Dynamics of the NGC 4636 globular cluster system^{★,★★}

An extremely dark matter dominated galaxy?

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ABSTRACT

Context. We present the first dynamical study of the globular cluster system of NGC 4636. It is the southernmost giant elliptical galaxy of the Virgo cluster and is claimed to be extremely dark matter dominated, according to X-ray observations.

Aims. Globular clusters are used as dynamical tracers to investigate, by stellar dynamical means, the dark matter content of this galaxy.

Methods. Several hundred medium resolution spectra were acquired at the VLT with FORS 2/MXU. We obtained velocities for 174 globular clusters in the radial range $0.90 < R < 15.5$, or $0.5-9 R_e$ in units of effective radius. Assuming a distance of 15 Mpc, the clusters are found at projected galactocentric distances in the range 4 to 70 kpc, the overwhelming majority within 30 kpc. The measured line-of-sight velocity dispersions are compared to Jeans-models.

Results. We find some indication of a rotation of the red (metal-rich) clusters about the minor axis. Out to a radius of 30 kpc, we find a roughly constant projected velocity dispersion for the blue clusters of $\sigma \approx 200 \text{ km s}^{-1}$. The red clusters are found to have a distinctly different behavior: at a radius of about $3'$, the velocity dispersion drops by $\sim 50 \text{ km s}^{-1}$ to about 170 km s^{-1} , which then remains constant out to a radius of $7'$. The cause might be the steepening of the number density profile at $\sim 3'$ observed for the red clusters. Using only the blue clusters as dynamical tracers, we perform Jeans-analyses for different assumptions of the orbital anisotropy. Enforcing the model dark halos to be of the NFW type, we determine their structural parameters. Depending on the anisotropy and the adopted M/L -values, we find that the dark matter fraction within one effective radius can vary between 20% and 50%, with most a probable range between 20% and 30%. The ambiguity of the velocity dispersion in the outermost bin is a main source of uncertainty. A comparison with cosmological N -body simulations reveals no striking disagreement.

Conclusions. Although the dark halo mass still cannot be strongly constrained, NGC 4636 does not seem to be extremely dark matter dominated. The derived circular velocities are also consistent with Modified Newtonian Dynamics.

Key words. galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: individual: NGC 4636 – galaxies: halos

1. Introduction

1.1. Work on NGC 4636

NGC 4636 is the southernmost bright elliptical in the Virgo cluster of galaxies. It is located 10° south of M87, within the Virgo Southern Extension. Surface brightness fluctuation (SBF) measurements yield a distance of 15 Mpc (Tonry et al. 2001), which we adopt throughout this paper. This value, however, has to be considered as a lower limit, since measurements based on the globular cluster luminosity function (GCLF) presented by Kissler et al. (1994) and Dirsch et al. (2005) point towards a larger distance of more than 17 Mpc. Table 1 summarizes the basic properties of NGC 4636.

Although NGC 4636, being an elliptical galaxy, predominantly consists of an old stellar population, there are some weak indications of an intermediate age population: firstly, it is a supernova Ia host galaxy (SN 1939a: Zwicky 1939; Giclas 1939), and there are theoretical considerations that this type of supernova originates in intermediate age populations rather than in very old ones (Yungelson et al. 1995; Yoshii et al. 1996). Secondly, far infrared observations by Temi et al. (2003) hint at a recent merger that supplied NGC 4636 with extra dust.

In the 1970s, NGC 4636 was the target of several H I-observations. Despite some claims of an extended H I-emission (Knapp et al. 1978; Bottinelli & Gouguenheim 1978), the deepest observations performed by Krishna Kumar & Thonnard (1983) yielded an upper limit of only $11.5 \times 10^7 M_\odot$ to the total H I mass of NGC 4636.

Because of its high X-ray luminosity, NGC 4636 has been studied extensively in this frequency range, and these observations have also been used to infer its dark matter content and distribution.

[★] Based on observations collected at the European Southern Observatory, Cerro Paranal, Chile; ESO program 69.B-0366.

^{★★} Appendix A is only available in electronic form at <http://www.aanda.org>

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Table 1. NGC 4636 basic data compiled from the literature (1) NED, (2) Tonry et al. (2001), (3) this work, (4) R3C, (5) Dirsch et al. (2005), (6) Bender et al. (1994), (7) Idiart et al. (2003), (8) Forman et al. (1985), and (9) Loewenstein et al. (2001).

Other names	UGC 07878, VCC 1939	
Position (J2000)	12 ^h 42 ^m 50 ^s +02° 41′ 17″	(1)
Galactic coordinates	$l = 297.75^\circ$ $b = 65.47^\circ$	
SBF distance modulus	$(m - M) = 30.83 \pm 0.13$	(2)
Distance	$D = 15$ Mpc	
Scale	$1'' = 73$ pc $1' = 4.4$ kpc	
GCLF distance modulus	$(m - M) = 31.24 \pm 0.17$	(5)
Heliocentric velocity	$v_{\text{helio}} = 906 \pm 7$ km s ⁻¹	(3)
Hubble type	E0+	(4)
Ellipticity	$\epsilon = 0.15$	(6)
Position angle	$PA = 145^\circ$	(5)
Effective radius	$R_e = 101''$ 7 (=7.5 kpc)	(7)
Blue magnitude	$B_T = 10.43$	(4)
Total apparent magnitude	$T1 = 8.70 \pm 0.05$	(5)
Metallicity	$[\text{Fe}/\text{H}] = -0.01$ dex	(7)
X-ray luminosity	$L_X = 1.78 \pm 0.10 \times 10^{41}$ erg/s	(8)
Nuclear X-ray emission	$\leq 2.7 \times 10^{38}$ erg/s	(9)

Forman et al. (1985) analyzed Einstein X-ray data from a large sample of early-type galaxies. For NGC 4636, they found extended emission (out to a radius of $R_{\text{max}} = 44$ kpc) and derived an X-ray luminosity of $L_X = 1.78 \pm 0.10 \times 10^{41}$ erg s⁻¹. They quote a mass-to-light ratio $M_{\text{total}}/L_B = 87$ for R_{max} , the second largest value in their sample.

Matsushita et al. (1998), using ASCA, found very extended X-ray emission around NGC 4636 out to 60′. This corresponds to a radius of almost 300 kpc in a distance of 15 Mpc. The authors suggest that the gravitational halo of NGC 4636 itself terminates in the region between 10 and 30 kpc. They observe an increase in mass beyond 30 kpc, forming a halo-in-halo structure whose size is comparable to that of a galaxy group.

Jones et al. (2002) used the Chandra X-Ray Observatory Advanced CCD Imaging Spectrometer (ACIS) to study the X-ray halo of NGC 4636 with a spatial resolution of ~ 50 pc. The observed X-ray features are so far unique: the images show symmetric, arm-like structures that surround a bright central region. These structures extend ~ 8 kpc from the galaxy center. The leading edges of these arms show changes in brightness by a factor of two on scales of just a few arcseconds. While these sharp fronts might be suggestive of a merger, the authors favor a nuclear outburst as the source of the observed morphology. They interpret the arms as the projected edges of paraboloidal shock fronts expanding from the nucleus. Jones et al. speculate that the unusually high X-ray luminosity of NGC 4636 might be due to the advanced state of the cooling that brought on the outburst and may be further enhanced by the shocks. When the gas halo returns to hydrostatic equilibrium, the X-ray luminosity could decline by an order of magnitude or more.

Loewenstein & Mushotzky (2003) used the Chandra X-Ray Observatory to measure the hot interstellar medium temperature profile of NGC 4636. Assuming hydrostatic equilibrium, they determined the total enclosed mass profile for the radial range $0.7 < r < 35$ kpc. These authors come to the conclusion that dark matter constitutes a large fraction (between 50% and 80%) of the total mass, even inside the effective radius.

Given all these peculiarities, it is of great interest to use globular clusters as dynamical tracers to evaluate the dark matter content of NGC 4636. This work continues our program on the dynamics of globular cluster systems (GCSs) around early-type

galaxies. Previous papers on NGC 1399, the central galaxy of the Fornax cluster, are Richtler et al. (2004) and Dirsch et al. (2003).

