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# Testing Different Models for the Rotation Curve of the Milky Way Using BURT Observations

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**Abstract**

Understanding the rotation curves (RCs) of our Milky Way galaxy represents a main tool to understand its dynamical evolution and the connection between different regions in the galaxy. The present work is intended to test the applicability of three rotation curve models against two datasets, the first being the well-known Sofue data, and the second being the Baghdad University Radio Telescope (BURT) data, both for the HI 21-cm emission line. The tested models are the Time of Events (ToE) model, the Brandt model, and the Navarro-Frenk-White (NFW) model. The fitting results showed that the ToE model provided the best prediction for the experimental data compared to the other two models for both BURT and Sofue data within all regions in the galaxy. The other two models applied slightly well only in the central region, while their results diverge near the edge region. The reduced $R^2$ values that we obtained for BURT and Sofue data are equal to 0.79 and 0.94, respectively. In addition, the ToE model worked as a calibration tool for the BURT data point, which can predict the behavior of the rotation curve and fill in the gaps of the missing points in the observed BURT data.

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## 1. Introduction

The study of galaxies' rotation curves is a highly active area in modern astronomy. Studying gas kinematics and mass distribution in the presence of dark matter poses significant hurdles [1], [2]. Historically, the rotation curve has been obtained from the rotation of stars and gas clouds, demonstrating how circular velocities vary with the radius of the center of the galaxy. Observations of rotation curves in spiral galaxies, including the Milky Way, show a continuous anomaly between the anticipated Keplerian fall of circular velocities and the actual flat at enormous galactic radius. This disparity has long been linked to dark matter halos, where the gravitational impact extends beyond visible matter [3], [4], [5]. Solving the problem of halo extension and predicting density profiles outside the galaxy's visual radius is challenging owing to the presence of dark matter and its entire mass [6]. The high-resolution data assisted in providing exact information on galaxies' masses and rotation curves [7]. Although accounting for around 95% of galaxies' mass, the nature of dark matter remains unknown [8]. The cusp-core issue and varying rotation curve characteristics among galaxies have resulted in several models with varied hypotheses [9], [10]. Every model may foresee and describe the rotation curve patterns of particular kinds of galaxies; however, it cannot suit all of them. Baes et al. [11], and Xu [12] examined the γ-model, which posits that the density profile fluctuates based on the $r^{-\gamma}$ relation. They evaluated several values for γ, including 5/2, 3/2, 2/3, 0.5, 1, 2, and 3. [13] and [14] used the quasi-isothermal halo model, which accounts for steady velocity dispersion caused by self-gravitating objects in the halo. A variety of models, from those that include dark matter halos to alternative hypotheses, have been put forth to explain the observed rotation curves [15]. One of the most extensively used models for dark matter halos is the Navarro-Frenk-White (NFW) profile, which explains the density distribution of cold dark matter [16], [17]. The NFW model, based on cosmic simulations, offers a solid foundation for studying gravitational lensing, halo dynamics, and rotation curve fitting. While several models addressed the halo density profile along with the bulge and disk density profiles, most models in the available research did not appear to account for the interaction between masses that occurs in all three of these places. The other rotation curve model that we will use in this work is based on a multiscale model that is built using a novel theory known as the time of events ToE model [18]. This research tests the applicability of three models: ToE [18], [19], Brandt [20], [21], and NFW [22] models. The work uses observed data from the BURT (Baghdad University Radio Telescope) on star velocities at different distances from the Galactic center [23]. By applying each theoretical model to this data, we can determine how well each model matches observed velocities and deduce attributes about dark matter and other mass components in the Milky Way. In addition, the ability of the new model to calibrate the results of relatively low-resolution data from BURT will be tested. This manuscript is structured as follows: A description of the data is provided in Section 2. Section 3 details the rotation curve models. In Section 4, interpret the results. Lastly, in Section 5, we summarize our conclusion.

