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A dynamical study of the Draco dwarf spheroidal galaxy

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ABSTRACT

We have observed 19 giant stars in the Draco dwarf spheroidal (dSph) galaxy and obtained good quality spectra for 17 of these. The velocity dispersion of the sample, calculated by the maximum-likelihood method, is $10.5\pm^{2.2}_{1.7}$ km s^{-1}. The mean velocity is $-293.8\pm^{2.6}_{2.7}$ km s^{-1}. The data were taken at a single epoch, so there is no direct information about possible binary star contamination. Assuming dynamical equilibrium, isotropy in the velocity dispersion and a negligible contribution from binary stars, the core mass-to-light ratio is $166\pm^{289}_{107}$ $M_\odot/L_\odot$ and the total mass-to-light ratio is $145\pm^{116}_{71}$ $M_\odot/L_\odot$, consistent with the presence of large quantities of dark matter.

Key words: galaxies: individual: Draco – galaxies: kinematics and dynamics – Local Group – dark matter.

1 INTRODUCTION

This paper presents the results for the Draco stars which were observed during the same runs as the Sextans and the Ursa Minor stars discussed in two previously published papers (Hargreaves et al. 1994a,b). A velocity dispersion and a mean velocity were calculated for Draco, and the possibility of rotation around either axis was explored as was the variation of the velocity dispersion with distance from the centre of the galaxy. The analysis of the data was identical to that employed for the other two galaxies, and so a full discussion of the procedures is not repeated here.

Draco is the second closest of the eight dwarf spheroidal (dSph) galaxies known to be in orbit around the Milky Way. It has no signs of extended or recent star formation, with a red horizontal branch on the Hertzsprung–Russell (HR) diagram and low metal abundance and range. Its orbit, like that of Ursa Minor, is consistent within the errors with a polar orbit along the direction of the Magellanic stream in the same direction as the motion of the Large Magellanic Cloud (LMC) (Scholz & Irwin 1994).

The rest of the paper is divided into several sections. First, the observations and the reduction procedure are described. Next, the errors on the observations are discussed. Then the velocity dispersion calculation is described, the results of the rotation analysis presented and a value for the mass-to-light ratio obtained. Finally, other possible contributions to the velocity dispersion are discussed.

2 OBSERVATIONS, DATA REDUCTION AND ERROR ANALYSIS

2.1 Observations

The observations were made on the nights of 1992 April 7–9 and 26–27. All the observations were made using the William Herschel Telescope (WHT) on La Palma.

The observations were carried out in the same way as those for the other two galaxies, using the red arm of ISIS and the R1200R grating to observe the Ca II triplet lines in the 8300–8570 Å wavelength range. The arc lamp was CuAr and CuNe. See Hargreaves et al. (1994a,b) for further details.

The stars observed were giant branch stars ranging in brightness from 15 to 18 mag in the *R* band. The 19 Draco targets were kindly provided by Ed Olszewski (private communication).

Good spectra were obtained for 17 members, and as no stars were observed more than once, no multi-epoch results were obtained. With no repeat measurements, it was impossible to estimate directly the measuring errors on individual spectra. The spectra were, however, obtained during the same runs as spectra from similar stars in the Sextans and Ursa Minor galaxies. The internal and external errors on the Draco velocities were therefore estimated by considering the combined data sets from the other two galaxies.

Additionally, four bright radial velocity (RV) standard stars were observed with integration times of only 5 s, one or two on each night of each run. These spectra provided an

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estimate of the random and systematic errors for high signal-to-noise ratio, short exposure spectra. The random part of this error gave an estimate of the minimum random error for the Sextans, Ursa Minor and Draco data, although it appears that the RV stars may have greater systematic error due to slit centring problems. The details of this are discussed in Hargreaves et al. (1994a). The RV stars were also used as a check on the data reduction procedure, because their actual velocities were already known, and as a base to obtain the absolute mean velocity of Draco.

The coordinates of all the Draco member stars that were observed, from Olszewski (private communication), are shown in Table 1.

Table 1. Coordinates of the Draco stars. The centre of the Draco dSph galaxy is at $17^h\ 19^m.5$, $57°\ 58'$.

