Robust velocity dispersion and binary population modelling of the ultrafaint dwarf galaxy Reticulum II

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ABSTRACT
We apply a Bayesian method to model multi-epoch radial velocity measurements in the ultrafaint dwarf galaxy Reticulum II, fully accounting for the effects of binary orbital motion and systematic offsets between different spectroscopic data sets. We find that the binary fraction of Ret II is higher than 0.5 at the 90 per cent confidence level, if the mean orbital period is assumed to be 30 yr or longer. Despite this high-binary fraction, we infer a best-fitting intrinsic dispersion of $2.8^{+0.7}_{-1.2}$ km s$^{-1}$, which is smaller than the previous estimates but still indicates Ret II is a dark matter dominated galaxy. We likewise infer a $\lesssim 1$ per cent probability that Ret II’s dispersion is due to binaries rather than dark matter (which would correspond to the regime $M/L \lesssim 2 M_\odot/L_\odot$). Our inference of a high-close binary fraction in Ret II echoes previous results for the Segue 1 ultrafaint dwarf and is consistent with studies of Milky Way halo stars that indicate a high-close binary fraction tends to exist in metal-poor environments.

Key words: binaries: spectroscopic; – galaxies: kinematics and dynamics.

1 INTRODUCTION
Ultrafaint dwarf (UFD) galaxies comprise the extreme end of the galaxy luminosity function being the faintest and most dark matter dominated galaxies known. Their high mass-to-light ratios (Simon & Geha 2007), paucity of gas and extremely low metallicities (Kirby et al. 2008) indicate they host very old and sparse star populations, with the bulk of their star formation occurring before the epoch of reionization and being quenched not long after (Brown et al. 2012). As a result of their high-dark matter content, UFDs are excellent laboratories for understanding the nature of dark matter in several respects: their expected abundance and density profile depends sensitively on the particle nature of dark matter, for example, if it is warm (Lovell et al. 2014) or has a significant cross-section for self-interactions (Rocha et al. 2013; Elbert et al. 2018). In addition they are excellent targets to search for the products of dark matter self-annihilation as a result of their low astrophysical backgrounds (Ackermann et al. 2015). The study of UFDs has been reinvigorated in the past few years by the recent discovery of several new candidate dwarf galaxies by the Dark Energy Survey (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Kim & Jerjen 2015; Koposov et al. 2015a; Luque et al. 2016, 2017b,a).

The estimated high-dark matter content of ultrafaint dwarf galaxies hinges on an accurate measurement of the line-of-sight velocity dispersion of their constituent stars, with dispersions typically in the range of 1–6 km s$^{-1}$ (Simon & Geha 2007). However, their low intrinsic dispersions make the task difficult for a few reasons. First, in many cases they are too distant for radial velocities of main-sequence turn-off stars to be measured by present instruments leaving only the red giants in the sample, which are relatively few in number. Secondly, spectrographs have systematic floors which limit the measurement of stellar velocities up to $\sim 2.2$ km s$^{-1}$. Finally, the dispersions are low enough that the orbital motion of close binary systems can inflate them significantly (Wilkinson et al. 2002; McConnachie & Côté 2010; Spencer et al. 2017).

Of these systematics binaries are perhaps the most worrisome, because unexpectedly high-radial velocity variations have been detected in several UFDs. This occurred, for example, among RGB stars in the Segue 1 sample, which did not inflate its dispersion dramatically due to a large sample of main-sequence turn-off stars (Simon et al. 2011). An initial velocity dispersion measurement of Triangulum II (Kirby et al. 2015; Martin et al. 2016) had 1–2 unresolved binaries that inflated its dispersion (Kirby et al. 2017). Similarly, the dispersion of Boötes II (Koch et al. 2009) is inflated due to a known binary (Ijii et al. 2016a), and Carina II’s dispersion would likely have been inflated if multi-epoch spectroscopy had not been obtained (see one epoch row of table 3 in Li et al. 2018). In classical dwarf spheroidals, measured binary fractions appear to
vary considerably with some being higher and others lower than the expected value for Milky Way field binaries (Olszewski, Pryor & Armandroff 1996; Minor 2013; Spencer et al. 2018, 2017). Besides dwarf galaxies within the Milky Way, there is mounting evidence that the fraction of close binaries is indeed higher in low-metallicity systems (Badenes et al. 2018; Moe, Kratter & Badenes 2018). Thus, there is a very real possibility that the measured dispersions of many ultrafaint dwarfs are significantly inflated due to binary motion; indeed, some may turn out to be diffuse globular clusters in disguise.