## 2. Methodology

Achieving the main goal of this research requires measuring the rotation curve of the Milky Way using observational data from BURT. Those measurements were conducted in previous research [23], and the results of the research have been used in this work for the purpose of testing the compatibility of the three models with the BURT rotation curve. A brief overview of measuring the Milky Way rotation curve has been presented in this section. The first step of the measurement requires recording observations of neutral hydrogen profile for Galactic coordinates of (b=0° and 0°≤ l ≤90°) from January to April, 2023, which is the optimum time for observing the Milky Way from Baghdad [24]. The spectrometer parameters of the telescope used to record the observations are (central frequency = 1420 MHz, Sweep time = 30s, Span = 10 MHz, RBW = 1000, and VBW = 1000). The method that was used for measuring the rotation curve is known as the Tangent Point Method, which involves determining the maximum radial velocity of the HI profile, which is simply the radial velocity at the closest distance to the center of the Galaxy. Then the rotational velocities and radial distances were determined and plotted against each other to produce the rotation curve.

## 3. Rotation Curve Models

Rotation curves are believed to be the most important source of knowledge on the galaxies' dynamics [25], [26]. Due to the complexity of the rotation curves, many models were derived to interpret the galaxy kinematics. Some of these models (e.g., NFW, Brandt, and ToE models) are described below.

### 3.1. NFW Model:

By means of an astronomical N-body simulation, the Navarro-Frenk-White (NFW) model captures the density distribution of dark matter halos in galaxies and galaxy clusters. As the equation, Navarro et al. predict [27]:

$$\rho(r) \propto \frac{1}{\left[r\left(1+\frac{r}{r_s}\right)^2\right]} \quad \dots(1)$$

where $r_s$ denotes the usual measure radius. This profile shows a "cuspy" core concentration and a consistently declining density at great distances. The NFW model expects higher velocities in the innermost areas than observed in particular low-surface-brightness and dwarf galaxies, indicating inconsistencies that justify alternatives such as cored patterns or changes to dark matter models as fit to galaxy rotation curves [9], [22].

### 3.2. Brandt Model:

This model is an empirical technique utilized to represent galaxies' rotation curves, notably during the earliest observational research. It gives an appropriate representation for rotational velocity as a function of radius, reflecting the general form of observable rotation curves without depending on a particular mass distribution model. The Brandt model represents the rotational velocity as follows [28]:

$$V(r) = V_{max}\left(\frac{r}{r_{max}}\right)\left[\frac{1}{3}+\frac{2}{3}\left(\frac{r}{r_{max}}\right)^m\right]^{\frac{-3}{(2m)}} \quad \dots(2)$$

Where $V_{max}$ is the maximum rotation velocity, $r_{max}$ is the radius where this happens, and $m$ is an attribute of shape that governs the steepness of the curve's fluctuation. This model was especially beneficial prior to the broad embrace of scientifically driven dark matter halo patterns because it enabled physicists to predict rotation curves with little data. However, more recent models that utilize mass distributions have completely replaced it, the Brandt model is still helpful for rapid estimates and instructional reasons [20].

### 3.3. Time of Events (ToE) Model:

To better comprehend galaxy rotation curves, Azeez et al. established the "Time of Events" (ToE) model. The foundation of this concept is a multiscale, non-adiabatic paradigm that views galaxies as complex systems. The ToE model offers a semi-empirical explanation of rotation curves by obtaining formulas that connect rotational velocity to galactic radius. When applied to some spiral galaxies, such as IC 2574, NGC 3198, NGC 1068, NGC 1097, and NGC 6503, it was shown that the predictions made by the model and the observations were well correlated. The ToE model represents the rotational velocity as follows:

$$V(r) = C_1 r^{5/2} + C_2 r + C_3 \frac{1}{r^{0.5}} + C_4 r^{7/2} + C_5 r^2 + C_6 r^{1/2} + C_7 r^3 \quad \dots (3)$$

Where $C_1$, $C_2$, and $C_3$ are the fitting parameters that are related to the transition region between the center of the galaxy and halo, central region, and near edge region, respectively. $C_4$ is the fitting parameter that represents the interaction between $C_1$ and $C_2$. $C_5$ is the fitting parameter that represents the interaction region between $C_1$ and $C_3$. $C_6$ is the fitting parameter that represents the interaction region between $C_2$ and $C_3$, and $C_7$ is the fitting parameter that represents the interaction region between $C_1$, $C_2$, and $C_3$. Particularly, the ToE model indicates that the center of the bulge has a greater effect on the rotation curves in barred galaxies than dark matter halos do in galaxies with protracted structures. This viewpoint highlights the significance of baryonic elements in galactic dynamics and provides an alternative to conventional dark matter-centric theories [18], [19].