Star	RA 1950	DEC 1950
24	17 19 10.3	58 00 16
249	17 19 15.5	58 02 04
267	17 18 56.1	58 00 34
361	17 19 45.0	57 56 27
473	17 18 47.3	57 59 26
536	17 19 43.9	57 54 38
562	17 20 04.4	57 58 49
576	17 19 49.0	58 02 05
iv-20	17 21 25.0	57 55 53
vi-1	17 19 54.6	57 51 37
vii-4	17 18 58.5	57 51 33
ix-5	17 18 24.5	57 55 32
xi-2	17 18 29.2	58 04 06
3053	17 18 46.9	58 01 45
3150	17 18 47.3	57 54 22
3157	17 18 52.9	57 55 16
3316	17 20 15.1	57 59 59
3363	17 19 59.5	58 02 48
3369	17 19 53.5	58 03 18

2.2 Data reduction

The processing of the CCD frames, data reduction and analysis was carried out in a very similar way to the Sextans and Ursa Minor data. The details are presented in Hargreaves et al. (1994a) so a brief summary will suffice.

Preliminary processing of the CCD frames to remove bias and cosmic ray events was carried out, mostly at the telescope, using FIGARO routines. IRAF was then used to perform the wavelength calibration, sky subtraction, and the cross-correlation of the data against the same template used for the Sextans data. The same line selection was used to throw out very poor Ca II lines from the spectra. The cross-correlation program FXCOR produces a Tonry & Davis R value (Tonry & Davis 1979) for each correlation, and it was this parameter that was used to produce a cut-off value below which the results were considered too inaccurate and were therefore discarded.

2.3 Errors in the velocities

There were no repeat measurements for the Draco stars so the errors on the Draco data were calculated by combining the data from the Sextans and Ursa Minor measurements, excluding the possible binary, star 8, in the Sextans data set. The procedure for calculating the errors was identical to that performed on the Sextans and Ursa Minor data presented in Hargreaves et al. (1994a,b): repeat measurements of the same stars (from the Sextans and Ursa Minor galaxies) were used to derive the error and calculate a suitable cut-off (R_{cut}) for the Tonry & Davis R value. (See Fig. 1 for the results of the error calculation for the combined data set.) We had four spectra (from stars 24, vii-4, ix-5 and 3150) which were very noisy over particular wavelength ranges, and this skewed the resulting cross-correlation profiles. In these cases, when the offending area was excluded from the analysis, the profile was improved and the remaining spectrum produced a consistent velocity. The poor areas were around the first or third Ca II triplet lines, the second line at 8542 Å being the strongest of the three. The velocities obtained from these stars were considered to be 'half' measurements, making them less strongly weighted in the later calculations, because only two of the three lines were contributing to the result. In other words, the error on these velocities was estimated to be a factor of $\sqrt{2}$ greater than that on the other velocities.

For a variety of values of R_{cut}, the error distribution for the Sextans and Ursa Minor repeat velocities was created from the differences of the velocities obtained from individual observations for a star compared with the real mean velocity of that star. The Gaussian 1σ width of this distribution was the appropriate error on an individual observation. The widths of the error distributions for R_{cut} of 0, 7, 7.5 and 8 were 5.5 ± 0.3, 2.3 ± 0.2, $2.0\pm^{0.1}_{0.2}$ and 2.0 ± 0.2, respectively. If the width of the distribution is denoted by σ_{err} then the error quoted here is such that the variance on σ^2_{err} is $2\sigma^4_{err}/N$.

In the case of Draco we adopted a value for R_{cut} of 7.0, because the value of 7.5 adopted for the other two galaxies excluded too high a proportion of the stars from the analysis. Having more stars is advantageous when it comes to looking at the rotation or the variation of velocity dispersion with radius. The error per star is, therefore, slightly greater for Draco than for the other two galaxies.

The resulting velocity for each star is displayed in Table 2, along with the Tonry & Davis R value for the correlation, and the weight assigned to each star according to the procedure described above.

3 RESULTS

3.1 The velocity dispersion calculation

Only the velocities derived from the observations that produced R values above the threshold were used in the velocity dispersion calculation. The width of the distribution of these velocities defined the velocity dispersion (σ_{obs}) of Draco. An unweighted Gaussian fit to the data was made to