1.2. The NGC 4636 globular cluster system

The GCS of NGC 4636 has been the target of three photometric studies. Hanes (1977) used photographic plates to assess the number and the luminosity of the GCs. He derived a specific frequency (i.e., the number of GCs normalized to the host galaxy's luminosity (Harris & van den Bergh 1981) of $S_N = 9$, which is unusually high for a quite isolated elliptical galaxy. Most field ellipticals have S_N values between 3 and 4. The first CCD-study was performed by Kissler et al. (1994), who observed a field of 7.5×7.5 centered on NGC 4636 in one band (Cousins V , limiting magnitude of 24.25). They estimated the total number of GCs to be 3600 ± 200 , which corresponds to $S_N = 7.5 \pm 2.0$, hence supporting the unusually high number of GCs.

The full extent of the GCS together with color information only became apparent in the recent study of Dirsch et al. (2005). They used the MOSAIC camera at the 4-m telescope at the Cerro Tololo Interamerican Observatory (CTIO). The bands were Kron-Cousins R and Washington C . The final images have a field-of-view of $34.7' \times 34.7'$. The color distribution of the GCs shows the familiar bimodal shape. The color of the minimum of the inner sample ($C - R = 1.55$) was chosen to divide red (metal-rich) from blue (metal-poor) clusters, frequently interpreted as two different sub-populations (e.g., Ashman & Zepf 1998; Kundu & Whitmore 2001; Larsen et al. 2001). For the total number of globular clusters, Dirsch et al. derived 3700 ± 200 , which agrees well with the previous measurement. The specific frequency S_N ranges between 5.8 ± 1.2 and 8.9 ± 1.2 , for the GCLF and SBF distances, respectively. An interesting feature shows up in the radial distribution of the clusters: While the (projected) radial number density distribution of the blue clusters can be described by one power-law ($n(r) \propto r^\alpha$) within $1' - 8'$, the density distribution of the red clusters changes the exponent within this radial interval. At a radial distance of $7'$ ($9'$) for the red (blue) clusters, the power-law exponent drops to about -5 (cf. Table 3 in Dirsch et al. 2005). Such behavior has not been observed in any GCS before. This abrupt decrease in number density might mark the limit of the GCS and possibly that of the galaxy itself. The photometric data by Dirsch et al. forms the basis of the candidate selection for our spectroscopic observations described in the following section.

2. Observations

The observations were carried out over four nights (May 7–10, 2002) at the European Southern Observatory (ESO) Very Large Telescope (VLT) facility on Cerro Paranal, Chile. The VLT Unit Telescope 4 was used with the FORS2 (FOcal Reducer/low dispersion Spectrograph) instrument equipped with the Mask EXchange Unit (MXU). The standard resolution collimator used for this program provided a field-of-view of 6.8×6.8 . The detector system consisted of two 4096×2048 red optimized CCDs with a pixel size of $15 \mu\text{m}$. For our observations, the chips were read out using a 2×2 binning. The grism 600B gave a spectral resolution of about $3 \text{ \AA}$. The spectral coverage was dependent on the slit position on the mask. In most cases, the usable coverage was about $2000 \text{ \AA}$, with limits on the red side varying between 5500 and $6500 \text{ \AA}$. We exposed 13 spectroscopic masks, the preparation of which is described in the next section. Flat

Table 2. Summary of observations (ESO program ID 69.B-0366(B)). The seeing values were determined from the acquisition images taken just before the MXU exposures.

Field	Center position (J2000)		Exp. time (sec)	Seeing	# Slits		# GCs	Night	UT (start)
					total	objects			
1.1	12:42:48.2	02:39:21.0	7200	1''1	111	79	39	2002-05-07	23:27
1.2	12:42:45.8	02:39:24.2	4500	0''9	98	61	47	2002-05-07	01:49
1.3	12:42:50.8	02:39:21.3	5400	1''2	106	65	26	2002-05-07	03:17
2.1	12:42:17.8	02:37:27.9	3600	1''0	101	51	3	2002-05-07	05:11
2.2	12:42:23.0	02:37:27.6	3600	1''0	99	48	2	2002-05-08	23:32
3.1	12:42:34.2	02:46:22.4	3600	0''8	113	77	26	2002-05-08	01:21
3.2	12:42:28.9	02:46:20.7	3600	1''1	113	54	14	2002-05-08	02:31
4.1	12:42:27.1	02:53:27.4	3600	1''3	98	44	2	2002-05-10	23:37
5.1	12:43:00.6	02:46:50.3	3600	0''9	105	17	59	2002-05-08	03:43
6.1	12:43:15.0	02:39:33.7	3600	1''2	107	53	8	2002-05-10	01:04
6.2	12:43:12.6	02:39:32.0	3600	0''9	110	55	16	2002-05-09	00:18
7.1	12:43:33.9	02:32:12.1	3600	0''9	109	52	0	2002-05-09	01:31
7.2	12:43:29.3	02:32:09.7	3600	0''8	113	59	2	2002-05-09	02:44

fielding was done with internal flat lamps. A Hg-Cd-He lamp was used for wavelength calibration. The observations are summarized in Table 2.

2.1. Mask preparation

Pre-images of the 13 pointings in 7 fields (see Fig. 1) were obtained in service mode in October 2000. Each pointing was observed in Cousins *V* and *I* filters for 30 s. The GC candidate selection was based upon the photometric work presented in Dirsch et al. (2005). Cluster candidates had to fulfill the following criteria: they had to be brighter than 22.7 in *R*, and the allowed color range was $0.9 < C - R < 2.1$. Further, the candidates should exhibit a star-like appearance on the pre-images to distinguish them from background galaxies. The ESO FORS Instrumental Mask Simulator (FIMS) software was then used to select the positions, widths, and lengths of the slits. A slit width of 1'' was chosen according to the sub-arcsecond seeing conditions on Paranal. To maximize the number of GC spectra obtained per mask, we chose to observe our targets and sky positions through separate slits of 2'' length. Obviously, the quality of the sky subtraction then depends on the accuracy of the wavelength calibration. As will be shown, it turned out to be satisfactory to obtain radial velocities with the desired accuracy. After positioning the slits for the selected GC candidates, the remaining space on the masks (especially in the outer fields) was used to include additional objects. Thus, background galaxies and point sources not matching the above-mentioned criteria were also observed.

2.2. The data set

The MXU-observations of our thirteen fields have exposure times in the range of 3600 to 7200 s (see Table 2 for a summary of the observations). To minimize the effects from cosmic ray hits, the observation of each mask was divided into two exposures – with the exception of Field 1.1, for which three science images were obtained. In addition to the spectroscopic observations, calibration measurements, i.e., bias, flat fields, and wavelength calibration exposures, were obtained during the daytime.

Fig. 1. Positions of the fields overlaid on a 33' × 33' DSS image centered on NGC 4636. For each mask, the entire FORS 2 6'8 × 6'8 field-of-view is shown. Note that the slit positions are confined to the central 4'3 × 6'8 region of each pointing.

3. Data reduction

The following section summarizes the reduction steps performed to obtain the final sky-subtracted spectra. Most of the data reduction was done within the IRAF-environment¹.

3.1. Basic reduction

The merging of the two CCD-frames was done with *fsmosaic*, which is available as a part of the ESO-FIMS software. The dimension of the combined images is 2050 × 2076 pixels. For cosmic ray removal, the task *bclean* from the *Starlink Figaro*-package was found to perform best. Biasing and flat-fielding

¹ IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. (<http://iraf.noao.edu/>).

was done in the standard way. Since the aim of this study is the measurement of radial velocities rather than the measurement of line strengths, we did not apply any response function fitting or flux calibration. To obtain one-dimensional spectra (aperture definition, tracing, and extraction) the IRAF task *apall* from the *apextract* package was used. Once the aperture positions were defined on the science images, they were checked and – where necessary – adjusted on the flatfield divided exposures. For the 2'' long slits used for most sources, an aperture size of 4 pixels (=1'') was found to yield the best results.

3.2. Wavelength calibration and sky subtraction

The one-dimensional arc lamp spectra were calibrated using the interactive task *identify* from the *noao.onedspec* package. The dispersion/wavelength solution was approximated by a seventh-order Chebyshev polynomial. The residuals of this fit were inspected for outliers, and if necessary, the deviant data points were excluded from the fit in the next step. The rms errors of the final fits were about 0.04 Å. As described above, sky spectra were measured through separate slits. To perform the sky subtraction for a given GC-spectrum, two or three adjacent (within 18'') sky spectra were combined. This combined sky spectrum was then subtracted using the *skytwake* task.

