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TO WHOM IT MAY CONCERN

This is to certify that Mr. Bijin Joseph of St Xaviers College, Mumbai has worked in Saha Institute of Nuclear Physics as an undergraduate associate for the period 21/10/2019 to 20/11/2019 under the guidance of Prof. Pijushpani Bhattacharjee.

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ROTATIONAL CURVE INTRODUCTION

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Contents

1 INTRODUCTION

During this 30 day period of time I got to do a very small research on the topic of dark matter under professor Pijushpani Bhattacharjee. I started with reading his research paper on rotational curves, followed by discussing the paper with him. On figuring out that there were certain topics that I am still yet to learn he suggested me two Books, Galactic Astronomy by James Binney and Michael Merrifield and Galactic Dynamics by Binney and Tremain. From the suggested books I managed to learn about basic mathematics that was necessary to understand the mathematics that was used in the paper.

2 GALACTIC ASTRONOMY

Galactic astronomy written by James Binney and Michael Merrifield gives basic insight into understanding the basic formulas required.

2.1 Astronomical Measurements

2.1.1 coordinate system

In Astronomy for easiness we use spherical coordinate system. One of the main coordinate system that we use in the Equatorial coordinate system. This coordinate system is the fundamental coordinate system that we use to make measurements from the earth's surface. The celestial sphere is an imaginary sphere of infinite radius centred on the earth. The Earth's Axis to the celestial sphere defines the **North and South celestial Poles** The direction at which the local vertical intersects the celestial sphere is called the **zenith** The great circle that passes through the celestial poles and the zenith is the **Meridian. Elciptic** is the circle traces by the sun's apparent motion due to the revolution of the earth around the sun. The great circle through the celestial poles and through a stars position is called **hour circle**. The star's **right ascension** α is the angle along the celestial equator from VE to the star's hour circle. The **declination** δ is the angular distance measured from the equator along a star's hour circle to the star. Using this coordinate system we are able to study celestial bodies from the earth.

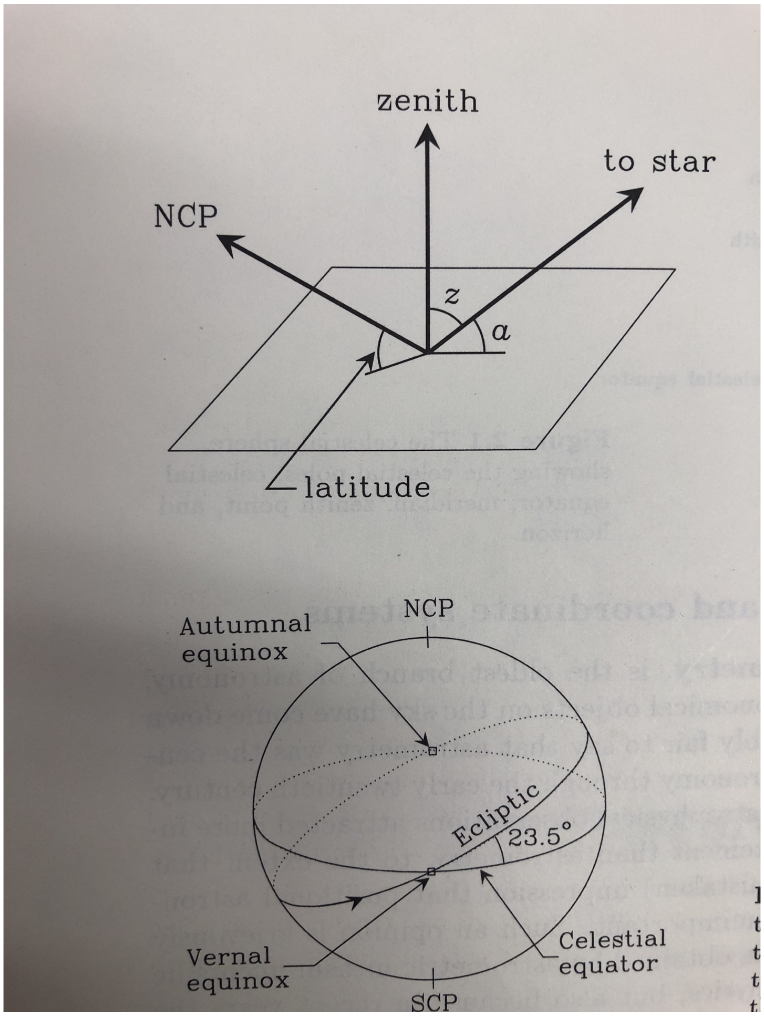

Figure 1: EQUATORIAL COORDINATE SYSTEM.