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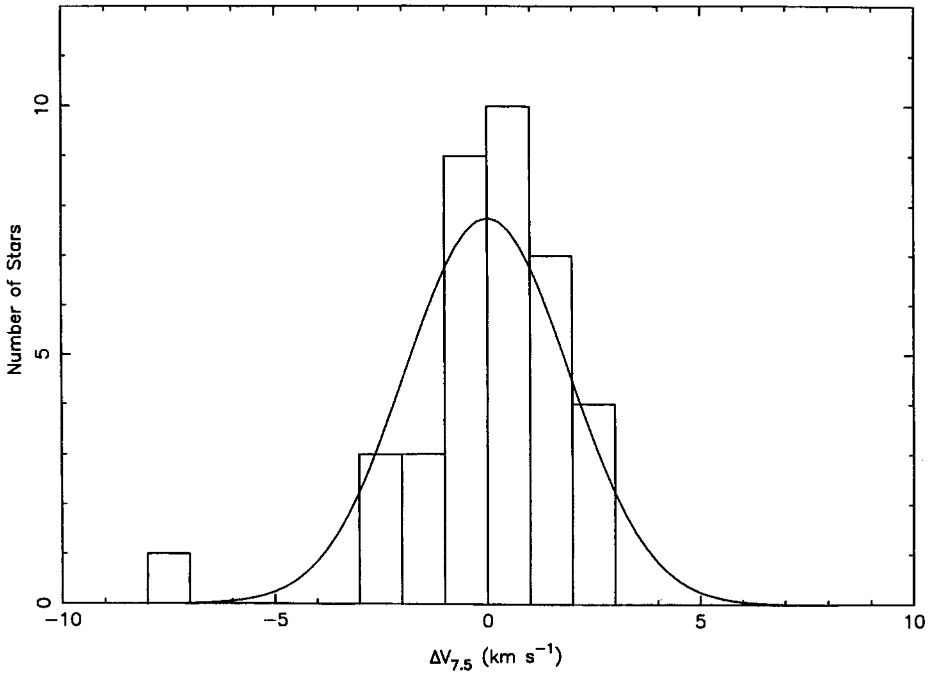

Figure 1. The Gaussian fit to the error distribution of the Sextans and Ursa Minor repeat velocity observations for $R_{\rm cut}$ of 7.5 with measuring error 2.0 km s^{-1}. The KS test of this fit produced a probability of 0.6.

compare with the error weighted fit. Out of the 17 stars, 13 were given identical measuring errors on the velocities. We would therefore expect the velocity dispersion obtained by calculating the standard deviation of the velocities, and then subtracting the error, to be very similar to the maximum-likelihood method, where the individual weight of each star is included separately. The results reported in the text are those for an $R_{\rm cut}$ value of 7.0. Other values of $R_{\rm cut}$ made little difference to the velocity dispersion result.

The result of a Kolmogorov–Smirnov (KS) test on the velocity sample showed consistency with a Gaussian distribution, so the standard deviation of the sample was equivalent to the velocity dispersion calculated from an unweighted Gaussian model. The result was $11.2 \pm^{1.8}_{2.1}$ km s^{-1}. The variance of $\sigma^2_{\rm obs}$ is $2\sigma^4_{\rm obs}/N$, so this is the error quoted. This dispersion has not had the contribution from measuring errors removed. The inclusion of this, as in equation B9 of Hargreaves et al. (1994a), gave a corrected velocity dispersion of $10.9 \pm^{1.7}_{2.1}$ km s^{-1}.

Using the maximum-likelihood method (Hargreaves et al. 1994a), the velocity dispersion for an $R_{\rm cut}$ value of 7.0 was $10.5 \pm^{1.8}_{2.1}$ km s^{-1}. As expected, this is very similar to the unweighted calculation. Fig. 2 shows the velocity distribution for an $R_{\rm cut}$ value of 7.0, with the fitted Gaussian derived using the maximum-likelihood method. Velocity measurements in Draco have been made over several years by Olszewski et al., the most recent published value for the velocity dispersion being 10.2 ± 1.8 km s^{-1} (Mateo 1994). More recently, Pryor, Olszewski & Armandroff (1995) have used a fibre optic system to measure the velocities of 84 Draco members with an accuracy between 1 and 10 km s^{-1} per observation, and obtained a velocity dispersion of 9.2 ± 0.8 km s^{-1}. Both of these results are consistent with the result we present here.

3.2 Rotation and the mean velocity

It is important to determine the degree of rotation about the axes of the dSph galaxy for several reasons: rotation would artificially increase the observed velocity dispersion providing that rotation was not in the plane of the sky; the rotation curve and velocity dispersion are both required to correctly determine the mass of the system; and if the Galaxy is exerting a large tidal torque which is affecting the dSph galaxy, this would be expected to generate rotation (Piatek & Pryor 1995). Finding the axis about which the dSph rotates is a test for dissipation, and triaxiality.