4. Measurement of radial velocities

The IRAF task *fxcor* from the *noao.rv* package performs a Fourier cross-correlation on the input object and template spectra. This program is based upon the technique developed by Tonry & Davis (1979). For the cross-correlation, a template with a high S/N and a spectrum similar to that of a globular cluster is required. NGC 4636 itself, however is not suitable due to its high velocity dispersion of about 200 km s⁻¹. Therefore, the velocities were measured using a spectrum ($S/N \sim 30$) of NGC 1396 as template. This spectrum was obtained in Dec. 2000, during observations of the NGC 1399 GCS, using the same FORS2 instrumental setup and has already been used as a template for investigating the kinematics of the NGC 1399 GCS (Dirsch et al. 2004). NGC 1396 is a dwarf elliptical galaxy close to NGC 1399, and its spectrum resembles that of a metal-rich globular cluster. Its velocity dispersion is only 65 ± 6 km s⁻¹ (Wegner et al. 2004). We adopted a heliocentric radial velocity of 815 ± 8 km s⁻¹ (Dirsch et al. 2004). The velocities obtained with this template were checked with a second template spectrum obtained during our observations (object 1.3:56), a bright star whose observed velocity was found to be -682 km s⁻¹, with respect to the galaxy template. The velocities measured with the two different templates agree very well. Since the *fxcor* uncertainty estimates were smaller for the galaxy template, only these velocities are used for the subsequent analysis. The accuracy of the velocity determination depends on the shape of the spectrum and the wavelength range for which the cross-correlation is performed. A range of $4700 < \lambda < 5500$ Å was found to be an appropriate choice in most cases. The upper limit was chosen to avoid the night sky emission lines found around the strong [OI] 5577 Å feature. In some spectra however, the relatively weak nitrogen line at 5199 Å left substantial residuals: where this was the case, the wavelength interval was adjusted accordingly. For the velocities of the NGC 4636 GCS, we applied a heliocentric correction of $v_{\text{hc}} = -18$ km s⁻¹; the correction for the NGC 1396

Fig. 2. Histogram of the velocity uncertainties calculated by the *fxcor*-task. The grey histogram shows the values for the blue clusters; the black histogram shows the same for the red clusters.

spectrum is $v_{\text{hc}} = -10$ km s⁻¹. The uncertainty for the velocities is estimated using:

$$\Delta v = \sqrt{\Delta v_{\text{fxcor}}^2 + \Delta v_{\text{template}}^2},$$

where Δv_{fxcor} is the velocity uncertainty output by *fxcor*, and $\Delta v_{\text{template}}$ is the velocity uncertainty of the template spectrum.

4.1. Zero point shifts

Since the wavelength calibration exposures for each mask were obtained during the day following the observation, the mask was moved into the focal plane again. The finite positioning accuracy of the MXU, and shifts due to instrument flexure under gravity (all calibration exposures are obtained with the telescope pointing at the zenith), result in an offset between the science and the calibration images. This offset manifests itself as a zero point shift in the observed wavelength of the strong telluric [OI] 5577 Å emission line. The zero point shifts in our data set were found to vary with the position of the slit along the y -axis of the mask. To quantify this effect, the wavelength of the 5577 Å line was measured in all spectra for a given mask. A linear function was fit to the data and provided a velocity correction for every aperture. These corrections have values in the range $-25 \text{ km s}^{-1} \leq \Delta v_{\text{MXU}} \leq 25 \text{ km s}^{-1}$.

To measure the systemic velocity of NGC 4636, we used the nine spectra of NGC 4636 from mask 1_1 and found a heliocentric velocity of 906 ± 7 km s⁻¹. In the NASA/IPAC Extragalactic Database (NED)², one finds seven optical velocity measurements with uncertainty estimates. The mean is 917 ± 31 km s⁻¹. Hence, our velocity agrees very well with previous measurements.

4.2. Velocity uncertainties

For the GCs, no trend is visible for the metal poor (blue) and the metal rich (red) subpopulations: both have very similar error distributions (see Fig. 2). Figure 3 shows the velocity uncertainties as a function of apparent R -magnitude. As expected, the measurements of fainter objects tend to have larger uncertainties. The uncertainties returned by the *fxcor* task are computed according to the formulae given by Tonry & Davis (1979).

² The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Table 3. Basic properties of the globular cluster sample.

	All	Blue	Red
Number of GCs	174	97	75
Mean velocity [km s ⁻¹]	904	911	887
Min. velocity [km s ⁻¹]	392	514	392
Max. velocity [km s ⁻¹]	1441	1441	1273
Mean vel. uncertainty [km s ⁻¹]	31	33	28
Velocity dispersion [$\sigma(R)$ km s ⁻¹]	203 $\pm$ 11	202 $\pm$ 15	199 $\pm$ 17
Color range $C-R$		0.85–1.55	1.55–2.15
Range in projected radius	0:91–15:43	0:91–15:43	1:00–11:90

Fig. 3. Velocity uncertainties versus R -magnitude for the globular clusters (crosses: blue clusters; open circles: red clusters).

To check whether these uncertainties are a realistic error estimate, we compared the velocities of those 40 objects for which we had two spectra, since they were present on two masks. The mean difference for the velocity measurements was found to be very similar to the mean of the uncertainties given by *fxcor*. Hence, the *fxcor* uncertainties can be considered a good error estimate. The velocities determined for the GCs are listed in Appendix A, which is available in electronic form.

5. Properties of the globular cluster sample

For every object with a velocity measurement, the color and magnitude information was extracted from the photometry-database from Dirsch et al. (2005) via coordinate matching. The coordinates, velocities, $C-R$ -colors and apparent R -magnitudes of these objects are listed in Appendix A. For two clusters, neither color nor magnitude information exists, since they happened to be located near a bad row of the MOSAIC-CCD.

5.1. Defining the sample

The first step was to divide our data set into GCs and foreground stars. A compelling distinction between stars and globular clusters would be given if the GCs could be resolved on the acquisition images. However, only a very few, about three, of our clusters are marginally resolved. Guided by Fig. 4, which shows the distribution of velocity versus color for all measured objects, a lower limit of 350 km s⁻¹ for the radial velocity of the GCs was chosen. However, one has to be aware that there might be a velocity domain where this identification is doubtful. Given that the Galactic rotation vector towards the position of NGC 4636 is -78 km s⁻¹, one cannot exclude that foreground stars have heliocentric velocities of up to 400 km s⁻¹. Neither can one rule out the presence of GCs with radial velocities of more than 500 km s⁻¹ relative to NGC 4636.

Fig. 4. Color vs. radial velocity. All objects with heliocentric velocities higher than 350 km s⁻¹ (dotted line) are regarded as globular clusters. The objects with velocities falling below this limit are foreground stars. The solid line marks the systemic velocity of NGC 4636.

The range in velocities occupied by foreground stars and globular clusters is $-248 \leq v \leq 313$ km s⁻¹ and $392 \leq v \leq 1441$ km s⁻¹, respectively. The data set comprises 174 globular clusters and 175 foreground stars. The basic properties of the GC sample are listed in Table 3. The so-defined GCs appear in Fig. 5, which shows their distribution around NGC 4636. The inner region is well sampled, but due to the sharp drop-off at $\sim 7'$, only a handful of clusters is located outside this radius.

5.2. Color and luminosity distribution

For any further investigation, it is important that the color distribution of the GCs with measured radial velocities resembles that of the entire cluster system. Indeed, the bimodality of the color distribution found in the photometric study by Dirsch et al. (2005) is clearly visible in our much smaller sample (see Fig. 6). For consistency, the same dividing color of $C-R = 1.55$ was used. Thus, we find 97 blue and 75 red globular clusters. The color magnitude diagram (CMD) for the GCs is shown in Fig. 6. Although the selection of GC candidates was obviously biased towards bright clusters, no clusters brighter than $R = 19$ were found. A few clusters are fainter than $R = 22$, but their velocities have large errors (cf. Fig. 3) and should be considered with caution. Figure 7 shows the histogram of the apparent R -magnitudes for the globular clusters. It illustrates that our spectroscopic study only probes the very bright part of the GCLF, well above the turnover magnitude at 23.33 (Dirsch et al. 2005). Furthermore, it shows that there is no significant difference between the distributions of blue and red clusters. The magnitude range of the GCs is $19.11 \geq m_R \geq 22.73$ in Kron R . When converted to absolute magnitudes (using the distance modulus of 30.83, Tonry et al. 2001), the globular clusters

Fig. 5. Spatial distribution of the globular clusters overlaid on a 33' × 33' DSS-image centered on NGC 4636. North is to the top, East to the left. GCs with velocities larger than the systemic velocity of NGC 4636 are marked by crosses. Circles denote GCs with negative relative velocities. The concentric circles have radii of 2, 7, and 15 arcmin.