## 4. Results and Discussion

Three models were used in this work: the ToE, NFW, and Brandt models for fitting the Milky Way rotation curve data from the BURT observatory and Sofue et al. Data [15], as shown in Figures 1, 2, and 3, respectively. The fitting parameters for these three models are listed in Table 1. The results show clearly that (ToE) model gives the closest prediction to the experimental data from both BURT and Sofue. From Table 1 and Figure 1 can be noticed that (for both Sofue and BURT data) $C_1$ has the lowest value among the first three terms, which indicates that this region has a minor effect on the rotation curve of the Milky Way galaxy. On the other hand, $C_2$ and $C_3$ both have larger values than $C_1$, but they are close to each other, which indicates that these regions have a major effect on the rotation curve in this galaxy. $C_4$ has the lowest value among all the other fitting parameters, which indicates minor interaction between the central and transition regions. $C_5$ and $C_7$ (for both BURT and Sofue data) have higher values than $C_1$, which indicates an interaction between the central and near edge regions. This also indicates that the transition region in our Milky Way galaxy has a lower mass density than the central and halo regions [29-32]. $C_6$ value (for Sofue data) is the least parameter among all other fitting parameters, which indicates minor interactions between the transition region and near edge region, while (for BURT data) $C_6$ has a value close to $C_5$ and $C_7$, this is due to uncertainty in observation and relative higher scattered points than Sofue data.

Table 1: Fitting Parameters for the Three Models

| Experimental Data | Theoretical Models | Parameters | | | | | | | | Adjusted $R^2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| SOFUE | ToE | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | Intercept | 0.937 |
| | | 162.8 | 1408 | -1556 | -15.47 | 961.7 | -30.06 | -628.3 | -74.26 | |
| | NFW | C | | | | | | | | - |
| | | 0.265 | | | | | | | | |
| | Brandt | M | | | | | | | | - |
| | | 0.1341 | | | | | | | | |
| BURT | ToE | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | Intercept | 0.788 |
| | | -4451 | -2.379 e+05 | 1.342 e+05 | 370.1 | -3.918 e+04 | -4.801 e+04 | 2.04 e+04 | 1.749 e+05 | |
| | NFW | C | | | | | | | | - |
| | | 0.247 | | | | | | | | |
| | Brandt | m | | | | | | | | - |
| | | 0.06982 | | | | | | | | |