Before looking for rotation, the velocities for the stars in Draco were corrected to a Galactocentric system to eliminate the differential heliocentric corrections over an object of large finite extent. The average change in the velocity of each star caused by this correction was 0.02 km s^{-1}, and using these values rather than the heliocentric values made negligible difference to the value of the velocity dispersion.

A bootstrapping method was used for finding the rotation. Many re-samplings of the data were randomly chosen and the best-fitting slope and intercept of each sample were calculated. The median and 1σ values from the resulting distributions of slope and intercept defined the rotation and 1σ errors. This procedure is discussed more fully in Hargreaves et al. (1994b).

The following values for the estimate of the rotation effect are the median values of the intercept and gradient produced taking a position angle of 82° and applying a bootstrapping procedure 1000 times.

Around the major axis,

$$\text{intercept} = -1.9 \pm^{2.4}_{2.0} \text{ km s}^{-1},$$

$$\text{gradient} = -5.0 \pm^{3.3}_{3.1} \text{ km s}^{-1} \text{ per 100 pc.}$$

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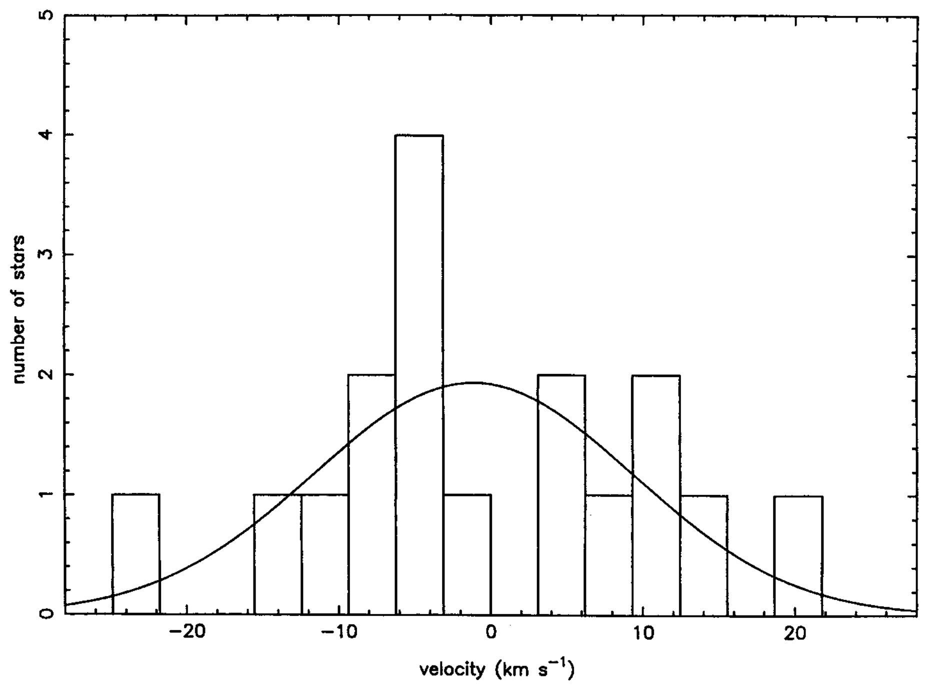

Figure 2. The velocity distribution of the Draco dSph galaxy with R_{cut} value of 7.0. The velocity dispersion calculated by the maximum-likelihood method is 10.5 km s^{-1}, and the average velocity −1.1 km s^{-1} with respect to the template plus 516 km s^{-1}.

The positive distances are on the north western side of the major axis.

Around the minor axis,

$$\text{intercept} = -2.3 \pm^{2.7}_{2.6}\ \text{km s}^{-1},$$

$$\text{gradient} = -0.7 \pm^{2.3}_{2.1}\ \text{km s}^{-1}\ \text{per 100 pc}.$$

The positive distances are on the north eastern side of the minor axis.

For both these cases the intercept is with respect to an arbitrary value which is actually the velocity with respect to the template plus 516 km s^{-1}. The errors quoted are the 68 per cent level of the distribution for each variable, holding the other one fixed. There is some evidence for rotation around the major axis, but this is only a 2σ result, and may well not be significant, given the relatively poor quality of the data set when compared with the Ursa Minor results presented in Hargreaves et al. (1994b).

Figs 3 and 4 show the velocity–distance data for the major and minor axes, the central fitted lines being those with the parameters quoted above; the bounding lines are the 68 per cent errors on the slope, holding the intercept fixed.