The most direct way to correct the dispersions of UFDs for binary motion is to perform spectroscopic follow-up over two or more epochs, and model the binary contribution to the radial velocities directly. This strategy was carried out in the case of Segue 1 (Martínez et al. 2011; Simon et al. 2011). While spectroscopic follow-up has been recently performed for a few of the recent DES dwarfs, including Reticulum II, the binary modelling is complicated by the fact that radial velocity measurements have been made using different instruments and different methods of analysis (Koposov et al. 2015b; Simon et al. 2015; Ji et al. 2016a; Roederer et al. 2016). This gives rise to systematic velocity offsets between the different data sets, which can masquerade as binary variability. As a result, any attempt to model the binary component of velocity variations should include systematic velocity offsets between data sets as model parameters.

In this paper we constrain the velocity dispersion of the ultrafaint dwarf Reticulum II, including the effects of binary orbital motion and systematic offsets between data sets, in a Bayesian analysis. By constructing the binary likelihood for each star and comparing it to the single-star likelihood, a probability of binarity can be inferred that does not rely on definitively identifying an individual star as a binary. The approach is similar to that employed for Segue 1, except that in addition we include systematic offset parameters to be inferred alongside the binary population parameters; hence, any degeneracy between the intrinsic dispersion, instrumental systematics, and binarity can be inferred in a consistent manner.

2 BAYESIAN METHOD: CORRECTING FOR BINARITY MOTION

In order to correct the velocity dispersion of Ret II for binary motion, we follow the method used in Martínez et al. (2011) and Minor (2013): we construct a multi-epoch likelihood for each star and compare it to the single-star likelihood, a probability of binarity can be inferred that does not rely on definitively identifying an individual star as a binary. The approach is similar to that employed for Segue 1, except that in addition we include systematic offset parameters to be inferred alongside the binary population parameters; hence, any degeneracy between the intrinsic dispersion, instrumental systematics, and binarity can be inferred in a consistent manner.

For some epochs we will fix the corresponding systematic offsets to zero, while for others we will vary the offsets as free parameters. The set of systematic offsets to be varied will be denoted as \( S = \{ \lambda_1, \lambda_2, \ldots \} \). Our velocity likelihood then becomes,

\[
\mathcal{L}(v_i|e_i, t_i, M; \sigma, \mu, B, S) = (1 - B)\mathcal{L}(\Delta v'_i, e_i) e^{-\frac{(i - m)^2}{2\sigma^2 + e_i^2}} + B \mathcal{L}_b(v_i|e_i, t_i, M; \sigma, \mu, S),
\]

where the first term gives the likelihood for non-binary stars, and the second is the binary star likelihood. Note that the non-binary likelihood has been factorized into a likelihood in the star’s mean velocity \( \langle v' \rangle \), and a likelihood in terms of velocity differences, denoted by \( \mathcal{L}(\Delta v'_i, e_i) \); the latter is given by

\[
\mathcal{L}(\Delta v'_i, e_i) = \frac{\sqrt{2\pi e_i}}{\prod_{n=1}^{\infty} 2\pi e_i} \times \exp \left\{ -\frac{1}{4} \sum_{i,j=1}^{n} \frac{(v'_i - v'_j)^2}{e_i^2 + e_j^2 + e_i^2 e_j^2 \left( \sum_{k=1}^{n} \frac{1}{c_k} \right)} \right\}.
\]