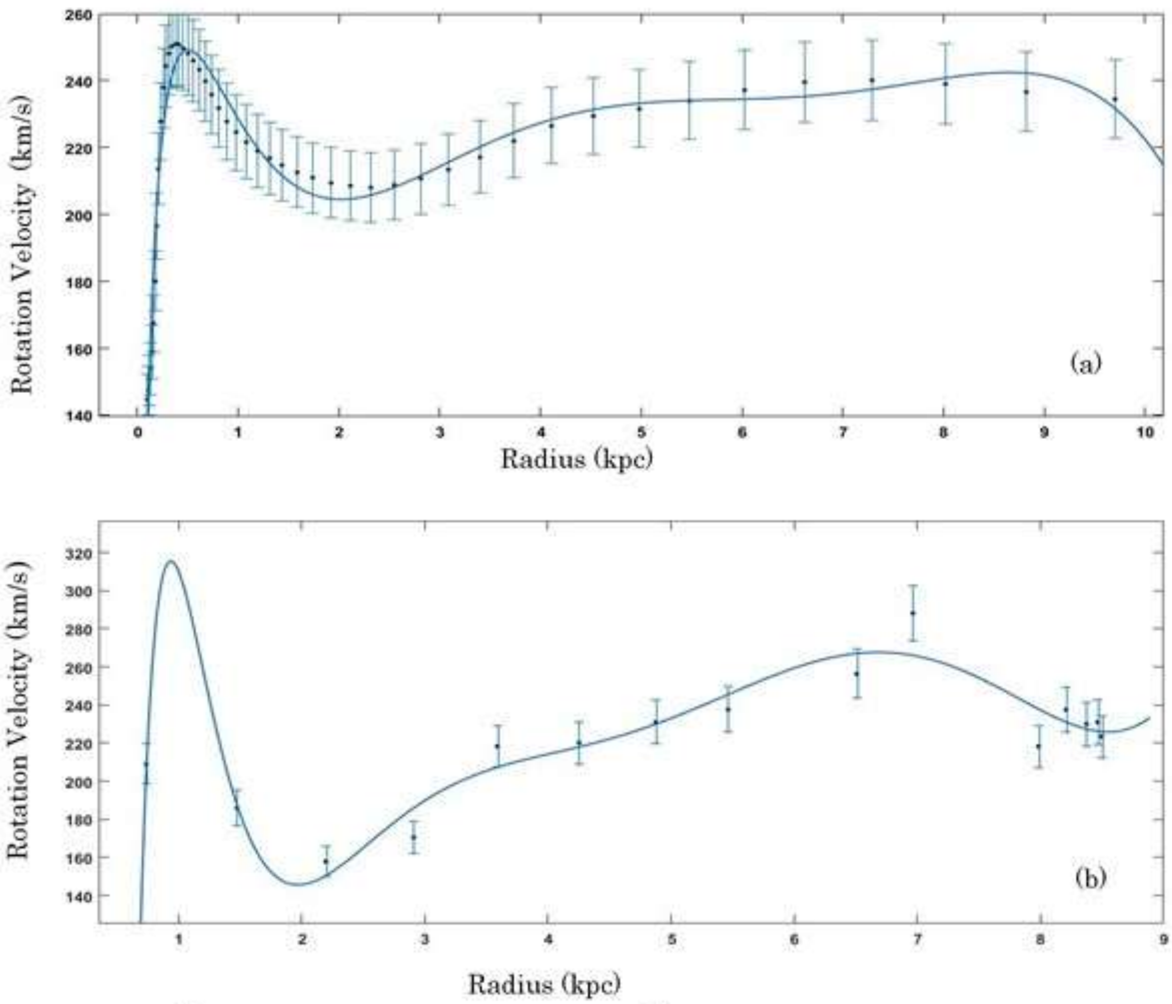


**Figure 1**: (a) Sofue data fitted with ToE model, (b) BURT data fitted with ToE. model

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From Figure 2, it can be noticed that the fitting from the NFW model deviates largely compared to the experimental data of both Sofue and BURT, especially near the edge region, due to the effect of the halo region. However, the NFW applies slightly in the central region. The Brandt model in Figure 3 shows a similar behavior to the NFW model (for Sofue data); it applies slightly in the central region and deviates near the edge due to the effect of the dark matter in the halo region. The Brandt model is not applicable to BURT data. Finally, it was noticed from the results that ToE model achieves the best convergence with the experimental data taken from the BURT observatory and from Sofue research, as this model has the ability to take into account the effect of dark matter near the edge of the galaxy, while the other two models partially agree with the experimental data in the central region of the galaxy, but they fail to predict the behavior of the rotation curve near the edge of the galaxy. Also, although the observed data points taken from the BURT observatory are few and scattered, the ToE model not only performed a fitting for the observed data, but also performed a calibration for this data by correctly predicting the behavior of the rotation curve for the BURT data in comparison to Sofue data.