The other result obtained was that for the systemic velocity of the Draco dSph galaxy. From the RV stars, the velocity of the template was found to be 223.3 km s^{-1}. The results quoted in Tables 2 and 3 are those relative to the template plus 516 km s^{-1}. The average velocity obtained by the maximum-likelihood method was $-1.1 \pm^{2.6}_{2.7}$ km s^{-1}, making the velocity of Draco $223.3 - 516 - 1.1 = -293.8 \pm^{2.6}_{2.7}$ km s^{-1}. Other estimates for this value are -289 ± 1 km s^{-1}, from a previous report of Olszewski's single star measurements, given in Zaritsky et al. (1989) and -291.9 ± 1.1 km s^{-1} from the fibre data of Pryor et al. (1995). These results are consistent, assuming slight underestimates of the measuring errors.

4 ANALYSIS

4.1 Variation of velocity dispersion with radius

The velocity dispersion in a King model (King 1962, 1966) of a stellar system, without an extended massive halo, should decrease with distance from the centre of the galaxy (see Hargreaves et al. 1994a). Table 3 shows how the velocity dispersion varies with distance for the Draco data, the 'radius' being the geometric mean radius since Draco is elliptical in shape ($e = 0.29$). The column in the table contains the results for the data with R_{cut} of 7.0. The dispersions and errors here were calculated as before, using the maximum-likelihood method. The derived dispersions appear to show an increase rather than a decrease towards larger radii. They are also consistent with a flat profile. However, they are only consistent with the profile expected for a King model with $c = 0.50$ (derived for Draco by Irwin & Hatzidimitriou 1993) at the 2σ level. In this sample there are only three stars which lie outside the core radius of the dSph galaxy. Outside one core radius, the decrease of velocity dispersion is more pronounced in a King model. Therefore, velocities for stars further from the centre of the galaxy will be required to extend this result. See Binney & Tremaine (1987) for figures of the variation of velocity dispersion with radius for a King model.

4.2 Mass-to-light ratios

The background to the methods used to calculate the mass-to-light ratio are given in Hargreaves et al. (1994a) and Richstone & Tremaine (1986). The resulting equations for the core and total mass-to-light ratios, hereafter called the core fitting method and Illingworth's method, respectively, are

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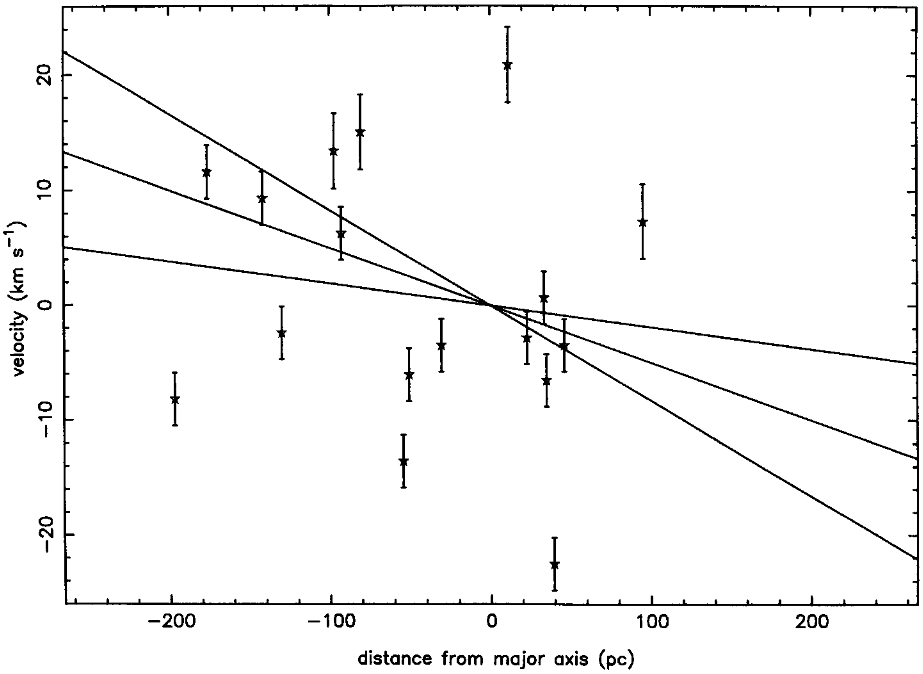

Figure 3. Rotation around the major axis of Draco. The best-fitting lines from the bootstrapping procedure are bounded by the errors. These are the 1σ errors for the slope of the fit, keeping the average velocity of the sample fixed.