The last term in the denominator of the exponent is implicitly zero when \( n = 2 \). To generate the likelihood for binary stars (the second term in equation 2), we first generate the binary likelihood in the centre-of-mass frame of the binary system, denoted by \( P_b(v'_i - v_{cm}|e_i, t_i, M) \). This is accomplished by the following procedure: for each star, we estimate the primary star’s mass (assuming it is a binary) using its measured magnitude by interpolating from an isochrone for a stellar age of 10 Gyr (the result is rather insensitive to the exact stellar ages). We then run a Monte Carlo simulation for a large number of binary systems with this primary mass to generate simulated velocity measurements with the same number of epochs and time intervals as in the real data, where the binary properties are drawn from distributions similar to those observed in the solar neighbourhood (see Minor et al. 2010, for details on the orbital parameters and their assumed distributions). For a given value of \( v_{cm} \) and offset parameters, we can estimate the likelihood in the corrected velocity measurements \( v'_i - v_{cm} \) by binning around this point in velocity space; we choose a hypersphere for the bin with two different trial bin sizes, corresponding to 0.36 and 0.6 times the average measurement error, respectively. The likelihood is then found by taking the fraction of points that lie within the bin and dividing by the volume of the hypersphere. This process is repeated over an entire table of bins corresponding to different \( v_{cm}, \lambda_i \) values. To ensure accuracy of the resulting likelihood, we begin with \( 10^5 \) simulated binaries, after which points are subsequently added to the bins until the binary likelihood (or rather, its average over the \( v_{cm} \) bins) converges to within a specified tolerance for all the offset values in the table; if the two bin sizes converge to likelihood values that differ by more than a given threshold (we choose \( 2 \times 10^{-3} \)), the bin sizes are halved and the process is repeated for a larger number of simulated stars until convergence is reached.\(^1\)

\(^1\)For stars with obvious binary velocity variations (and hence, a small non-binary likelihood given by equation 3), the bins will lie in the tail of the velocity distribution, and hence a much larger number of stars is required.
With these likelihood tables now in hand to evaluate the binary likelihood for chosen values of the galaxy’s systemic velocity \( \mu \) and dispersion \( \sigma \), we interpolate in the offset parameters \( \lambda \), and integrate over the tabulated \( v_{\text{cm}} \) values as follows:

\[
L_b(\sigma, \mu, S) = \int_{-\infty}^{\infty} P_b(v'_e - v_{\text{cm}}|e_i, t_i, M) e^{\frac{(v_{\text{cm}} - v_{K15})^2}{2\sigma^2}} dv_{\text{cm}}. \tag{4}
\]

From a hierarchical modelling point of view, this can be thought of as marginalizing over \( v_{\text{cm}} \) for each star, assuming a Gaussian prior whose hyperparameters \( \mu, \sigma \) will be determined at the next level of inference (indeed, this has already been done implicitly for the non-binary likelihood to give the Gaussian factor in equation 2).

As in Martinez et al. (2011), we assume a log-normal period distribution for the binaries; however, we do not vary the period distribution parameters of the underlying binary population since the constraints would be very poor, given the sample size. However, for the sake of comparison we will test two models: one in which the period distribution is similar to Milky Way field binaries with a mean period of \(~180\) yr (Duquennoy & Mayor 1991), and one in which the mean period is \(10^3\) d \(\approx 27\) yr. As we discuss in Section 4, the latter choice is motivated by the mean period inferred in low-metallicity halo stars in Moe et al. (2018). In both cases, the width of the log-period distribution is assumed to be \( \sigma_{\log p} = 2.3 \), similar to that of binaries in the solar neighbourhood as determined by Duquennoy & Mayor (1991) and independently by Raghavan et al. (2010).

### 3 DATA

We make use of three different radial velocity data sets from Ret II, composed entirely of red giant stars with high probability of membership. The bulk of the velocity measurements come from Simon et al. (2015) using the Magellan or M2FS spectrograph (hereafter referred to as S15), of which 25 stars were identified as members, and Koposov et al. (2015b) using VLT or Giraffe with 18 member stars (hereafter K15). Nearly all of the stars in the K15 sample were also included in the S15 sample, with the observations being made 18 d apart. Hence, only very short period binaries with periods less than a year can be expected to show significant velocity variations beyond the measurement error between these two data sets. We also include high-resolution velocity measurements of nine member stars from Ji et al. (2016b) using the Magellan or MIKE spectrograph along with four additional high-resolution measurements from Roederer et al. (2016; hereafter J16 or R16). Compared to the original S15 data set, these later measurements occur 226 and 268 d later, respectively, so these stars may be expected to show velocity variations if they are binaries with periods of order a few years or shorter. Although we have only 11 stars with repeat measurements over time-scales of several months, these latter measurements carry greater relative weight due to the small measurement errors (\(~0.1–0.2\) km s\(^{-1}\)) in the J16 or R16 data sets.