2.1.2 Galactic coordinates

Since the Galactic coordinate system is geocentric it provided inappropriate view point for problems of galactic structures and dynamics. The **Galactic latitude** b of a star is the angle from the Galactic equator to the star along the hour circle. The **galactic longitude** l is measured with respect to the direction to the galactic centre.

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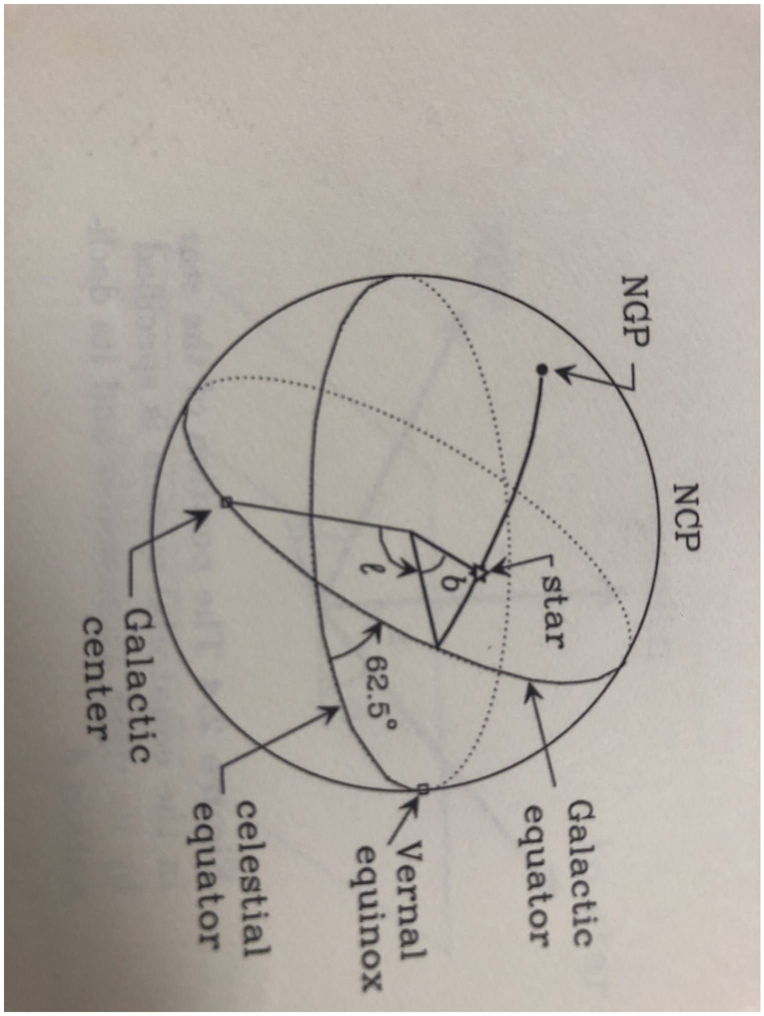

Figure 2: GALACTIC COORDINATE SYSTEM.

3 GALACTIC DYANAMICS

Galactic Dynamics written by James Binney and Scott Tremaine discusses about the motions of different bodies in the universe. It discuss about the motion of stars, clusters, galaxies, how we figured out there motion, the challenges and how those challenges where over come.

3.1 Stars

Bolometric Luminosity is the the total rate of energy output integrated over all wavelengths. Since the earth atmosphere is opaque to most wavelengths it quite difficult to determine this Luminosity. Therefore astronomical Luminosities are measured in on or more specific wavelength bands. Also Luminosities are sometimes expressed in logarithmic scale.

$$M = -2.5 log_{10} L + constant$$

This is known as the absolute luminosity. The constant is chosen separately and arbitrarily for each wavelength.
The apparent magnitude,

$$m = M + 5 log_{10}(d/10pc) = -2.5 log_{10}[L(10pc/d)^2] + constant$$

The **distance modulus** $m - M$ is used as a measure of distance. The **effective temperature** T_{eff} , defined as the black body with the same radius and bolometric luminosity as the star in question. For a stellar radius of R, then the Bolometric luminosity is

$$L = 4\pi R^2 \sigma T_{eff}^4$$

The third measure if the surface temperature of a star is its spectral class, O, B, A, F, G, K, M, L and T and each class is divided into 10 numbered divisions i.e, B0, B1,...B9.