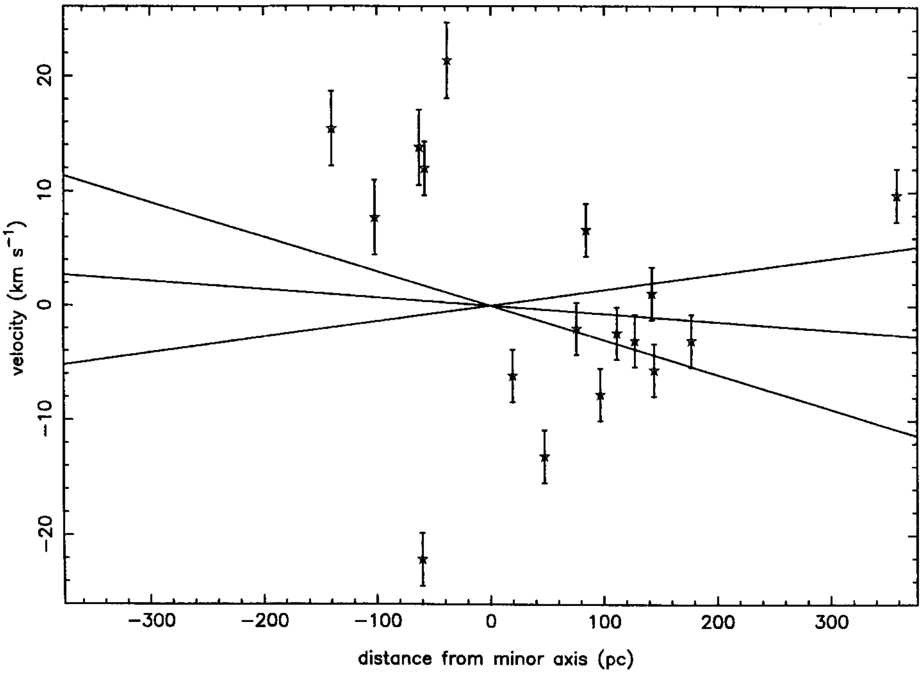

Figure 4. Rotation around the minor axis of Draco. The best-fitting lines from the bootstrapping procedure are bounded by the errors. These are the 1σ errors for the slope of the fit, keeping the average velocity of the sample fixed.

$$\frac{\rho_0}{I_0}=\eta\frac{333\sigma_0^2}{r_{\rm hb}S_0}, \qquad (1)$$

and

$$\frac{M_{\rm tot}}{L_{\rm tot}}=\frac{166.5r_{\rm c}\mu}{\beta L_{\rm tot}}, \qquad (2)$$

where η and μ are parameters given by the particular King model, σ_0^2 and $1/\beta$ are the observed squared-velocity dispersion ($\sigma_{\rm obs}^2$), adjusted according to the King model and average radius of the stars observed, I_0 and $L_{\rm tot}$ are the central surface brightness and total luminosity of the dSph, and $r_{\rm c}$ and $r_{\rm hb}$ are the core and half-brightness radii, respectively. Illingworth's method is far more model sensitive because η

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Table 2. The velocities and Tonry & Davis R values for the Draco observations. (The columns are explained in the table footnotes.)

Star	Date	R	V_t km s^{-1}	V_7 km s^{-1}	Error Weight
24	A92-1	11.70	18.9	18.9	0.5
249	A92-1	7.18	-8.6	-8.6	1.0
267	A92-1	7.33	4.3	4.3	1.0
361	A92-1	3.69	26.7	—	1.0
473	A92-2	9.45	-4.5	-4.5	1.0
536	A92-2	10.75	-7.9	-7.9	1.0
562	A92-2	9.60	-4.6	-4.6	1.0
576	A92-2	8.70	7.5	7.5	1.0
iv-20	A92-2	7.60	-9.6	-9.6	1.0
vi-1	A92-2	11.96	9.8	9.8	1.0
vii-4	A92-2	9.86	13.0	13.0	0.5
ix-5	A92-2	8.38	5.1	5.1	0.5
xi-2	A92-2	8.38	-24.7	-24.7	1.0
3053	A92-2	5.00	-1.2	—	1.0
3150	A92-2	7.89	-11.3	-11.3	0.5
3157	A92-2	8.75	-5.6	-5.6	1.0
3316	A92-2	7.16	-1.0	-1.0	1.0
3363	A92-2	9.56	-5.2	-5.2	1.0
3369	A92-2	8.36	15.3	15.3	1.0

Notes. Date: A92-1 and A92-2 are abbreviations for the 1992 April runs, A92-1 being the run at the start of April, and A92-2 the one at the end.
V_t: this is the heliocentrically corrected velocity with respect to the template.
R is the Tonry & Davis R value.
V_7: this is the velocity for a star where data which produced a correlation with $R<7.0$ is replaced by a dash.
Error weight: those stars which were given $\sqrt{2}$ times the error were those which had part of the spectrum selected out of the correlation. They were considered to be half measurements in the velocity dispersion calculation so they are marked by a 0.5 in this column.

