Inferring the kinematics of Globular Cluster Populations of the NGC-1052 DF4

Is It a Truly Dark Matter Deficient Galaxy?

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INTRODUCTION

Ultra-diffuse galaxies (UDGs) like NGC 1052-DF4, characterized by low matter densities and luminosities, have sparked controversy due to its apparent lack of dark matter (van Dokkum et al. 2015; Koda et al. 2015). van Dokkum et al. (2019) found that NGC 1052-DF4's low velocity dispersion suggests a dark matter deficiency. Other hypotheses suggest that dark matter loss is due to interactions with nearby galaxies (Ogiya and Hahn 2018) or from a "bullet dwarf" collision (van Dokkum et al. 2022). Recent studies confirmed that NGC 1052-DF4 is experiencing tidal stripping which may account for the galaxy's low dark matter content. Montes et al. (2020) showed that NGC 1052-DF4 is tidal stripping by NGC 1035, while Keim et al. (2022) suggested the central galaxy NGC 1052 may also play a role. Later, Golini et al. (2024) found NGC 1052-DF4 does appear to exhibit tidal tails which concluded that gravitational interactions may have removed the dark matter from this galaxy. Dark matter deficiency claims can also be based on dynamical modelling that assumes no rotation (Lewis, Brewer, and Wan 2020). Such rotation shifts the balance between pressure and rotational support, and hence, neglecting it will bias the inferred dark matter mass (Wasserman et al. 2018; Laudato and Salzano 2022). Inspired by the work of Lewis, Brewer, and Wan (2020), a statistical analysis of NGC 1052-DF4's globular clusters was undertaken in this study.

METHODOLOGY & OBJECTIVES

Goal: To ascertain whether the population of globular clusters rotates.

Seven globular clusters of NGC 1052-DF4 have been investigated, using Bayesian inference to determine the parameter posterior probability distributions based on the data analyzed.

The line-of-sight velocity due to rotation is:
$v_r(\theta) = A\sin(\theta - \varphi)$, **(1)**
where A signifies the rotational amplitude and φ is the rotation axis of the globular clusters.

The likelihood function are assumed to have a Normal Distribution with mean $v_r(\theta)$ and dispersion of $\sigma^2 + \sigma_i^2$:
$v_i \mid \omega \sim \text{Normal}(v_r(\theta) + v_{sys}, \sigma^2 + \sigma_i^2)$, **(2)**
where σ for velocity dispersion and ω is the vector of the unknown parameters.

The marginal likelihood estimated using Nested Sampling introduced by Skilling (2004).

Simple Uniform Prior

Non-rotation Model Rotation Model

A model comparison is performed using Bayes factor.

Complex Prior – Student t distribution

Alternative Model. In this case, the question being answered changed from ``Is the amplitude zero or non-zero?" to ``Is the amplitude small or large?“

The existence of a rotating component is relevant to the estimation of the mass of the galaxy, and therefore the question of whether NGC 1052-DF4 is truly deficient of dark matter.

$$M(<r) = \left(\left(\left(\frac{v_{rot}}{\sin(i)}\right)^2 + \sigma^2\right)\right)\frac{r}{G}, \quad \textbf{(3)}$$

where, v_{rot} is the rotational velocity given in equation 1. According to the standard astronomical definition, i is the rotation's inclination angle, r is the reference radius of 7.5 kpc, and G is the Newtonian gravitational constant.

RESULTS & DISCUSSION

NON-ROTATIONAL MODEL

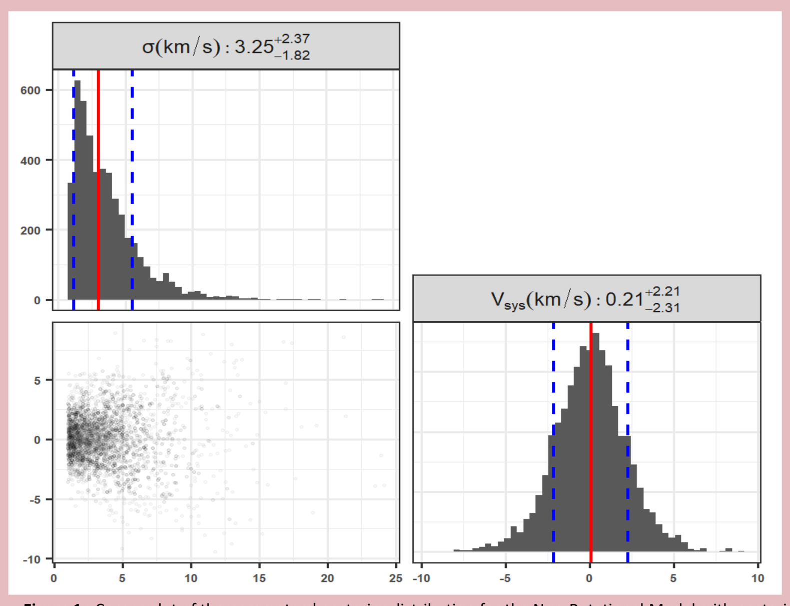

Figure 1: Corner plot of the parameters' posterior distribution for the Non-Rotational Model with posterior summary statistics of parameters. The estimates presented in the figure were the median value and the 68% central credible interval. All of the values were rounded to 2 d.p.