Fig. 6. *Top:* Color magnitude diagram for the globular clusters. Plotted are $C-R$ vs. R . *Bottom:* Color distribution for the GCs (bin width = 0.05 mag). In both panels, the dotted line at $C-R = 1.55$ indicates the color dividing blue from red clusters (Dirsch et al. 2005).

in our sample span the range $-11.6 \leq M_R \leq -8.1$ in R and $-11.25 \leq M_V \leq -7.6$ in V (for $V-R = 0.47$, Dirsch et al. 2005). Assuming a typical mass-to-light ratio of $M/L_V = 2$, one finds that the masses of the brightest clusters are of the order $7-8 \times 10^6 M_\odot$. For comparison, the absolute visual magnitude of ω Centauri (NGC 5139) is $M_V = -10.29$ (Harris 1996), and its mass is about $5 \times 10^6 M_\odot$.

Fig. 7. Globular cluster luminosity distribution (bin width = 0.2 mag). The dotted line at 23.33 indicates the turnover magnitude of the GCS. Histograms for blue (solid grey) and red clusters.

Fig. 8. *Left:* radial velocity as a function of apparent R -magnitude. *Right:* radial velocity of the GCs plotted vs. the $C-R$ -color.

5.3. Spatial distribution

As can be seen in Fig. 5, our target clusters are not uniformly distributed with respect to the center of NGC 4636. At the time of the mask preparation, before the photometric data set was fully analyzed, the projected globular cluster number density was overestimated. Some fields were placed at larger projected distances (see Fig. 1), at the expense of a more uniform azimuthal coverage. Yet in total, only 15 of the 174 GCs in our sample are found at projected radii larger than $7.5''$. Thus, any measurement of the line-of-sight velocity dispersion beyond this radius is clearly doubtful. Note that the radius at which the power-law index of the projected globular cluster density drops (cf. Sect. 1.2) lies in the range $7''$ to $9''$.

5.4. Velocity distributions

In the left panel of Fig. 8, the velocities are plotted against the R -magnitudes. As expected, they are found to be concentrated towards the systemic velocity. The brightest clusters, however, tend to avoid the systemic velocity. A larger sample is needed to confirm whether this effect is real or due to low-number statistics. The right panel of Fig. 8 shows the velocities plotted against the $C-R$ colors of the clusters. Again, no clear trend is visible, although one notes that the five clusters with the highest velocities are blue. The top right panel of Fig. 9 plots all GC radial velocities versus the projected radii in arcminutes. This figure once more shows how few velocities were obtained for large radii. The more important observation, however, is that the scatter of the velocities about the systemic velocity is rather small at a radial distance of about $2''-4''$. As will be shown in Sect. 7, this translates directly into a decrease of the projected velocity

Fig. 9. The *left panels* show the histograms of the GC velocities for the entire sample, the blue subsample, and the red subsample, respectively. In each panel, the grey histogram shows the distribution of the corresponding error-selected ($\Delta v < 35 \text{ km s}^{-1}$) sample. The dashed line indicates the systemic velocity of NGC 4636, and the bin width is 70 km s^{-1} . The *right panels* show the radial velocities versus projected galactocentric distance for all, the blue, and the red clusters. The crosses in circles denote data points with $\Delta v < 35 \text{ km s}^{-1}$, i.e. they form the error selected samples. Plain crosses denote data points with larger velocity uncertainties. Again, the dashed line marks the systemic velocity of NGC 4636.

dispersion in this radial interval. On the other hand, only relatively few GCs fall into this radial range. The middle and lower right panels of Fig. 9 show the same diagram for blue and red clusters, respectively. In the radial range around $2'-4'$, the scatter about the systemic velocity is larger for the blue than for the red clusters, hence the radial behavior of the velocity dispersions for the subsamples will turn out to be rather different (see Sect. 7).

6. Rotation

Due to the inhomogeneous azimuthal coverage of our sample, it is obvious that statements concerning rotation have to be considered with caution. The diagnostic diagram that we have to analyze is a plot of radial velocities vs. the position angle. Côté et al. (2001) give a useful discussion of the relation between the intrinsic and projected rotational velocity field of a spherical system, and we do not repeat that here. If the intrinsic rotation velocity field is stratified on spheres, and the galaxy is not seen pole-on, we measure radial velocities that depend sinusoidally on the azimuth angle. Therefore, we fit the following relation:

$$v_r(\Theta) = v_{\text{sys}} + A \sin(\Theta - \Theta_0), \quad (1)$$

where v_r is the measured radial velocity at the azimuth angle Θ , v_{sys} is the systemic velocity, and A the rotation amplitude. Figure 10 shows the radial velocities of three samples versus the azimuth angle, which goes from North past East. The uppermost panel is the full sample, then follow the blue and the red clusters.

A very marginal rotation signal is present in the full sample with the parameters $A = 28 \pm 18 \text{ km s}^{-1}$ and $\Theta_0 = 63 \pm 43$. The blue sample does not show a significant signal ($A = 11 \pm 27 \text{ km s}^{-1}$), while the red sample shows significant rotation, which leaves its imprint on the whole sample. The signal and its significance depend on the color dividing blue and red clusters. The strongest signal is found for clusters redder than $C-R = 1.6$. In this case, we find $A = -87 \pm 18 \text{ km s}^{-1}$ and $\Theta_0 = 60 \pm 22$ for the entire red sample, which means a rotation around the minor axis with the southeastern region approaching. Both the amplitude and the position angle remain within the uncertainty limits for subsamples selected in radial bins. Selecting red clusters with projected distances below 5 arcmin yields $A = -105 \pm 36 \text{ km s}^{-1}$ and $\Theta_0 = 72 \pm 24$. Radii less than 4 arcmin give $A = -114 \pm 44 \text{ km s}^{-1}$ and $\Theta_0 = 72 \pm 25$. However, a confirmation of the rotation of the red clusters is desirable, given the relatively low number statistics and the inhomogeneity regarding radius and position angle. Attempts to interpret the rotation, for example, as a dynamical sign for a merger event therefore seem premature. In any case, it may be that rotation influences the velocity dispersion of the red clusters, making their use as dynamical tracers more complicated.

7. Velocity dispersion

The top left panel of Fig. 9 shows the velocity distribution of the entire velocity sample. The bin size was chosen to be 70 km s^{-1} , which is larger than the mean uncertainty. The mean velocity

Fig. 10. This plot shows radial velocity vs. the position angle (North past East). The *upper panel* plots the entire sample, the *middle panel* the blue clusters, and the *lower panel* the red clusters. A marginal rotational signal is detected in the entire sample, which is due to the stronger signal of the red clusters, which seem to rotate around the minor axis with an amplitude of about 90 km s^{-1} . The blue clusters do not rotate.

of $906 \pm 16 \text{ km s}^{-1}$ is in excellent agreement with the systemic velocity of NGC 4636 we determined from the galaxy spectra (cf. Sect. 4.1). The shape of the distribution appears Gaussian (the Anderson-Darling test for normality yields a p -value of 0.81 (Stephens 1974)). This is what one would expect for a kinematical sample that is close to isotropic and in dynamical equilibrium (see, e.g., Binney & Tremaine 1987). The most important observable that we want to extract from our data is the projected velocity dispersion and its dependence with radius. Throughout this analysis, it is assumed that our velocity measurements are drawn from one normal distribution. To calculate the velocity dispersions presented in the following section, we employed the maximum likelihood dispersion estimator presented by Pryor & Meylan (1993). We fixed the systemic velocity of NGC 4636 to $v_{\text{sys}} = 906 \text{ km s}^{-1}$. Then, the velocity dispersion σ is calculated (by iteration) according to:

$$\sum \frac{(v_i - v_{\text{sys}})^2}{(\sigma^2 + \delta_i^2)^2} = \sum \frac{1}{\sigma^2 + \delta_i^2}, \quad (2)$$

where the sum is taken over all velocities and the δ_i are the uncertainties of the individual velocity measurements. The uncertainty of the resulting velocity dispersion is computed according to the expression given by Pryor & Meylan. Calculating the dispersion for all clusters yields: $\sigma_{\text{all}} = 203 \pm 11 \text{ km s}^{-1}$. The velocity dispersions for the blue and red cluster populations are $\sigma_{\text{blue}} = 202 \pm 15 \text{ km s}^{-1}$ and $\sigma_{\text{red}} = 199 \pm 17 \text{ km s}^{-1}$, respectively, i.e., they are equal within the uncertainties. To study the radial dependence of the velocity dispersion, we chose to divide our samples radial bins of $1'.5$ width. The results are listed in Table 4 and plotted in Fig. 11.