Since the stars in our sample have velocity measurements from multiple data sets using different spectrographs, any systematic offset between the data sets would bias the inferred binary fraction in our analysis. To guard against this, we will model such systematic offsets explicitly as free parameters. To get a sense of whether such offsets are present, in Fig. 1(a) we plot a comparison of velocity measurements between the S15 and K15 data sets for stars that are common to both. Interestingly, most stars lie well above the line \( v_{S15} = v_{K15} \), and in a few stars this difference is beyond 2\( \sigma \) for the measurement errors in either data set. Since the measurements were taken only 18 d apart, this apparent offset in a large number of stars is unlikely to be explained by binary motion unless the binary population is quite extreme. The implication is that either the K15 data may have a positive systematic offset, S15 may have a negative offset, or perhaps some combination of the two. Likewise, in Fig. 1(b) we compare the J16 measurements with S15 and K15. Since the measurements in this figure were taken 7–8 months apart, we may expect up to a few of the velocity differences to be due to binary motion. With this caveat in mind, a few stars in both S15 and K15 seem to have a positive velocity difference relative to J15 that lies beyond 2\( \sigma \).

With this in mind, we will include offsets in S15 and K15 as free parameters. There is little to be gained by including an extra systematic offset parameter for the J16 and R16 measurements, because the systemic velocity of the galaxy is not known a priori; hence, an offset to all the measured velocities would simply translate the resulting mean velocity and thus there would be no unique solution for all the offsets and systemic velocity. If it turns out that J16 and R16 in fact have a systematic offset relative to S16 and K16, our analysis would result in a biased inferred systemic velocity, but otherwise this would not affect our inferred dispersion or binary fraction.

### 4 RESULTS

For our fiducial binary population model, we assume a mean period of \(10^3\) d, or roughly 27 yr. This is motivated by the work of Moe et al. (2018), who infer this mean period for metal-poor Milky Way halo stars using data from Latham et al. (2002; see also Carney et al. 2005). We will then compare our fiducial result to the case of a 180-yr mean period, which was inferred for G-dwarf binaries in the solar neighbourhood by Duquennoy & Mayor (1991). For simplicity, in either case we assume a dispersion of periods similar to that of Milky Way field binaries (\( \sigma_{\log p} = 2.3 \)). Our velocity offset parameters are defined as the offset in the K15 data set \( \lambda_{K15} \), and the relative offset between the S15 and K15 data sets, \( \Delta_{SK} = \lambda_{SK} - \lambda_{S15} \). In our fiducial analysis we assume a Jeffrey’s (non-informative) prior in the velocity dispersion, which is equivalent to having a uniform prior in \( \ln \sigma \); for all other parameters we assume a uniform prior (which is in fact equivalent to the Jeffrey’s prior for those parameters).

In Fig. 2 we show the resulting posteriors for our fiducial model with mean period of 27 yr. Although a large range of binary fractions is allowed (\( B > 0.2 \)), a high binary fraction is still preferred even for this relatively short-mean period. The most probable velocity dispersion is \( 2.8^{+0.7}_{-0.2} \) km s\(^{-1}\), where the uncertainties here denote the 68 per cent credible interval. There is a small tail in the posterior extending to \( \sigma = 0 \) km s\(^{-1}\); note that this tail requires a binary fraction \( B > 0.8 \), since binaries must make up all of the dispersion in this case. In addition, while there is a large uncertainty in either of the offsets \( \lambda_{S15} \) and \( \lambda_{K15} \), we find the relative offset \( \Delta_{SK} \) is well constrained to \( 1.2 \pm 0.5 \) km s\(^{-1}\). The solution where both offsets are zero lies just outside the 95 per cent probability contours. Hence, there seems to be a clear offset between the K15 and S15 data sets, but whether one or both of these data sets are offset with respect to the J16 measurements is quite uncertain given the small number of stars in the J16 sample.

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Figure 1. Comparison of velocity measurements between data sets for stars that are common to both data sets. The error bars represent 1\(\sigma\) errors for each data set. The dashed line corresponds to equal velocities being measured, e.g. in (a) it represents \(v_{S15} = v_{K15}\). Note that the S15 and K15 measurements are separated by only 18 d, and therefore binary orbital motion is unlikely to account for the majority of offsets between the two data sets in figure (a).