This study first considered a scenario in which the globular cluster population does not rotate. Under this assumption, the amplitude A in Equation (1) will be equal to zero, and hence the velocity v_i is entirely dependent on the velocity dispersion σ. This leaves only two parameters to be estimated, σ and v_{sys}. Figure 1 displays the summary statistics of parameter estimates and the posterior distributions for systematic velocity v_{sys} and velocity dispersion σ. The distribution of σ is right-skewed, whereas the distribution of v_{sys} is symmetric. Finally, this Non-Rotational Model has a marginal likelihood of ln{Z} = -25.6095 ± 0.1762. The marginal likelihood estimate for the Non-Rotational model is slightly larger than the Rotational Model.

ROTATIONAL MODEL

The second model considered includes a nonzero rotational amplitude A. The posterior distribution in Figure 2 reveals a significant portion of the posterior probabilities for the A and σ are close to zero. This implies the rotational amplitudes of the globular clusters in NGC 1052-DF4 are extremely small. Moreover, the right-skewed posterior distribution of σ results from the small sample size, as high values of σ cannot necessarily be ruled out. The posterior distribution of v_{sys} is symmetric. Interestingly, the posterior distribution for θ is weakly bimodal, as there are multiple ways of dividing the globular clusters into a red-shifted half and a blue-shifted half (on average). Note that the apparent large bimodality is an artifact of the periodicity of the parameter space --- the smaller, actual bimodality can be seen when angles are redefined to be centered around zero. The median values of amplitude, A, is 4.07 km\s, which are somewhat higher than those of velocity dispersion, σ. The marginal likelihood of the Rotational Model is ln{Z} = -26.5079 ± 0.1919.

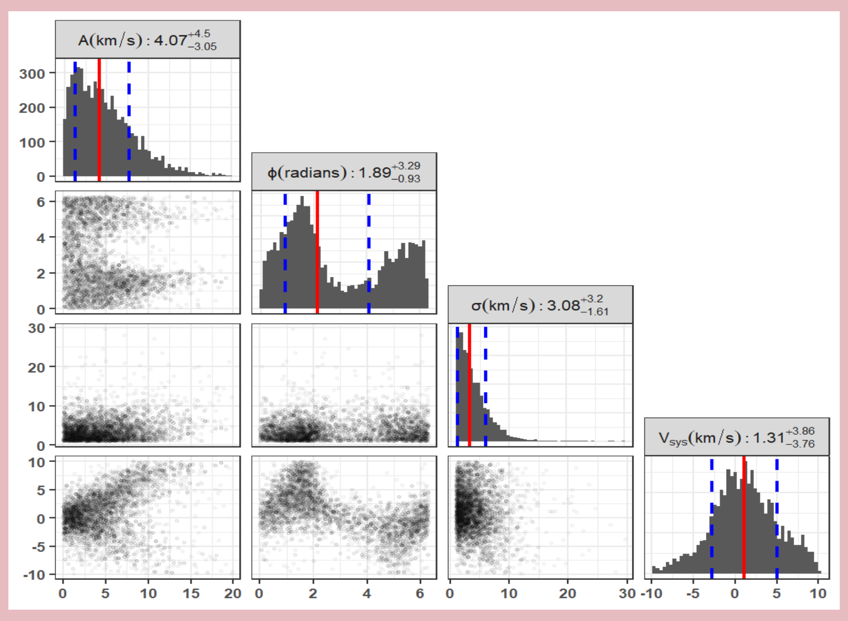

Figure 2: Corner plot of the parameters' posterior distribution for the Rotational Model with posterior summary statistics of parameters. The estimates presented in the figure were the median value and the 68% central credible interval. All of the values were rounded to 2 d.p.