7.1. All clusters

The upper left panel of Fig. 11 shows the radial dependence of the velocity dispersion for all 170 GCs within $R \leq 9'.0$. For comparison, the line-of-sight velocity dispersion measurements of the central region from Bender et al. (1994) are shown as diamonds. These authors used a long-slit spectrum (with the slit positioned along the major axis) to derive a central velocity dispersion of $\sigma_c = 200 \pm 10 \text{ km s}^{-1}$, and for the average velocity dispersion measured along the major axis ($R < 32''$), they

Table 4. Projected velocity dispersion as a function of projected galactocentric radius. The upper section shows the values for all, the blue, and the red clusters. The dispersions for the corresponding error-selected samples are listed in the lower section. The data are shown in Fig. 11. The values in brackets are those obtained when omitting the two (blue) GCs with velocities above 1400 km s^{-1} .

R (arcmin)	σ (all) (km s^{-1})	σ (blue) (km s^{-1})	σ (red) (km s^{-1})
no error selection			
1.7	228 ± 23	218 ± 30	241 ± 39
3.2	157 ± 22	160 ± 33	155 ± 32
4.7	204 ± 24	205 ± 33	207 ± 37
6.2	206 ± 25	196 ± 30	190 ± 39
6.2	(169 ± 21)	(126 ± 21)	
7.7	207 ± 43	220 ± 63	196 ± 65
9.2	105 ± 41		
error-selected samples ($\Delta v < 35 \text{ km s}^{-1}$)			
1.7	221 ± 25	198 ± 32	241 ± 38
3.2	185 ± 37	207 ± 64	172 ± 46
4.7	175 ± 24	181 ± 34	168 ± 33
6.2	226 ± 34	227 ± 46	194 ± 42
6.2	(178 ± 27)	(121 ± 27)	
7.7	162 ± 260		
9.2	105 ± 41		

found $\sigma_{\text{maj}} = 200 \pm 30 \text{ km s}^{-1}$. Within the uncertainties, our data points agree with the Bender et al. measurements. Albeit consistent with a constant velocity dispersion of about 200 km s^{-1} , this plot suggests a decrease of $\sigma(R)$ by about 50 km s^{-1} (from ~ 220 to $\sim 170 \text{ km s}^{-1}$) in the radial distance range of roughly $2'-4'$. To check whether this behavior is merely an artifact produced by velocity measurements with large uncertainties, we next consider an error selected sample ($\Delta v < 35 \text{ km s}^{-1}$) (cf. Fig. 9, lower panel, to see which data points are omitted). The plot for this smaller (120 GC velocities) sample is shown in the upper right panel of Fig. 11. Apparently, the decline is not due to large individual uncertainties. As will be shown next, this pattern is the result of the different behaviors of the blue and red subpopulations.

7.2. Blue and red clusters

The middle and lower panels of Fig. 11 show the radial dependence of the velocity dispersion for the blue and the red subpopulations, respectively. The values derived for the error selected ($\Delta v < 35 \text{ km s}^{-1}$) samples, which consist of 56 blue and 56 red clusters, are shown in the right panels. While the blue clusters show a constant velocity dispersion of about 200 km s^{-1} , the velocity dispersion of the red clusters drops from a value of $\sim 240 \text{ km s}^{-1}$ to $\sim 170 \text{ km s}^{-1}$ at a radius of about $2'-3'$. From this radius on, out to at least $5'.5$, the velocity dispersion apparently remains at the constant, low value. Considering these results for blue and red clusters, one can attribute the drop seen for the whole error selected sample to the red clusters. However, the number of red clusters is rather high in the innermost radial bins, giving the large dispersion at small radii a high degree of confidence. On the other hand, the lower velocity dispersion at larger distances may be uncertain for the individual bins, but that the overall velocity dispersion is lower than for the innermost bin can be stated with high confidence as well. This is a new feature that has not been seen before in any of the few kinematic GC samples of other galaxies. We offer a simple explanation in the context of the spherical Jeans equation in the next section.

Fig. 11. The *left panels* show the velocity dispersion versus projected galactocentric radius for the whole, the blue, and the red cluster samples, respectively. The *right panels* show the same for the corresponding error-selected $\Delta v < 35 \text{ km s}^{-1}$ samples. The velocity dispersions were calculated for radial bins of $1'5$ width, and the number of velocities used for the measurement is shown below each data point. The values plotted here are listed in Table 4. In all panels, the diamonds indicate the dispersion measurements from Bender et al. (1994). The open circles show the dispersion values at $6'$ that are obtained when omitting the two (blue) GCs with velocities above 1400 km s^{-1} .

8. The mass profile

The line-of-sight velocity dispersion $\sigma_{\text{los}}(R)$ of the GCS and its radial dependence is used to estimate the mass profile of NGC 4636. Given that the number of spectroscopically observed GCs is still far too low for an axisymmetric treatment, we will assume spherical symmetry. This is justified since the deviation from sphericity is modest in the inner parts of the galaxy (Dirsch et al. 2005) where most of our clusters are found. A further argument is the high M/L_B found by Kronawitter et al. (2000) (see Sect. 8.3). Given that a flattening in the line of sight leads to an underestimation of M/L (Magorrian & Ballantynes 2001), it is hard to imagine that such a high value is still underestimated.

8.1. The mass profile from the Jeans equation

The collisionless Boltzmann equation is used to derive the spherical, non-rotating Jeans equation (see Binney & Tremaine 1987 for a full treatment),

$$\frac{d(\ell(r) \sigma_r^2(r))}{dr} + 2 \frac{\beta(r)}{r} \ell(r) \sigma_r^2(r) = -\ell(r) \frac{G \cdot M(r)}{r^2}, \quad (3)$$

$$\text{with} \quad \beta \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2}.$$

Here, r is the radial distance from the center and ℓ is the spatial (i.e., three-dimensional) density of the GCs; σ_r and σ_θ are

the radial and azimuthal velocity dispersions, respectively. β is the anisotropy parameter, and G is the constant of gravitation. To derive the enclosed mass $M(r)$, one needs to know β . In other words: the potential and the anisotropy are degenerate in the spherical approximation. Information about the anisotropy must be inferred from higher moments of the velocity distribution, for which one needs much larger samples than ours. Merritt & Tremblay (1993) used M 87 as an example and estimated that several hundred, perhaps as many as a thousand velocities, would be required to detect a velocity anisotropy.

8.2. The Jeans-analysis: principle

For our analysis, we use the expressions given by, e.g., Mamon & Łokas (2005) (see also van der Marel 1994). Given a mass distribution $M(r)$, a three-dimensional mass or number density of a tracer population $\ell(r)$, and a *constant* anisotropy parameter β , the solution to the Jeans equation (Eq. (3)) reads:

$$\ell(r) \sigma_r^2(r) = G \int_r^\infty \ell(s) M(s) \frac{1}{s^2} \left(\frac{s}{r}\right)^{2\beta} ds. \quad (4)$$

This expression is then projected using the following integral:

$$\sigma_{\text{los}}^2 = \frac{2}{I(R)} \left[\int_R^\infty \frac{\ell \sigma_r^2 r dr}{\sqrt{r^2 - R^2}} - R^2 \int_R^\infty \frac{\beta \ell \sigma_r^2 dr}{r \sqrt{r^2 - R^2}} \right], \quad (5)$$

where $I(R)$ is the projected number density of the tracer population.