Figure 2. Joint posteriors in the systemic velocity \(v_{sys}\), intrinsic velocity dispersion \(\sigma\), binary fraction \(B\), the velocity offset in the K15 data set \(\lambda_{K15}\), and the relative offset \(\Delta\lambda_{SK} = \lambda_{K15} - \lambda_{S15}\). In this analysis, the mean period of Ret II is assumed to be \(10^4\) d (\(\approx 27\) yr), with a spread in the log-normal period distribution identical to Milky Way field binaries \(\sigma_{\log P} = 2.3\). The posteriors are plotted using a Jeffreys’s prior in the dispersion, which is equivalent to having uniform prior in \(\ln \sigma\), with uniform priors in the other parameters.
The metallicity spread of Ret II is already strong evidence that Ret II is a galaxy rather than a globular cluster (Willman & Strader 2012). Here we check whether its velocity dispersion paints a consistent picture of Ret II being a dark-matter dominated galaxy. If we assume the extreme scenario of no dark matter, we can estimate what the expected intrinsic dispersion of Ret II would be. Globular clusters of the Milky Way typically have mass-to-light ratios of $1−2 M_\odot/L_\odot$. To be conservative, we choose the upper end of this range ($2 M_\odot/L_\odot$) and using formula 2 in Wolf et al. (2010), we find this corresponds to $\sigma \approx 0.21$ km s$^{-1}$. Thus, we define the ‘no dark matter’ scenario to be the regime $\sigma \leq 0.21$ km s$^{-1}$, where nearly all of Ret II’s dispersion would be due to binaries. For our fiducial 27-yr mean period and a non-informative (log) prior in the dispersion, we infer a 1 per cent probability for $M_\odot/L_\odot < 2$; assuming a 180-yr mean period (as in solar neighbourhood binaries), the probability drops to 0.4 per cent. In this regime where Ret II’s dispersion is due to binaries, the posteriors show there must be a positive offset of $1−3$ km s$^{-1}$ between the K15 velocities and the J16 velocities; in this case, the velocity changes due to binaries would be more dramatic, and hence requires a very high binary fraction. On the other hand, if the offsets are smaller ($K15 \lesssim 1$ km s$^{-1}$; $S15 \lesssim 0$ km s$^{-1}$) this does not rule out a high binary fraction, but it does rule out the zero-dispersion scenario.

How sensitive are our results to the assumed binary population and priors? In Fig. 3 we plot the inferred dispersion posterior using a few different models. First, we repeat the analysis but without including binaries or offsets (black line). In this case the most probable inferred dispersion is 3.5 km s$^{-1}$, and there is essentially zero probability of having an intrinsic dispersion less than 2 km s$^{-1}$. We plot our fiducial model with a mean period of 27 yr (blue solid line), which used a log-prior in the dispersion; the same model with a uniform prior in the dispersion (blue dotted line) significantly reduces the probability of having a dispersion dominated by binaries with essentially zero probability of $\sigma \approx 0$ km s$^{-1}$, while the most probable value is relatively unchanged. Finally, we try a model with a mean period of 180 yr, similar to G-dwarfs in the Milky Way field, with a log-prior in dispersion (red solid line) as well as a uniform prior (red dashed line). Note that the most probable intrinsic dispersion is fairly robust to these changes in model or priors, in all cases being roughly 0.7 km s$^{-1}$ lower compared to the uncorrected dispersion estimate. In addition, the tail going to very small intrinsic dispersions is only significant in our fiducial model (27-yr mean period, log-prior in dispersion). With that said, it is certainly possible to increase the odds of having a binary-dominated dispersion if one assumes a shorter mean period; although it seems unlikely, this possibility cannot be ruled out entirely.

To check that the inferred offsets are consistent with a Gaussian velocity distribution plus binaries, we take the best-fitting values for the offsets ($\lambda_{S15} = −1.48$, $\lambda_{K15} = −0.35$) and apply the correction to the appropriate measurements in the data by subtracting these offsets. In Fig. 4(a) we plot the cumulative distribution of $\Delta_e/\sigma_{2e}$, where $\Delta_e = |v_1 − v_2|$ is the velocity difference between two consecutive epochs for each star and $\sigma_{2e} = \sqrt{\sigma_1^2 + \sigma_2^2}$ is the corresponding uncertainty in this difference. For simplicity, we have only included the S15 and K15 data sets in this figure, for which the measurements are only 18 d apart, to minimize the effects of binaries. When the offset correction is not applied (red solid line), the cumulative distribution is systematically above what would be expected for a purely Gaussian distribution if the measurement errors properly reflect reality (although this is not statistically significant for any individual star except for the two that lie beyond $3\sigma_{2e}$; the latter two have a high probability of being short-period binaries). However, when the measurements are adjusted for the best-fitting offset values, the distribution follows a Gaussian quite closely (blue dashed line) with the exception of the two probable binary stars. Thus, the best-fitting model does indeed appear consistent with a Gaussian velocity distribution plus a binary tail due to short-period binaries. We should note that the effect of the offsets is not fully captured by the deviation of the red curve from Gaussianity here, because it does not indicate the sign of $v_1 − v_2$; an unaccounted-for measurement error could in principle produce the same deviation with no overall systematic offset. However, Fig. 1(a) clearly indicates that most of the S15 measurements are systematically higher than the K15 measurements, so we can say with confidence that the correction applied here is reasonable.

