_{rot} (kms^{-1}) plotted against distance from the galactic centre R (km). The curve shows the characteristic "flat" portion at high values of R, rather than the reduction in V_{rot} expected if only allowing for the gravitational effects of visible matter.

1.3 Assumptions Made

For observations of neutral hydrogen for rotation curves it is assumed that it is evenly distributed throughout the Galaxy, and that the signal received by the telescope contains contributions from galactic HI emissions along the full length of its line of sight. Furthermore, motion is assumed to be circular. Additionally, if mass estimations are to be calculated, the rotational motion of the galaxy is assumed to be Keplerian motion at high values of R but around a rigid rotating body for low R values, close to the galactic centre.

A significant assumption made when generating rotation curves this way is that only the visible matter present in the target galaxy is being used to generate the curves. This was the method by which the theory of dark matter was first developed, as it became clear that the amount of visible mass present was not sufficient to cause the observed rotational velocities and characteristics of measured galaxies (Rubin and Kent Ford JR., 1970 and Freeman, 1970). The disparity between galactic dynamics and visible matter had been noted as early as 1940 by Oort, and his conclusions on galactic masses were still relevant by the 21st century (Rubin and Sofue, 2000). If only visible matter had a gravitational effect on galaxies, the rotation curve would be expected to peak and then decline as the distance from the centre of the galaxy increased; the rotation curves do not demonstrate this behaviour, and therefore it must be assumed that "dark" matter, which cannot be observed (due to not interacting with the electromagnetic field in any manner), has a gravitational effect on the visible matter of galaxies.

An additional assumption is related to the real motion of the matter being observed by the radio telescope. The above calculations and rotational curve measure the distribution and relative velocity of hydrogen in the Milky Way, with the assumption that the HI gas that is being observed is rotating around the galaxy at the same rate as the stars in the galaxy (in the local region of the gas). The hydrogen clouds are also not being directly observed, and their velocity is inferred as a function of distance from the Galactic Centre. Additionally, for a complete rotation curve of the Milky Way (considering the dark halo and furthest edges of the galaxy), it is necessary to investigate the rotational velocities of bright objects at R > 8kpc.

2.0 Significance of the Results with respect to the Milky Way

As the calculated rotation curve does not demonstrate the "visual matter only" expectation of a peak and a sharp drop-off with increasing R, instead demonstrating a flat segment of V_{rot} at high R, it can be inferred that the Milky Way is permeated by enough dark matter to significantly alter its gravitational characteristics. This is consistent with the rotation curves that have been calculated over the past 50 years, for both the Milky Way and other galaxies. The curve also suggests that the dark matter component of the MW is dynamically dominant at large radii, and likely extends far beyond the disc of visible and luminous matter. Figure 3 details the possible extent and distribution of dark matter as inferred from the galactic rotation curve.

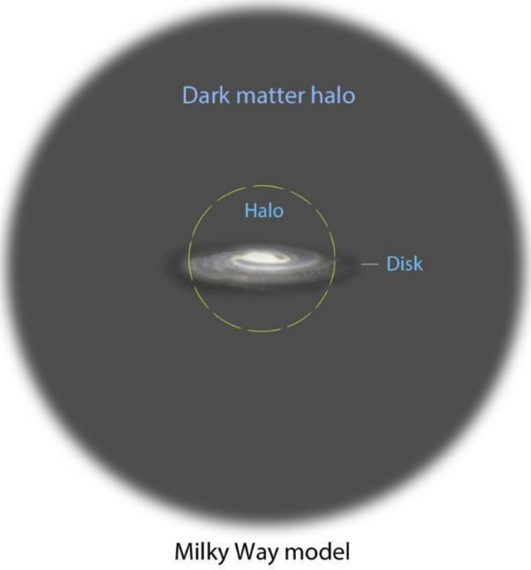

Figure 3: The "dark matter halo" - a possible distribution of dark matter in the Milky Way (extending to far greater distances from the galactic centre than visible baryonic matter) that would explain the flat portion of the rotation curve at large radii R. Credit: University of Zurich.

The rotation curve suggests that the visible matter in the Milky Way does not experience Keplerian motion (whereby V_{rot} decreases with increasing R). This means that when considering the orbit of an object or objects in galaxies, they cannot be approximated as an orbit around a central point mass in the same way that orbital calculations may be completed for solar system planets, or satellites. This is likely due to the fact that even though supermassive black holes (SMBHs) at the centre of galaxies are especially massive (such as Sgr A* at the centre of the Milky Way calculated as >4,000,000 Solar masses) (The GRAVITY Collaboration, 2019), they do not have sufficient mass relative to the whole galaxy to be considered a central mass point.

Rotation curves like the calculated curve shown in Figure 4 allow cosmologists to infer galactic masses and the presence of structures in a galaxy. The results show that determining rotation curves using only visible matter, and the following calculation of galactic masses, is not an accurate method. Galactic mass calculations based on rotation curves must consider dark matter as an explanation for why galactic rotation curves do not demonstrate Keplerian motion.

3.0 Rotation Curves for Other Galaxies

A critical difference between calculating rotation curves of the Milky Way compared to other galaxies is that other galaxies can be observed in their entirety, whereas the Milky Way is observed from within. The most notable obstacle to observations within our own galaxy is the Zone of Avoidance towards the galactic centre, where extinction is too high to effectively observe, especially in the visual portion of the spectrum. Rotation curves for galaxies other than our own can be calculated but for these galactic observations resolution is a critical characteristic (due to the cosmological distances observed). In their 2016 paper, Sofue describes the similarities between the Milky Way and other spiral galaxies, which (in the case of spiral galaxies with high outer disc resolution) can also be calculated using the same intensity-weighted average velocity method as used in this report.

Whilst other spiral galaxies show similar structures to the calculated shape of the Milky Way, the generation of rotation curves for other classifications than spiral can be problematic. Spiral galaxies do not represent a majority of galaxies in the universe, instead the majority are classed as elliptical with a large minority having irregular shapes (Garcia Lopez, 2021). The rotation curves of irregular galaxies are difficult to generate properly using this report's method, and oftentimes they do not appear to contain any structures that allow for classification as a specific Hubble type. HI observations have been used for samples of irregular galaxies and show general agreement with higher resolution Hα curves (Swaters et al. 2008), but such observations require consideration of beam smearing, as well as making assumptions regarding the domination of luminous mass in central regions. In their 2016 paper, Sofue also states that rotation curve analyses are not applicable to elliptical galaxies, meaning that around 60% of galaxies cannot be analysed using rotation curves.

In addition to HI observations, the rotation curves of other galaxies and our own Milky Way are often determined using visual observations, Hα spectrum lines, observations of HII regions, Cepheids, masers and many more objects and methods depending on the desired radii of the curve, the distance to the galaxy, the resolution of instruments and the extinction experienced when observing.

4.0 References

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