8.3. Luminous matter

To assess the mass distribution of the luminous (stellar) component, we proceed as follows: The photometric study by Dirsch et al. (2005) provides a surface brightness profile in Kron-Cousins R . It reads:

$$\mu(R) = -2.5 \log \left(a_1 \left(1 + \frac{R}{R_1} \right)^{-\alpha_1} + a_2 \left(1 + \frac{R}{R_2} \right)^{-\alpha_2} \right), \quad (6)$$

with $a_1 = 3.3 \times 10^{-7}$, $R_1 = 0.11'$, $\alpha_1 = 2.2$, $a_2 = 5.5 \times 10^{-9}$, $R_2 = 8.5'$, and $\alpha_2 = 7.5$. To obtain the luminosity density $[L_\odot/\text{pc}^3]$, the intensity profile $I(R) = 10^{-0.4 \mu(R)}$ has to be deprojected. This was done using the Abel deprojection integral (Eq. (7)). For the cutoff-radius r_t , we chose a value of $2000''$, roughly twice the distance of the last photometric datapoint

$$\varepsilon(r) = -\frac{1}{\pi} \left[\int_r^{r_t} \frac{dI(R)}{dR} \frac{dR}{\sqrt{R^2 - r^2}} - \frac{I(r_t)}{\sqrt{r_t^2 - r^2}} \right]. \quad (7)$$

Further assumptions are spherical symmetry and a distance of 15 Mpc. Moreover, we have to take into account that we use an R -surface brightness profile: to translate it into solar luminosities, we need the absolute magnitude of the Sun in this filter. We use a value of $V - R = 0.370$ (Bessell et al. 1998) for the Sun, i.e., $M_{R,\odot} = 4.46$. The deprojected luminosity density was then (numerically) integrated to yield a cumulative luminosity (in units of $L_\odot$). The latter was fit by a sixth-order polynomial $\sum m_i \cdot R^i$ (R in parsec) with the coefficients: $m_0 = 6.38 \times 10^8$, $m_1 = 3.22 \times 10^6$, $m_2 = -70.0$, $m_3 = 5.62 \times 10^{-4}$, $m_4 = 3.54 \times 10^{-9}$, $m_5 = -8.92 \times 10^{-14}$, and $m_6 = 4.22 \times 10^{-19}$. The polynomial is a good representation in the range $2 < R < 70$ kpc.

To convert the cumulative luminosity into a mass profile, the stellar mass-to-light ratio is required, i.e., M/L_R . Kronawitter et al. (2000) quote a value of $M/L_B = 9$ for a distance of 20.5 Mpc. Because M/L is inversely proportional to the distance, one has to apply a factor of 1.36 to get $M/L_B = 12.2$ at a distance of 15 Mpc. This value is suspiciously high. Although it formally fits old, metal-rich populations with steep mass functions, Bell et al. (2003) quote $M/L_B = 10$ as an upper limit found for their large 2MASS-sample. According to their relation of $(B-R)$ versus M/L_B , NGC 4636 would have an M/L_B of approximately 6. Further uncertainties are the distance (Dirsch et al. 2005) and the tangential anisotropy (Kronawitter et al. 2000) of NGC 4636. Obviously, there is some freedom in adopting the mass-to-light-ratio of the stellar population. First, we assume $M/L_B = 12.2$, according to Kronawitter et al., but we shall also consider other values. To transform this mass-to-light ratio into an M/L_R value, one has to apply the factor of $10^{-0.4((B-R)_{4636} - (B-R)_\odot)}$. With $(B-R)_{4636} = 1.6$ and $(B-R)_\odot = 0.97$, a factor of 0.56 results, hence $M/L_R = 6.8$. Further, we make the assumption that M/L_R of the stellar light is constant for the entire galaxy. This is justified since the color gradient of NGC 4636 is relatively shallow ($\Delta(C-T) \simeq -0.1$ in the range $0.5-4'$), and the stellar populations seem to be well-mixed (Dirsch et al. 2005).

For our modeling (cf. Sect. 8.6), we assume that the stellar mass is contained within 70 kpc, yielding $M_{\text{stars}} = 4.2 \times 10^{11}$ and $2.6 \times 10^{11} M_\odot$ for $M/L_R = 6.8$ and 4.3, respectively. The lower value shall illustrate the dependence on M/L . We adopt $M/L_V = 5.5$ from Loewenstein & Mushotzky (2003), which results in $M/L_R = 4.3$.

Fig. 12. Projected radial number density of blue GCs. The data points are from Dirsch et al. (2005), the solid line is the a double power-law (cf. Eq. (8)) fit to the data, and the dashed line is the re-projected 3D number-density. It deviates only marginally from the 2D-fit. For comparison, we also show the projected light profile according to Dirsch et al. (2005).

8.4. Blue GCs as tracer population

Since the projected number density $N(R)$ of the blue globular clusters follows a double power-law, the de-projection is somewhat tricky. We proceeded as follows: following Zhao (1997), we adopt the double power-law

$$N(R) = n_0 \left(\frac{R}{B} \right)^{-\gamma_1} \left[1 + \left(\frac{R}{B} \right)^{1/\alpha_1} \right]^{-(\beta_1 - \gamma_1)\alpha_1}. \quad (8)$$

Capitals mean values in projection. γ_1, β_1 , and α_1 are the slope of the inner power-law, the slope of the outer power-law, and the width of the transition region, respectively. B is a scale radius. This function was fitted to the number-counts, resulting in $n_0 = 8.02 \text{ GCs} \times \text{arcmin}^{-2}$, $B = 8.86'$, $\gamma_1 = 0.33$, $\beta_1 = 7.19$, and $\alpha_1 = 0.54$. This function was then deprojected using Eq. (7), and, in turn, fitted with the same function, resulting in $n_0 = 0.38 \text{ GCs} \times \text{arcmin}^{-3}$, $b = 8.86'$, $\gamma_1 = 1.0$, $\beta_1 = 7.71$, and $\alpha_1 = 0.4$. As a check, this 3D-profile was re-projected, using the Abel projection operator

$$I(R) = 2 \int_R^{r_t} \frac{\varepsilon(r) r dr}{\sqrt{r^2 - R^2}}, \quad (9)$$

and found to be in good agreement with our 2D data (see Fig. 12).

For simplicity, the anisotropy parameter β is assumed to be constant with radius. With our limited sample, we cannot put any constraints on possible radial variations of β . As a tracer population, we choose the error-selected blue clusters. The red clusters show a more complex behavior. They seem to rotate, their projected number density is best described by three power-laws, and the projected velocity dispersion also shows more complex features. Therefore, we postpone any inclusion of the red clusters in the dynamical analysis until more data becomes available.

However, the blue clusters also pose problems. As can be seen in Figs. 9 and 11, the velocity dispersion value of the outermost bin is strongly affected by two outliers. Including those objects, one obtains $227 \pm 46 \text{ km s}^{-1}$ instead of $121 \pm 27 \text{ km s}^{-1}$. The high value would mean an almost constant dispersion out to 7 arcmin. As seen later on, this would be inconsistent with a sharp drop of the cluster system at this radius. This issue can only be resolved with future data. For now, we calculate our models for both values. This argument cannot be transferred easily to the red clusters. If they rotate, a constant velocity dispersion is plausible since we average azimuthally.

Fig. 13. Mass models for a stellar M/L -ratio of 6.8. The *left* and *right* panels are distinguished by the value of the last bin. The *topmost* panels show the measured velocity dispersions (cf. Fig. 11 and Table 4) together with the modeled line-of-sight velocity dispersions. The *second* panels show the circular velocity curves of the dark matter components. Below that, the circular velocity curves for the sum of luminous and dark matter are shown. The circular velocity of the stars alone is shown as dotted line. Circles show the values derived by Kronawitter et al. (2000). The mass-to-light ratio as a function of radius is shown in the *bottom* panels. Different line types indicate results for different anisotropy parameters, as labeled in the second panel on the left.

8.5. Dark matter

For the dark component, we adopt a density profile of the form:

$$\varrho_{\text{dark}} = \varrho_{\text{dark},0} \left(\frac{r}{r_{\text{dark}}} \right)^{-1} \left(1 + \frac{r}{r_{\text{dark}}} \right)^{-2}, \quad (10)$$

i.e., an NFW profile (Navarro et al. 1997; Bullock et al. 2001). For this density profile, the cumulative mass $M(r)$ reads

$$M_{\text{dark}} = 4\pi \cdot \varrho_{\text{dark},0} \cdot r_{\text{dark}}^3 \cdot \left(\log \left(1 + \frac{r}{r_{\text{dark}}} \right) - \frac{\frac{r}{r_{\text{dark}}}}{1 + \frac{r}{r_{\text{dark}}}} \right). \quad (11)$$

The task is now to find values for the characteristic density $\varrho_{\text{dark},0}$ and the characteristic radius r_{dark} resulting in a dark component which, when added to the luminous matter, can reproduce the observed projected velocity dispersion in the radial range of the globular clusters.