3.2 The Galaxy

In a galaxy, the galactic plane, the region where most of the stars are present, this plane serves as the equator of Galactic coordinates (l,b), where l is the

galactic longitude and b is the galactic latitude. The sun is located at a distance R_O from the centre of the galaxy.
The **Local Standard of Rest** is an inertial reference frame centered on the sun and traveling at speed V_O in the direction of galactic rotation. Since most of the nearby disk stars are on nearly circular orbits, their velocities relative to the local standard of rest are much smaller than V_O.since the sun doesn't have a proper circular rotation, it is also considered to have a motion with respect to the LSR i.e 13.4 km$s^{-}1$ in the direction $l = 28^o, b = 32^o$.

4 ROTATION CURVE OF THE MILKY WAY OUT TO 200 KPC

BY PIJUSHPANI BHATTACHARJEE, SOUMINI CHAUDHURY AND SUSMITA KUNDU. In this paper the Newtonian mechanics has been used to obtain the rotational curve (RC) of a galaxy up to a distance of 200 kpc i.e, $V_C(r) = \sqrt{GM(r)/r}$. We can use an RC to obtain the local density of DM and the rotational velocity of DM. How we do this is by assuming a tracer to be in the orbit of a galaxy and following a circular trajectory at a desired radius. A tracer is usually and object which leaves a trail for us to understand its path. To reduce the error of our calculation we use galactic coordinates and we have to make corrections for LSR velocity. At the time the paper was published it was quite complicated to obtain the Peculiar motion of a celestial body and the only velocity we can obtain is the **Line of sight velocity**, which was also difficult to obtain due to factors like dust extinction, absorption by telescope, etc. After obtaining the LOS velocity we can use **Jeans Equation** to obtain the peculiar motion of the body. A new term that I came across in this paper is the Anisotropy parameter β. This parameter is a measure of the velocity Anisotropy of radial velocity with tangential velocity. Anisotropy in astronomy defines properties in different directions.

$$\beta = 1 - \sigma_t^2/2\sigma_r^2$$

β is very difficult to figure out as we cannot just observe with our naked eye, therefore we take different values of β, however now due to the presence of technologically advanced telescopes it is possible to figure out a more accurate value for β. The lowest value of the rotation speed at any r obtains for the case of complete radial anisotropy ($\beta = 1$) of the non-disk tracers we can get a lower limit on the galaxy's mass.

$$v_{LSR} = v_h + U_{(.)} \cos(b) \cos(l) + V_{(.)} \cos(b) \sin(l) + W_{(.)} \sin(b)$$

$(U_{(.)}, V_{(.)}, W_{(.)})$ denote the peculiar motion of the sun with respect to the LSR. The circular velocity with respect to galactic centre rest frame, V_c, to V_{LSR} is

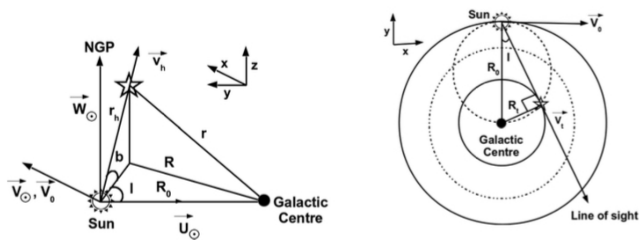

Figure 3: left is the coordinate system and the right shows the tangential point method

$$V_c(R) = \frac{R}{R_o} \left[\frac{V_{LSR}}{\sin(l)\cos(b)} + V_o \right] \qquad (R < R_o)$$

the obtained galactocentric velocity can be applied into the jeans equation to obtain the peculiar velocity from which we can obtain the mass of the galaxy.

5 SUMMARY

Using different tracers we can obtain a calculated mass of the galaxy up to 200 pc. The calculated data due to several complexities will have some amount of errors due to technical issues, and other errors like dust extinction, etc. After removing maximum amount of errors we obtain the Rotational curve. However the RC was not in accordance to what was predicted. The rotational curve was almost constant even though the radius from the galactic centre was increasing and this tells that there is either a large amount of mass in the galaxy that we cannot observe that is, in more scientific words, these mass do not interact with light and is only found to be interacting with gravity, or our present knowledge about Gravity is wrong. Plenty of scientists have tried to come up with modified gravity theories couldnt cope up with the observational evidence. Further observations, especially the bullet nebula has shown us that the later is not true and that there is indeed a large amount of mass in the universe that lurks without interacting with even light. This mass which is hidden in darkness was nicknamed by the scientist as **dark matter**