Table 3. How velocity dispersion varies with radius. $R_c=158$ pc.

Radius range (pc)	Average radius (pc)	No. in bin	Velocity dispersion (km s^{-1})
62–95	79	6	$9.3\pm^{3.8}_{2.4}$
99–119	110	6	$7.3\pm^{3.1}_{2.0}$
127–272	175	5	$13.8\pm^{6.0}_{3.7}$

is always close to 1 but μ varies considerably with small changes in the concentration of the King model.

Irwin & Hatzidimitriou (1993) have found the best King model fit for Draco is that with $c=0.50$ implying $W_0=2$, $\eta=0.96$ and $\mu=2.7$. Fig. 5 shows the photometric data fitted by this King model (solid line) and the best-fitting exponential profile (dashed line).

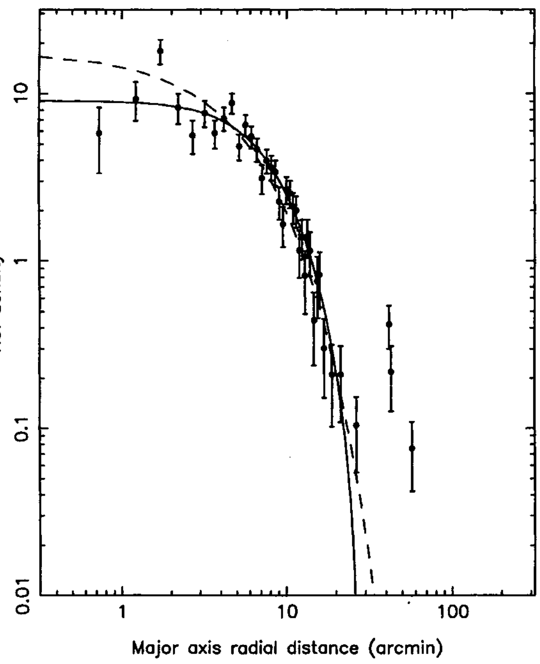

Figure 5. The best King model fitted to the Draco dSph galaxy (by Irwin & Hatzidimitriou 1993 from the APM results) with a concentration of 0.50. The dashed line is an exponential fit. 1 arcmin is equivalent to 20.9 pc at the distance of Draco (72 kpc).

Irwin & Hatzidimitriou (1993, 1995) also calculated the following parameters for the dSph galaxy:

$r_c=158\pm14$ pc,

$r_{hb}=120\pm11$ pc,

$r_t=498\pm47$ pc,

$M_V=-8.3\pm0.5$,

$L_{tot,V}=(1.8\pm^{1.0}_{0.7})\times10^5$ L$_\odot$,

$S_{0,V}=2.2\pm^{1.3}_{0.8}$ L$_\odot$ pc^{-2}.

All the distances quoted here are geometric mean distances. The average geometric distance from the centre of the Draco galaxy of the observations was 118 pc, which is $0.75r_c$, leading to $\sigma_0=\sigma_{obs}/0.87$ and $1/\beta=\sigma^2_{obs}/0.54^2$, where σ_{obs} is the observed velocity dispersion. The velocity dispersion for the data with R_{cut} of 7.0 was $\sigma_{obs}=10.5\pm^{2.2}_{1.7}$ km s^{-1}. The mass-to-light ratios were calculated by simulating a distribution assuming Gaussian errors and taking the median value. The result for the core mass-to-light ratio was $\rho_0/I_{0,V}=165\pm^{289}_{107}$. Similarly the total mass-to-light ratio was $M_{tot}/L_{tot,V}=145\pm^{116}_{71}$. The errors quoted here include those due to the half brightness and core radii, the luminosity and the velocity dispersion, and they are taken at the 68 per cent level of the derived distribution, the luminosity error contributing more than half the total error.