8.6. Results

Having chosen a value for the stellar M/L and β , we calculate the product of radial velocity dispersion squared and the 3-dimensional number density according to Eq. (4). This we project according to Eq. (5). For each pair of M/L and β , we vary the dark matter parameters (r_{dark} , $\varrho_{\text{dark},0}$) until the projected model dispersion shows minimal residuals with regard to the

observed dispersion. For simplicity, the four data points were given equal weights and the residuals were calculated using

$$\text{rms} = \sqrt{\frac{\sum (\sigma_{\text{model}} - \sigma_{\text{los}})^2}{n}}. \quad (12)$$

We defined a set of radii ($r_{\text{dark}} \in \{5, 10, 40, 80, 120, 240\}$ kpc) for which we then adjusted the density. Table 5 lists the model parameters together with derived quantities such as the virial mass and radius, the M/L_R -values, and the dark matter fractions within 30 kpc and 7.5 kpc (the effective radius). We determined the virial radius according to the Bullock et al. definition (i.e., at R_{vir} , the mean density of the halo is 337 times the mean mass density of the universe, $\rho_0 \cdot \Omega_m$). Note that the virial quantities were calculated for the dark component alone, with the aim of comparing their properties to those of simulated N -body halos (cf. Sect. 9.1). Thus, having neglected the stellar component, the quoted virial masses are lower limits.

Our models are displayed in Figs. 13 and 14, which show our analysis for the two different stellar M/L_R -values of 6.8 and 4.3, respectively. Table 5 lists the halo parameters. The left and right panels refer to the difference in the last data bin, as seen in the topmost panels, which show the comparison between our models and the data. The observed velocity dispersion together with their statistical uncertainties are indicated. We emphasize the importance of the uncertain outermost bin, which is clearly dominated by systematics as mentioned above. The various anisotropic models are distinguished by different line styles

Fig. 14. Same as Fig. 13, but for a lower stellar M/L -ratio of 4.3. See Table 5 for the model parameters.

Table 5. Parameters of the dark matter halos. The first column labels the models. The mass-to-light ratio M/L_R and the dark matter fraction are calculated for two radii ($7.5 \text{ kpc} \approx R_{\text{eff}}$ and 30 kpc is the radius within which the GCs used in the analysis are found). From the NFW parameters of our model halos, we calculate the virial radius, the virial mass, and the concentration parameter ($c_{\text{vir}} = R_{\text{vir}}/r_{\text{dark}}$) using the definitions of Bullock et al. (2001). Then we give the total mass within 30 kpc , the mass-to-light ratios (R -band), and the dark matter fraction within 30 kpc and 7.5 kpc (effective radius). Note that the virial quantities were calculated for the dark halos without adding the stellar component. Thus, the virial masses presented below are lower limits.

#	β	r_{dark} [kpc]	$\rho_{\text{dark},0}$ [$M_{\odot} \text{ pc}^{-3}$]	rms [km s^{-1}]	R_{vir} [kpc]	M_{vir} [$10^{12} M_{\odot}$]	c_{vir}	$M_{<30 \text{ kpc}}$ [$10^{11} M_{\odot}$]	M/L_R ($r = 30 \text{ kpc}$)	M/L_R ($r = 7.5 \text{ kpc}$)	$M_{\text{dark}}/M_{\text{total}}$ ($r = 30 \text{ kpc}$)	$M_{\text{dark}}/M_{\text{total}}$ ($r = 7.5 \text{ kpc}$)
$M/L_R = 6.8, \sigma_{\text{los}}(27 \text{ kpc}) = 121 \text{ km s}^{-1}$ (cf. Fig. 13, left panels)												
1	-2.0	5	0.12	23	207	0.52	41.4	5.5	10.9	0.37	9.6	0.29
2	-0.5	10	0.033	20	255	0.96	25.5	5.5	12.0	0.43	9.4	0.27
3	0	40	0.003	21	395	3.6	9.9	6.6	13.1	0.48	8.4	0.19
4	0.5	120	0.00075	26	655	16.6	5.5	7.2	14.3	0.52	8.2	0.17
5	1.0	240	0.00050	46	1100	77.9	4.57	9.2	18.3	0.63	8.7	0.22
$M/L_R = 4.3, \sigma_{\text{los}}(27 \text{ kpc}) = 121 \text{ km s}^{-1}$ (cf. Fig. 14, left panels)												
6	-2.0	5	0.195	22	248	0.90	49.6	5.5	10.9	0.61	8.9	0.52
7	-0.5	5	0.230	20	264	1.01	52.8	6.1	12.1	0.64	9.7	0.56
8	0	20	0.0135	20	358	2.7	17.9	5.3	10.6	0.59	5.9	0.27
9	0.5	120	0.00100	25	743	24.1	6.2	7.2	14.3	0.70	6.2	0.30
10	1.0	120	0.00145	45	870	39.0	7.3	9.4	18.7	0.77	7.0	0.37
$M/L_R = 6.8, \sigma_{\text{los}}(27 \text{ kpc}) = 227 \text{ km s}^{-1}$ (cf. Fig. 13, right panels)												
11	-2.0	120	0.0012	18	803	30.5	6.7	9.4	18.7	0.64	9.0	0.25
12	-0.5	80	0.0019	25	650	16.0	8.1	9.0	26.7	0.75	10.5	0.35
13	0.0	120	0.0011	32	773	27.2	6.4	9.0	17.7	0.62	8.8	0.23
14	0.5	120	0.0012	47	803	30.5	6.7	9.5	18.7	0.64	9.0	0.25
$M/L_R = 4.3, \sigma_{\text{los}}(27 \text{ kpc}) = 227 \text{ km s}^{-1}$ (cf. Fig. 14, right panels)												
15	-2.0	80	0.0023	16	703	20.4	8.8	9.0	18.0	0.76	7.1	0.39
16	-0.5	120	0.0011	24	774	27.3	6.5	7.7	15.2	0.72	6.3	0.32
17	0.0	120	0.00135	27	845	35.4	7.0	9.0	17.7	0.76	6.8	0.37
18	0.5	120	0.0014	42	858	37.0	7.15	9.2	18.2	0.76	6.9	0.38

that can be identified in the second panel, which shows the associated dark matter circular velocities. The degeneracy of potential and anisotropy is nicely visible. Only the models without dark matter, which are shown separately in Fig. 15, seem to be excluded.

The third panels show the total circular velocities, i.e., the sum of dark and luminous matter. The stellar component is indicated with a dotted line. The circular velocity values derived by Kronawitter et al. are shown as circles. Since our stellar mass-to-light ratio of 6.8 was adopted from the Kronawitter et al. analysis, it is not surprising that they do not fit well in the case of $M/L = 4.3$.

The bottom panels show the radial dependence of the corresponding M/L_R -values (cf. Table 5 for a listing of mass-to-light ratios at $R = 30$ and 7.5 kpc).

Of course, since the stellar M/L -value enters as a free parameter, the dark matter fraction would rise with declining M/L . However, $M/L_R = 4.3$ is already low for an old, metal-rich stellar population. Further constraints on the M/L ratio have to come from a more precise analysis of the dynamics of the stellar body.

In all four model families, the $\beta = 1$ (i.e., totally radial) models perform worst. Besides being a poor fit to the data, these models require very massive ($M_{\text{vir}} > 10^{13} M_\odot$) and extended dark matter halos.

The observed GC velocity dispersion (calculated omitting the two extreme velocities), as shown in the left panels of Figs. 13 and 14, can be reproduced for a range of anisotropy parameters ($-2 < \beta < 0.5$). The tangential models result in less massive and more concentrated dark halos. The isotropic model has a virial radius of about 360–400 kpc (depending on the stellar M/L value), which is compatible to the extent of the X-ray emission.

Although the virial masses of the dark halos differ by more than one order of magnitude, the total mass within the radial range probed by the GC dynamics changes by only a factor of 1.5. Hence, we can put constraints on the amount of dark matter in NGC 4636 within 30 kpc ($\approx 4 R_{\text{eff}}$), while the shape of the halo remains largely unknown.