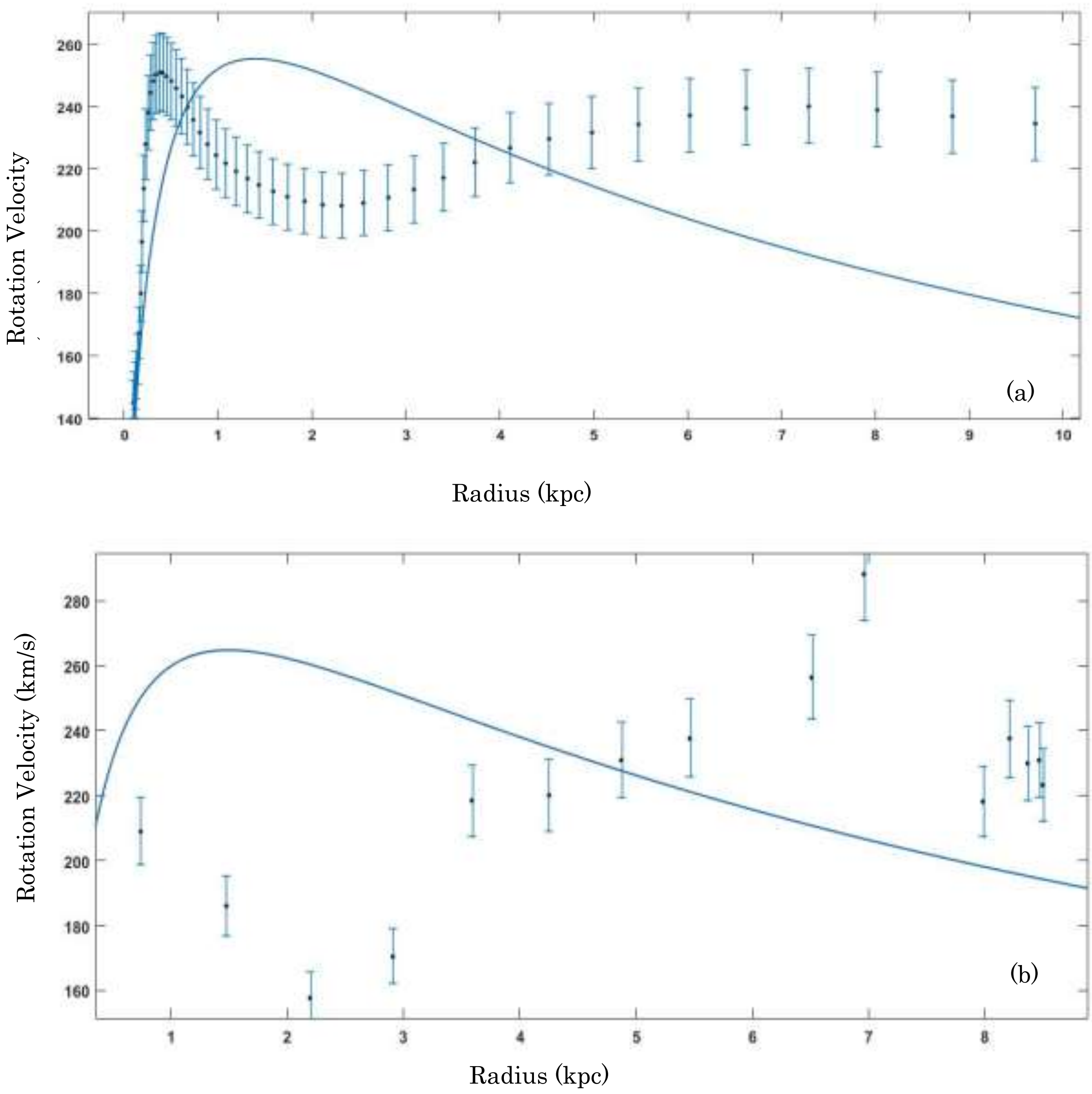


Figure 2: (a) Sofue data fitted with NFW model, (b) BURT data fitted with NFW model