ALTERNATIVE MODEL

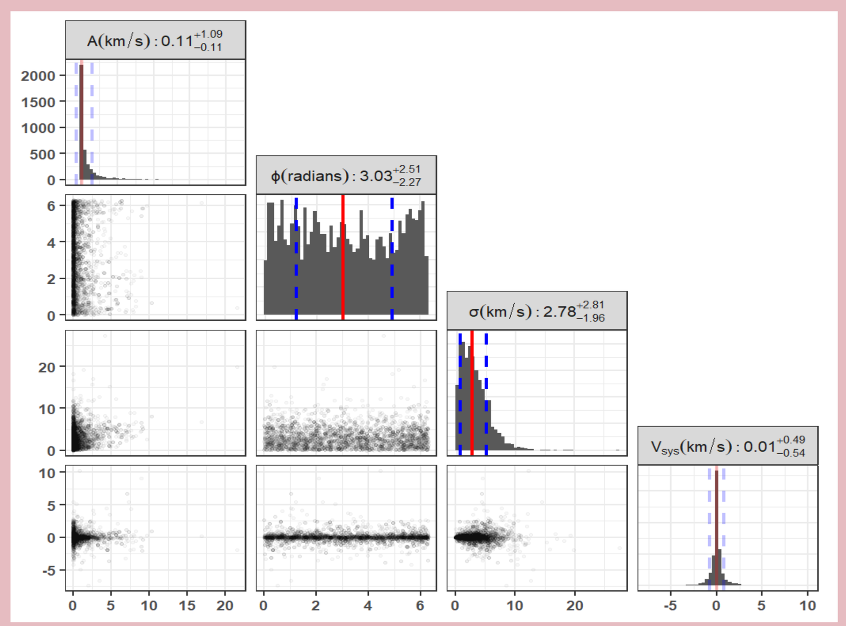

Figure 3: Corner plot of the parameters' posterior distribution for the Alternative Model with posterior summary statistics of parameters. The estimates presented in the figure were the median value and the 68% central credible interval. All of the values were rounded to 2 d.p.

Finally, the rotational model but with a more complex student-t prior distribution is considered. The idea is that the rotational amplitude is likely not to be precisely zero but may be small, moderate, or large. Roughly speaking, the rotating and non-rotating (or, more accurately, hardly-rotating) possibilities are here represented in the parameter space of a single parameter estimation problem, rather than being represented in two separate models, as we have done so far. Figure 3 demonstrates a similar outcome to Figure 2. Still, the median value of A is smaller than that of σ. The marginal likelihood of the Rotational Model is ln{Z} = –23.0067 ± 0.1014.

MODEL COMPARISON

Models	Ln Z
Non-Rotational	-25.61 ± 0.18
Rotational	-26.51 ± 0.19

Table 1. Table of Marginal likelihood estimates for the Non-Rotational and Rotational Model. All of the values were round to 2 d.p.

$$BF(M_1, M_2) = \frac{\exp(logP(D \mid M_1))}{\exp(logP(D \mid M_2))} = \frac{\exp(-25.6095)}{\exp(-26.5079)} \approx 2.46, \quad \textbf{(4)}$$

The study will not compare the marginal likelihood of Alternative Model to the other two models since it is intended to capture both possibilities within a single model. According to the value (2.46) of the Bayes factor calculated in Equation 4 there is only very weak evidence to support the Non-Rotation Model (guides for interpretation of Bayes Factors may be found in Kass and Raftery (1995)). In other words, the rotation of NGC 1052-DF4's globular clusters is not completely ruled out. However, if it does exist, it is small.

Based on equation 1, the amplitude is directly proportional to the rotational velocity. Also, from equation 3, it can be seen that the rotational velocity and the velocity dispersion, σ, are directly related to the mass of the galaxy. Consequently, a low amplitude value (around 0) and a slightly larger value of σ indicate that the globular cluster rotational velocities will likewise be small, resulting in a very low estimated mass of the NGC 1052-DF4 galaxy, which is about the same as in the previous study (van Dokkum et al. 2019). Hence, these results further imply that the NGC 1052-DF4 galaxy contains little dark matter, which is consistent with the result of a newly published paper from Shen et al. (2023).

CONCLUSION

This project explores the globular cluster population of NGC-1052 DF4, a dark matter deficient galaxy, using Bayesian inference to search for the presence of rotation. The rotational characteristics of seven globular clusters in NGC-1052 DF4 were investigated, finding that a non-rotating kinematic model has a higher Bayesian evidence than a rotating model, by a factor of approximately 2.5. In addition, we find that under the assumption of rotation, its amplitude must be small. This distinct lack of rotation strengthens the case that, based on its intrinsic velocity dispersion, NGC-1052 DF4 is a truly dark matter deficient galaxy. The result from this study is consistent with the previous studies (van Dokkum et al. 2019; Golini et al. 2024) and reinforces the conclusion from Shen et al. (2023).

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