Our values for the mass-to-light ratios are consistent with previously published values, the most recent being Pryor et al. (1995) who obtained 110 ± 20 M$_\odot$/L$_\odot$, the error quoted

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here being only that owing to the error in the velocity dispersion.

For a mass-to-light ratio of 3, σ_{obs} would be about 1.5 km s^{-1}. This is well outside the 99.9 per cent confidence value of 5.6 km s^{-1} from the maximum-likelihood calculation. At this level, the error on the measurements would outweigh the actual velocity dispersion, since the dispersion caused by the errors alone is 2.5 km s^{-1}.

4.3 Other possible explanations of the velocity dispersion

As for both Sextans and Ursa Minor, the velocity dispersion observed here may not truly reflect the mass of the system. Anisotropy in the velocity dispersion could inflate the mass-to-light ratio by a factor of 3 at most, although the actual factor is likely to be considerably less. This is, however, an unmeasurable effect.

The data presented in this paper tell us nothing about how many binaries may be contaminating the sample because there are no multi-epoch observations: the presence of binaries would increase the measured velocity dispersion.

Hargreaves, Gilmore & Annan (1996) have made a closer examination of the possible influence of binary stars on the velocity dispersion, and have analysed how effective repeat observations may be in weeding out those binary stars which are affecting the results obtained from the sample. To provide an oversimplified summary of the relevance of that investigation to this specific data set, it seems unlikely that unidentified binarism can be contributing substantially to the velocity dispersion in Draco.

The other alternative is that the dSph galaxies are being tidally disrupted by the Milky Way, so that the assumption of dynamical equilibrium underlying equations (1) and (2) is invalid. For a mass-to-light ratio of 3, the mass of Draco would be 5.1×10^5 $M_\odot$. Assuming this mass and a Keplerian potential for the Galaxy implies that the tidal distance of Draco is 187 kpc. This tidal distance is the distance at which a galaxy of a certain size and mass would have to be in order to be disrupted by the galaxy according to a simple balance of forces argument. The actual distance of Draco is 72 kpc, indicating that Draco ought to be undergoing tidal disruption at present. See Hargreaves et al. (1994a, b) for a more complete discussion.

Hodge & Michie (1969), and many subsequent authors (cf. the several papers in Dwarf Galaxies, eds Meylan & Prugniel 1994, as recent examples), have suggested that a tidally disrupted satellite of the Galaxy ought to become elongated along the direction of its orbit, and calculations of the proper motion of Draco (Scholz & Irwin 1994) indicate that, like Ursa Minor, its orbit is consistent with the direction of the Magellanic Stream (although the measuring errors here are large) and in the same orbital direction as the motion of the LMC (Scholz & Irwin 1994). It is possible that Ursa Minor, Draco and the LMC used to be part of the same object: if this is the case, and Ursa Minor is undergoing tidal disruption at present, then it is likely, given the similarities in luminosity and size between the two dSph galaxies, that the same thing is happening to Draco.

Should all these ideas fail to account for the high mass-to-light ratios, the alternative is that Draco contains large amounts of dark matter, with a core dark matter density of around 1.5 $M_\odot$ pc^{-3}.

5 CONCLUSION

The internal central velocity dispersion of the Draco dSph galaxy is $10.5 \pm^{2.2}_{1.7}$ km s^{-1} measured from 17 giant stars. It is possible that Draco may be rotating around the major axis but the value of $-5.0 \pm^{3.3}_{3.1}$ km s^{-1} per 100 pc derived here is only a 2σ result [from Fisher randomization (Hargreaves et al. 1994b)]. The limit on rotation around the minor axis is $-0.7 \pm^{2.3}_{2.1}$ km s^{-1} per 100 pc. The mass-to-light ratios from core fitting and Illingworth's methods are, respectively, $165 \pm^{289}_{107}$ and $145 \pm^{116}_{71}$ in solar units.

Apparently purely stellar systems such as globular clusters and the stellar Galactic disc, have mass-to-light ratios of about 3. Thus the observed internal velocity dispersion of the Draco dSph galaxy is several times larger than the value of about 1.5 km s^{-1} that is expected if the galaxy is a self-gravitating stable system whose gravitational potential is dominated by the mass in the visible stars.

Effects such as anisotropy in the velocity dispersion and contamination of the data with binary stars cannot be discounted as contributing factors to this very large mass-to-light ratio. It is by no means unreasonable, given Draco's size and distance, that it may be undergoing tidal disruption by the Galaxy. Another possible explanation for the results is a substantial dark matter density in this galaxy.

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