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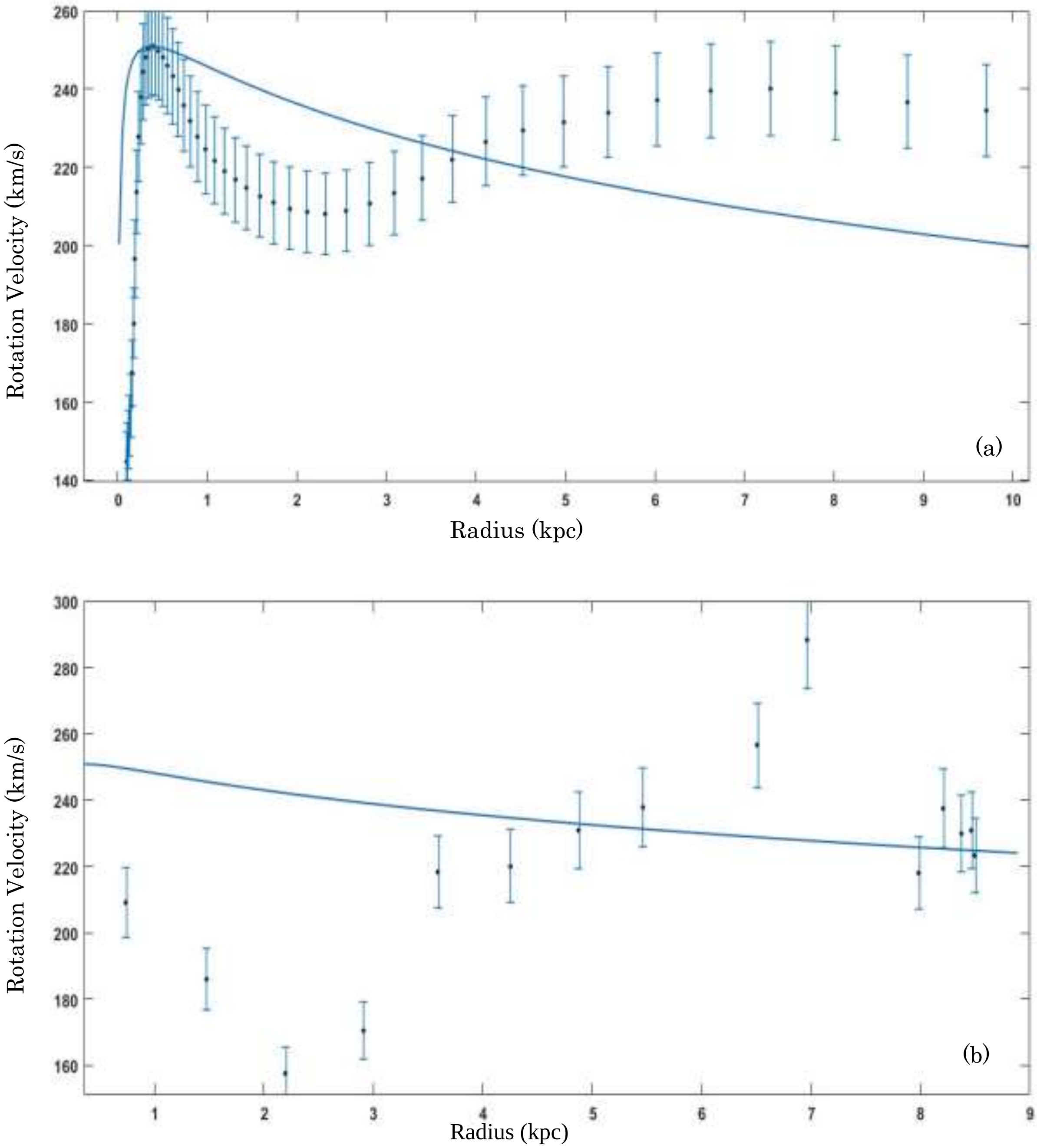


Figure 3: (a) Sofue data fitted with Brandt model, (b) BURT data fitted with Brandt model

**5. Conclusions**

In the present work, three models were tested on the rotation curve of the Milky Way galaxy observed previously by BURT and Sofue. The models are the Time of Events (ToE), Navarro-Frenk-White (NFW), and Brandt models. The fitting results showed that the ToE model gives the closest prediction from the experimental BURT and Sofue data, for all regions from the galaxy center to the edge of the galaxy. The other two models show slight closeness to the experimental data within the central region, while they diverge and fail to predict the data in the near-edge region. The slightly higher compatibility of the ToE model with Sofue observations is attributed to the fact that Sofue observations have higher sensitivity and resolution than those of BURT because it is a small radio telescope with a diameter of 3 meters. However, such small radio telescopes are still able to produce the rotation curve of the Milky Way. In addition, ToE model can predict the interaction between different regions in the galaxy, it also works as a calibration model that can predict the missing points in the BURT data compared to Sofue data. The ToE model showed the best $R^2$ values with 0.94 for Sofue data and 0.79 for BURT.

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