Next, we plot the distribution of $\Delta_e/\sigma_{2e}$ with all the measurements included in Fig. 4(b). The red dashed curve corresponds to the data with the best-fitting offset corrections applied; note that, compared to the short time-scale subset we plotted in Fig. 4(a), there are significantly more measurements with velocity variations beyond the Gaussian expectation. Since these extra velocity changes occur over longer time-scales (~1 yr), they can be interpreted as being due to binary motion. This indicates that the two stars with large variations over 18 d between the S15 versus K15 are not the sole driver behind the large binary fraction we have inferred. We verified this by repeating our analysis with those two stars removed from the sample, and found that a high binary fraction is nevertheless preferred by the data as a result of the significant velocity changes measured by the J16 or R16 data. Finally, to verify that a galaxy with our best-fitting parameters can reasonably reproduce the distribution of velocity variations we see in Ret II, we do random resamplings of the data and plot the resulting distributions. The blue dotted line shows a typical case with a binary fraction of zero; note that the large velocity changes in the tail are not well reproduced, which is typically the case for many different random realizations. We then plot a typical case with a mean period of 27 yr and a binary fraction of 0.5 (meaning half the stars in the sample are randomly assigned
as binaries, and their binary properties are randomly sampled). It should be emphasized that due to the small sample size, the effect of binaries can vary considerably from realization to realization, depending on how many close binaries are present; in a few cases, there is no discernible binary tail at all. More typically, however, a tail exists and in many cases, as shown here, there may be one or two stars with velocity changes exceeding $5\sigma_{2e}$, in some cases as large as $30–40 \text{ km s}^{-1}$. Such short-period binaries are likely to have a velocity far from the galaxy’s systemic velocity at any given time, and hence would probably have been flagged as non-member stars. With that caveat aside, many realizations do show distributions that are broadly consistent with the data.

5 TEST OF OUR METHOD ON SIMULATED RET II DATA SETS

Our analysis shows that although Ret II appears to have a high binary fraction: its apparent velocity dispersion of $\sim 3 \text{ km s}^{-1}$ is unlikely to be dominated by binary motion unless the measurements of K15 are systematically offset from those of J15 by $\approx 1–3 \text{ km s}^{-1}$. The latter possibility is disfavoured by the data, but not beyond 95 per cent confidence limits. This begs the question: if the close binary fraction does tend to be high in ultrafaint dSphs given such small samples, can we be confident our method will distinguish between galaxies whose dispersion is strongly inflated by binary motion versus those that are not?

To investigate this question, we generate mock data by assuming a high binary fraction $B = 0.9$ and short-mean period of 27 yr and resample all the velocities. We investigate two scenarios: in scenario 1, the intrinsic dispersion is $\sigma = 0 \text{ km s}^{-1}$ (so any apparent velocity dispersion would be due entirely to binaries and measurement error); in scenario 2, we assume an intrinsic dispersion of $\sigma = 2.7 \text{ km s}^{-1}$, which is close to our best-fitting dispersion of Ret II for the mean period assumed here. For each realization, we first calculate the uncorrected dispersion using $3\sigma$-clipping: we find the maximum likelihood values of $\mu$, $\sigma$, then remove stars that lie beyond $3\sigma$, and repeat as needed until no such outliers are present. In order to find cases that roughly resemble Ret II, we repeat many random realizations and keep three cases for which the uncorrected dispersion $\sigma_{\text{clip}}$ lies between $2.5–3.5 \text{ km s}^{-1}$. This required several realizations before three such cases were found for either scenario. In scenario 2 ($\sigma = 2.7 \text{ km s}^{-1}$), we did choose one realization with $\sigma_{\text{clip}} = 2.3 \text{ km s}^{-1}$ to see if a non-zero intrinsic dispersion can be recovered even for a lower $\sigma_{\text{clip}}$ value. After applying our analysis to these mock data, the resulting posteriors in the intrinsic dispersion are plotted in Fig. 5(a) for the scenario where $\sigma = 0 \text{ km s}^{-1}$. In all three cases we infer that $\sigma < 1.5 \text{ km s}^{-1}$ at greater than 90 per cent confidence; the most probable intrinsic dispersion is well below $1 \text{ km s}^{-1}$ in all cases. Thus, our method appears unlikely to find a peak at $\sigma > 2 \text{ km s}^{-1}$ if the apparent velocity dispersion is dominated by binaries. In Fig. 5(b) we plot the resulting posteriors for the cases where the true $\sigma = 2.7 \text{ km s}^{-1}$. Here we see that $\sigma = 0 \text{ km s}^{-1}$ is ruled out in all cases; in none of these cases do we find a most probable intrinsic dispersion lower than $2 \text{ km s}^{-1}$. This builds confidence that, despite the relatively small sample size, our binary-corrected velocity dispersions can be trusted.

