Obtaining the Rotation Curve of the Milky Way

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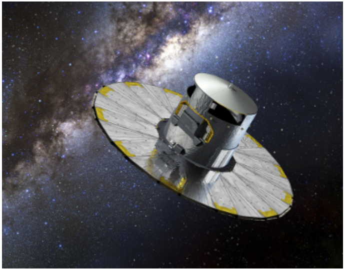
Description of Gaia

- Launched in 2013
- Collected data for 1.7 billion astronomical objects
- Hipparcos collected data for 118,000 stars
- The data Gaia collects consists of quantities that pertain to the position, velocity, and luminosity of a star



(a) Gaia satellite

(b) Hipparcos, the forerunner of Gaia

The Goal of Our Research

- Our goal is to extend galkin to gaia data
- Galkin 12 contains 12 data sets analyzed by various collaborations
- By consistently including more data, we can obtain a more accurate rotation curve

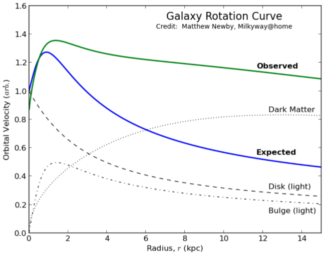


Figure: A typical rotation curve

3 Baryonic Components of the Milky Way

- The baryonic components of the Milky Way are:
  - Bulge
  - Thick disk
  - Thin disk
- Their corresponding densities are:
  - $\rho_{bulge} = \frac{\rho_{b,0}}{(1+r'/r_0)^\alpha} e^{[-(r'/r_{cut})^2]}$
  - $\rho_{disk} = \frac{\Sigma_{d,0}}{2z_d} e^{(-\frac{|z|}{z_d} - \frac{R}{R_d})}$ (works for thin and thick disks)

McMillan, Arxiv:1102.4340

Figure: The Milky Way

Circular Velocity of a Particle

- Assume the only force is gravitational
- $F = -\nabla U = -m\nabla\phi = m{v_c}^2/r \implies v_c = \sqrt{-r\nabla\phi}$
- Where $\phi = -G\int \frac{\rho}{\mathscr{r}}\mathrm{d}V$ is the gravitational potential

Theoretical Rotation Curve (Baryons only)

- Using $\rho = \rho_{bulge} + \rho_{thin\,disk} + \rho_{thick\,disk}$ to calculate Vc

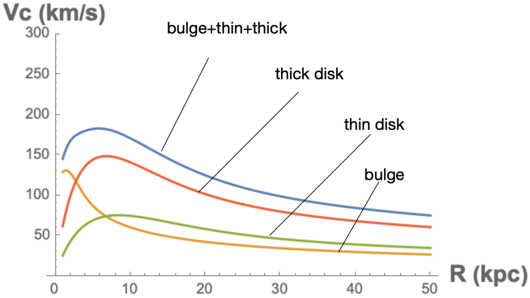


Figure: Theoretical rotation curves from experimentally motivated models

- $v_c(R)$ is called the rotation curve
- So far we've considered only baryonic components
- Alternatively, we can find $v_c(R)$ directly from the Gaia data

First the Method

- First we obtain the position of each star and transform to galactic coordinates (r,b,l)
  - r is the distance to the star relative to the sun
  - r=1/p where p is the parallax
  - b is the galactic latitude of the star
  - l is the galactic longitude of the star
  - It will be useful to use a cartesian basis:
  - $\hat{x}$ points towards galactic center, $\hat{y}$ points towards increasing l, $\hat{z}$ points towards galactic north

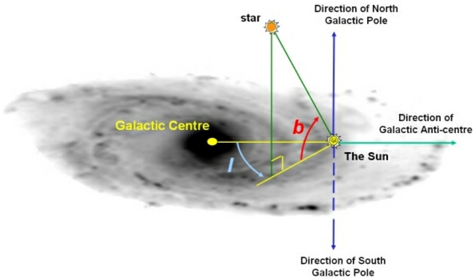


Figure: Galactic coordinate system

First the Method

- First, we calculate the position $\vec{r}_{sh} = (r\cos b\cos l,\ r\cos b\sin l, r\sin b)$
- The velocity is
  $\vec{v}_{sh} = (-r(\mu_b\cos l\sin b + \mu_{l*}\sin l) + v_r\cos b\cos l, r(-\mu_b\sin b\sin l + \mu_{l*}\cos l) + v_r\cos b\sin l, r\mu_b\cos b + v_r\sin b)$
- Where $\mu_b = \dot{b}, v_r = \dot{r}, \mu_{l*} = \dot{l}\cos b$
- Gaia DR2 contains quantities: $p, l, b, \mu_b, \mu_{l*}, v_r$
- This gives us the velocity of the star (s) relative to the sun (h)
- We need the velocity relative to the galactic center (c)
- Using a Galilean transformation (vector addition) we obtain
- $\vec{r}_{sc} = \vec{r}_{hc} + \vec{r}_{sh} \implies \vec{v}_{sc} = \vec{v}_{hc} + \vec{v}_{sh}$
  - Where $\vec{r}_{hc} = (8.33, 0, 0.025)(kpc)$ and $\vec{v}_{hc} = (11.10, 242.24, 7.25)(km/s)$

McMillan, Arxiv:1102.4340

Finding the Rotation Curve Obtained by Gaia

- Like before, we care about stars that are close to the galactic plane and stars traveling in a circle
- These stars have small radial velocities
- Lets also require the height is less than 100 pc of the galactic plane
- Lets choose stars whose velocity is sufficiently tangential by requiring $\left|\frac{\vec{v}_{sc}\cdot\hat{r}_{sc}}{|\vec{v}_{sc}|}\right| < \epsilon$

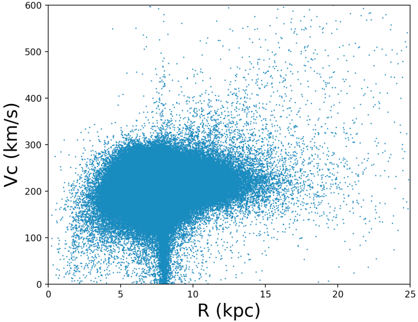


Figure: v_c vs. R unbinned

Actual Rotation Curve

- After binning using a width of 0.5 kpc we obtain a preliminary rotation curve

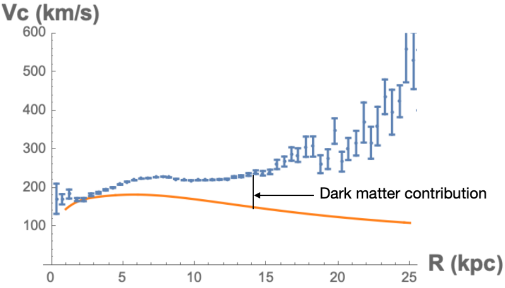


Figure: Actual curve obtained from Gaia (blue) (errors are bootstrapped), Baryonic component (orange)

- Next steps:
  - Understand the sharp increase in velocity for large radii
  - Study matter morphology
  - Combine results with galkin