A Revised Velocity for the Globular Cluster GC-98 in the Ultra Diffuse Galaxy NGC 1052-DF2

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We recently published velocity measurements of luminous globular clusters in the galaxy NGC 1052-DF2, concluding that it lies far off the canonical stellar mass – halo mass (SMHM) relation (van Dokkum et al. 2018a) [vD18]. Here we present a revised velocity for one of the globular clusters, GC-98.

LOST AND FOUND: THE LRIS SPECTRUM OF GC-98

GC-98 has been the subject of some debate. In vD18 we listed its velocity as \( \text{cz} = 1764_{-11}^{+11} \text{ km/s}, 39 \text{ km/s removed} \) from the central value of the sample. We inferred that the intrinsic velocity distribution of NGC 1052-DF2 is consistent with a Gaussian only for the narrow range \( 8.8 < \sigma_{\text{intr}} < 10.5 \text{ km/s} \) (at 90% confidence), with the lower limit driven by GC-98. Martin et al. (2018) [M18] derive a 90% upper limit of \( \sigma_{\text{intr}} < 17.3 \text{ km/s} \) if GC-98 is included and \( \sigma_{\text{intr}} < 14.3 \text{ km/s} \) if it is not. Although all these estimates imply a strongly dark matter-deficient galaxy (see Discussion), the quantitative constraints on the halo mass are sensitive to the treatment of this single object.

As discussed in vD18 most of the clusters were observed using two different spectrographs (DEIMOS and LRIS on Keck). We thought we had observed GC-98 only once, with DEIMOS. However, we recently realized that we also observed the object in one of the LRIS masks. The combined 28,800 s LRIS+DEIMOS spectrum is shown in Fig. 1. Using the methodology described in vD18 we derive a radial velocity of \( \text{cz} = 1784_{-10}^{+10} \text{ km/s} \). The large change can be attributed to systematic residuals in the fit to the DEIMOS spectrum (see vD18, Fig. 2).

REVISED VELOCITY DISPERSION

The velocities of the 10 clusters are shown in Fig. 1, ordered by their absolute distance from the mean. The red curve is the expected distribution if the galaxy has very little dark matter; this is approximated by a Gaussian with \( \sigma_{\text{stars}} = 7.0_{-1.3}^{+1.6} \text{ km/s} \) perturbed by the errors. We determined \( \sigma_{\text{stars}} \) using the Wolf et al. (2010) relation with \( M_{\text{stars}} = 2.0_{-0.7}^{+1.0} \times 10^8 \text{ M}_\odot \) and \( R_e = 2.2 \text{ kpc} \). The black curve is the expected dispersion of a halo with mass \( 6 \times 10^{10} \text{ M}_\odot \), assuming that \( \sigma_{\text{ap}}(0.1R_e) = (0.6 \pm 0.1)V_v \) (see Lokas & Mamon 2001; Rodríguez-Puebla et al. 2017).

In the right panel we show the constraints on the intrinsic dispersion, using two methods: the likelihood and Approximate Bayesian Computation (ABC; Beaumont et al. 2002). The main advantage of ABC is that it does not assume a particular form of the likelihood function. In vD18 we used the biweight scale as the ABC summary statistic; here we simply use the rms. We derive a revised dispersion of \( \sigma_{\text{intr}} = 5.6_{-1.2}^{+5.2} \text{ km/s} \) (\( \sigma_{\text{intr}} < 12.4 \text{ km/s at 90% confidence} \)). The likelihood gives \( \sigma_{\text{intr}} = 7.8_{-2.2}^{+5.2} \text{ km/s} \) (\( \sigma_{\text{intr}} < 14.6 \text{ km/s} \)).
Figure 1. Top: combined DEIMOS+LRIS spectrum of GC-98. Left: velocities of the 10 globular cluster-like objects in NGC 1052-DF2. Right: constraints on the intrinsic velocity dispersion. We find $\sigma_{\text{intr}} = 5.6^{+5.2}_{-3.8}$ km/s. The stars alone contribute $\sigma_{\text{stars}} = 7.0^{+1.5}_{-1.3}$ km/s; the expectation from the SMHM relation is $\sigma_{\text{intr}} = 35 \pm 6$ km/s.

DISCUSSION

The revised velocity dispersion is nearly identical to that expected from the stars alone, and does not significantly alter the analysis of vD18. The implied ratio $M_{\text{halo}}/M_{\text{stars}}$ is of order unity and consistent with zero. The expectation from the SMHM relation is $M_{\text{halo}}/M_{\text{stars}} \sim 300$.

M18 suggest that NGC 1052-DF2 might not be dark matter deficient, based on the upper limit that they derive on its $M/L$ ratio. Specifically, M18 infer that $M/L$ could be as high as 8.1 within $R = 7.6$ kpc, from their 90% upper limit on the dispersion ($\sigma_{\text{intr}} < 17.3$ km/s). However, $M/L$ is a strong function of radius, and we caution against using this quantity by itself as a proxy for halo mass. An $M/L$ ratio < 8.1 implies a dark matter mass within $R = 7.6$ kpc of $< 6 \times 10^8 M_\odot$, and a halo mass $< 1 \times 10^9 M_\odot$ (see also Laporte et al. 2018). As the expected halo mass from the SMHM relation is $\sim 6 \times 10^{10} M_\odot$, the M18 analysis implies that NGC 1052-DF2 lies at least a factor of 60 below the SMHM relation. Because of their large spatial extent for their luminosity, the expected $M/L$ ratio for UDGs on the SMHM relation is of order 30–100, as observed in Virgo and Coma (see Fig. 4 in Toloba et al. 2018).

In summary, the existence of NGC 1052-DF2 adds to the evidence that the SMHM relation has considerable scatter at the low mass end (e.g., Martin et al. 2014; Oman et al. 2016). It is impossible to say whether the galaxy has no dark matter at all but it is clearly extremely dark matter deficient. Next we aim to measure the stellar velocity dispersion of NGC 1052-DF2, to test whether the velocity distribution of the globular clusters is approximately isotropic. Finally, we emphasize that the kinematics and size are not the only remarkable aspects of NGC 1052-DF2, as its globular
cluster population is different from all other known galaxies (see van Dokkum et al. 2018b). It seems likely that the unusual properties of NGC 1052-DF2 have a common origin, but what this might be is still elusive.

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