As we mentioned above, despite Ret II having a most probable intrinsic dispersion of $3 \text{ km s}^{-1}$ in our analysis, there is still a non-zero probability of $\sigma = 0 \text{ km s}^{-1}$. What are we to make of this? First keep in mind that if the K15 measurements are not systematically offset from the higher resolution J15 measurements by $\approx 1–3 \text{ km s}^{-1}$, the probability of Ret II having $\sigma = 0 \text{ km s}^{-1}$ essentially vanishes. If we retain the possibility of a large offset between the K15 and J15 data sets, then there are three possible explanations: either (i) Ret II’s true intrinsic dispersion is in fact somewhere between $0–3 \text{ km s}^{-1}$, and the peak appearing at $3 \text{ km s}^{-1}$ is merely due to the small sample

Figure 4. The fraction of stars with velocity changes greater than the combined measurement error $\sigma_{2e}$, where $\sigma_{2e}^2 = \sigma_1^2 + \sigma_2^2$ and $\sigma_1$ and $\sigma_2$ are the measurement errors in the first and second measurements respectively. In (a) we only include the S15 and K15 measurements, which are separated by only 18 d. Note that without correcting for offsets between data sets, the distribution (red solid curve) deviates from the expectation from Gaussian measurement error (solid black curve). However, when we apply a correction using our best-fitting offset values (dashed blue), the distribution more closely follows the Gaussian limit, albeit with two outlier stars that are likely to be short-period binaries. In (b) we include all the measurements, again showing the data distribution (red dashed curve), along with the distribution of randomly resampled velocities assuming no binaries (dotted blue curve), and likewise assuming a mean period of 27 yr and binary fraction of 0.5 (magenta curve).
size; (ii) Ret II has a close binary fraction even higher than what we have assumed in the above mock data, and hence show velocity variations beyond what the realizations above could produce; or (iii) there is some additional systematic in the velocity measurements that is producing velocity changes that appear consistent with short-period binary motion. Additional spectroscopic measurements will be necessary, to distinguish between these scenarios with a high degree of confidence. Nevertheless, our mock data runs bolster confidence that Ret II’s apparent dispersion is unlikely to be entirely dominated by binary orbital motion.

6 DISCUSSION

The result that Ret II’s dispersion is unlikely to be entirely due to binaries is not surprising, given that its very low metallicities and metallicity spread clearly identify it as a dwarf galaxy rather than a globular cluster. However, the clear preference for a high binary fraction and/or short-mean period in Ret II is consistent with a similar result found for the Segue I dSph (Martinez et al. 2011). If this pattern of a high-close binary fraction holds up in other ultrafaints, it would be strong evidence that the close binary fraction of a star population is a strong function of metallicity, with low-metallicity populations harbouring a greater fraction of close binaries. This anticorrelation between close binary fraction and metallicity has already been pointed out in Milky Way field binaries (Badenes et al. 2018; El-Badry & Rix 2018; Moe et al. 2018). Whether this is due to a high binary fraction, a short-mean period, or some combination of the two remains to be determined; as discussed in Minor (2013), the degeneracy between binary fraction and the period distribution cannot be broken purely by radial velocity measurements without a very large sample with measurements at several epochs. Unfortunately such a large sample is unattainable at present for individual ultrafaint dwarfs.

The most promising approach for breaking the degeneracy between binary fraction and period distribution would be to combine radial velocity measurements with CMD fitting; the latter approach is demonstrated in Geha et al. (2013) and is sensitive only to the binary fraction and stellar masses, not to the periods. An additional independent handle on the binary fraction is possible if main-sequence stars are included in the sample, for which binary spectral fitting is possible (El-Badry et al. 2018a,b). As we have hinted in Section 2, our method for generating the binary and non-binary likelihoods can be recast in the form of a hierarchical Bayesian model: for individual stars, their orbital parameters (e.g. $v_{\text{rot}}$, $P$, $q$) are marginalized over, while the prior distributions in these parameters are constrained for the whole population at the next level of inference. This approach, which has been used elsewhere to constrain the distribution of orbital parameters in binaries and exoplanets (Hogg, Myers & Bovy 2010; Foreman-Mackey, Hogg & Morton 2014; Price-Whelan et al. 2018), can be incorporated naturally into the methodology used here; in principle, it allows for colour–magnitude information and radial velocities to be fit under the same hierarchical framework, and could be applied to a combination of dSph data sets over many epochs to find detailed binary constraints. The demonstration of this more generalized approach in the context of dwarf galaxies is left to future work.

The decrease of the velocity dispersion due to the binary correction has implications for the implied dark matter halo of Ret II. The half-light mass ($M_{1/2}$) of a dispersion supported system is well measured at the half-light radius and it is proportional to $\sigma^2$ (Walker et al. 2009; Wolf et al. 2010). The binary corrected half-light mass will decrease by a factor $\sigma^4$. Assuming $\sigma = 3.3$ (Simon et al. 2015), we find that the half-mass decreases by a factor of 0.72, decreasing to $M_{1/2} = 4.0 \pm 1.7 \times 10^4 M_\odot$ (from $M_{1/2} = 5.6 \times 10^5 M_\odot$). Searches for dark matter annihilation in ultrafaint dwarfs require an accurate determination of the J-Factor, an integral over the dark matter density squared. The J-Factor is proportional to $\sigma^4$ (Pace & Strigari 2018) and for Ret II the J-Factor will decrease by a factor 0.52. Using the J-Factor value from Pace & Strigari (2018), we find the binary corrected J-Factor to be $\log_{10} \left( J/\text{GeV}^2 \text{ cm}^{-2} \right) = 18.60 \pm 0.38$ (from $18.88 \pm 0.38$).
7 CONCLUSION

We have applied a Bayesian method to model multi-epoch radial velocities in the ultrafaint dwarf Reticulum II, fully accounting for the effects of binary orbital motion and systematic offsets between different spectroscopic data sets. Our primary results are encapsulated in Figs 2 and 3, where we infer the intrinsic dispersion and binary fraction of Ret II. Despite the relatively small sample size (26 stars in total), we find that the binary fraction of Ret II is higher than 0.5 at the 90 per cent confidence level, if the mean orbital period is assumed to be 30 yr or longer. Despite this high binary fraction, the best-fitting intrinsic dispersion of Ret II is 2.8$^{+1.7}_{-1.2}$ km s$^{-1}$, consistent with Ret II having a large mass-to-light ratio. Our best-fitting velocity dispersion is smaller than previous estimates and implies a weaker dark matter annihilation signal, with the J-factor reduced by a factor of ≈0.5 compared to the results of Simon et al. (2015). Assuming a mean period of 10$^4$ d (which was recently inferred in low-metallicity Milky Way binaries in Moe et al. 2018), we estimate a ≈ 1 per cent probability that Ret II’s dispersion is due to binaries rather than dark matter, corresponding to the regime $M_\odot/L_\odot \approx 2$. These results are thus consistent with Ret II being a dark matter-dominated galaxy to high significance, in agreement with the expectation from its large metallicity dispersion (Simon et al. 2015).

Beyond the importance of obtaining unbiased mass estimates of ultrafaint dwarfs, binary populations in these objects are interesting in their own right as they may hold clues to star formation in extremely metal-poor environments. The fact that Ret II appears to have a high-close binary fraction is consistent with previous results from the Segue 1 ultrafaint dwarf, and echoes similar results from Milky Way halo stars that suggest that metal-poor star populations have a relatively high fraction of close binaries. A more robust and detailed characterization of binary populations in dwarf galaxies will require a larger multi-epoch sample for a large number of dwarfs, a combination of deep photometry and high-resolution spectroscopy, and the application of a fully hierarchical version of the Bayesian method we have applied in this paper. Over the long term, the binary populations in these extreme objects might hold vital clues to a deeper understanding of the physics underlying star formation.

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