For completeness, we also included the values of $\sigma_{\text{los}}(R)$ obtained when including extreme velocities of two GCs in the last radial bin in our analysis. The resulting almost constant line-of-sight velocity dispersion of the GCs, as shown in the right panels of Figs. 13 and 14, can only be reproduced with a very extended dark matter component. The best agreement in the sense of lowest residuals is found for the $\beta = -2$ tangential models. The radial $\beta = 0.5$ models provide rather poor fits, and the completely radial $\beta = 1$ models (not shown), result in even poorer fits.

9. Discussion

9.1. Comparison to cosmological simulations

How do our model dark matter halos compare to cosmological N -body simulations? Is such a comparison meaningful? In particular, the less massive halos are expected to have experienced contraction during the galaxy formation process. On the theoretical side, the universality of dark matter halos is still under discussion (see Reed et al. 2004 and references therein), so that a possible disagreement may not provide a solid basis for deeper conclusions. We therefore refrain from lengthy considerations and only point out basic tendencies.

For comparison with simulations, we choose the study of Bullock et al. (2001). They analyzed a sample of ~ 5000 simulated halos in the range 10^{11} – $10^{14} M_\odot$. They found (like

Fig. 15. Projected velocity dispersions for models *without* dark matter. *Upper panel:* $M/L_R = 6.8$; *lower panel:* the same for a stellar mass-to-light ratio of $M/L_R = 4.3$. The line styles are the same as in Figs. 13 and 14, i.e., the solid lines correspond to $\beta = 0$, and the long and short dashed lines to the tangential models $\beta = -\frac{1}{2}$, -2 , respectively. The radial models $\beta = \frac{1}{2}$, 1 are shown as dot-dashed and dot-dot-dashed lines. Only the models with a high stellar mass-to-light ratio in conjunction with tangential anisotropies are marginally consistent with the measured line-of-sight velocity dispersions.

others) that the concentration parameter c_{vir} decreases with growing mass, but the scatter in the halo profiles for a given mass is still quite large. A comparison with Fig. 4 of Bullock et al. shows that for our model family shown in the left column of Fig. 13 (i.e., $M/L_R = 6.8$, omitting the two extreme blue clusters), the $\beta = 0$ halo (model 3) best fits the simulations. The halos corresponding to the models with tangential bias have higher concentration parameters than halos of the same mass shown by Bullock et al., but still may be consistent. The models with radial anisotropies have small concentration parameters, but are as well not excluded. This is true even for the completely radial models (which give the worst fits to the observations). The question therefore is whether, given the large range of permitted halo shapes indicated by the simulations, one can meaningfully compare theoretical simulations with observations of our kind at all, not to mention the complications if dissipative effects of galaxy formation are taken into account. All we can say is that our model halos do not contradict the simulations of Bullock et al.

9.2. Mass profile and comparison with X-ray mass profiles

NGC 4636 has recently been a target for various X-ray studies (e.g., O’Sullivan et al. 2005; Ohto et al. 2003; Xu et al. 2002; Jones et al. 2002), emphasizing the highly disturbed X-ray pattern. However, mass profiles derived from X-rays have, until now, only been published by Matsushita et al. (1998) and Loewenstein & Mushotzky (2003). Figure 16 shows the various mass profiles. The two solid lines are our models, with the lowest and the highest mass within 30 kpc (models 1 and 14). The dotted line is the model with the highest dark matter content within one effective radius (model 7). The long-dashed line is the mass profile from Loewenstein & Mushotzky (2003). The total mass enclosed within 30 kpc is for the latter profile, $1.25 \times 10^{12} M_\odot$, which is distinctly higher than our highest value. Furthermore, the mass profile is steeper than most of our models, rising as $R^{1.2}$. However, a very concentrated dark halo, even surpassing this X-ray profile at small radii, is not excluded. One can speculate

Fig. 16. Various mass profiles. This graph shows various mass profiles of NGC 4636. The solid lines are the models with the lowest and highest mass within 30 kpc, respectively (models 1 and 14). The dotted line is the model with the highest dark matter content within 30 kpc (model 7). The dashed dotted line approximates one mass profile from Matsushita et al. (1998), showing the flattening at about 10 kpc. The long-dashed line represents the mass profile from Loewenstein & Mushotzky (2003). See text for more details.

that the difference at larger radii might have to do with different hydrodynamical situations at small and large radii.

The dashed-dotted line is the mass profile from Matsushita et al. (1998) (based on ASCA data), read off from their log-log diagram (their Fig. 3, solid line, scaled down to our distance of 15 Mpc), which shows the flattening of the mass profile at 10 kpc radius most distinctly. However, their range of mass profiles consistent with the X-ray analyses is rather large, apparently including the possibility that there is no such flattening. In their work, NGC 4636 is extremely dark matter dominated, with the luminous mass already falling short by a factor of 2–3 at small radii. Matsushita et al. quote $M/L = 8$ for the stellar component, so we cannot comment further on that. The agreement with the GC analysis out to 10 kpc is reasonably good. Outside this radius, the discrepancy is caused by the flattening of the profile, for which we see no indication. A similar flattening of the mass profile has been observed with ASCA in the cases of NGC 1399 (Ikebe et al. 1996) and in Abell 1795 (Xu et al. 2002). However, it has not been seen in the ROSAT data for NGC 1399 (Jones et al. 1997). Jones et al. (2002) interpret the high X-ray luminosity of NGC 4636 as the transient phenomenon of an enhanced cooling rate. Hence, it is possible that the total gravitating mass of this galaxy cannot be accurately determined from the X-ray emission. An interesting point is the large radial extension of the X-ray emission found by ASCA. If the dark matter fraction in NGC 4636 is low, then this emission might indicate a dark halo not related to NGC 4636 itself. One could speculate about a dark substructure in the general Virgo potential, formerly hosting a galaxy group, which formed NGC 4636 as the result of the merging of several galaxies. The quite abrupt termination of the GC system between 7'–9' would speak in favor of this scenario. Stars or GCs, respectively, near their escape energy are expected to show a drop in their radial density profile. If NGC 4636 were embedded in a deep dark matter potential reaching smoothly out to large radii, then one would expect to find GCs at large radii that are still bound to NGC 4636, and accordingly, a sharp boundary would not fit into the picture. However, it is interesting to note that the blue clusters apparently do not trace the dark halo, as has been suggested for other galaxies, e.g., NGC 1399 (Forte et al. 2005). Deeper insight could come from a more

complete sampling of GCs or Planetary Nebulae at or beyond a radius of 9', which would be a difficult observational task.

9.3. Modified newtonian dynamics

The CDM paradigm is the most widely accepted view of structure and galaxy formation. Alternative concepts to explain the kinematics of galaxies without resorting to dark matter have been minority views until today. One of these alternative concepts is MOND (MODified Newtonian Dynamics), which is discussed with increasing frequency. (e.g., Milgrom 1983; Sanders & McGaugh 2002). As a phenomenological recipe, the Newtonian acceleration g_N has to be replaced by the MOND acceleration in the case of small accelerations g through the relation

$$g_N = \mu(g/a_0) \cdot g, \quad (13)$$

with

$$a_0 \approx 1.2 \times 10^{-8} \text{ m s}^{-2}$$

being a universal constant and $\mu(g/a_0)$ an unspecified function interpolating between the Newtonian and the MOND regimes. Bekenstein & Milgrom (1984) presented a Lagrangian formalism of MOND. In the case of a spherical mass distribution, this formalism reduces to the simple formula above.

MOND proved to have an impressive predictive power (e.g., Sanders & McGaugh 2002). Many arguments have been raised against MOND, including its apparent arbitrariness, but until now, no convincing case has been found which would disprove MOND. Meanwhile, MOND also has a theoretical foundation in the work of Bekenstein (2004). Perhaps the most serious objection is that MOND does not remove the need for dark matter on cluster scales (Sanders 2003; Pointecouteau & Silk 2005). However, ignoring the pros and cons for the moment, we examine MOND's performance in the case of NGC 4636.

MOND works successfully in the cases of spiral galaxies and dwarf galaxies. Giant ellipticals are more difficult test objects, due to the fact that MOND effects start to become visible at radii where the low surface brightness is an obstacle for reliable investigations of the galaxy's dynamical behavior. However, Gerhard et al. (2001), in their sample of 21 elliptical galaxies, found the onset of increasing M/L -values at accelerations, which are a factor of 10 higher than in spiral galaxies. This would remove the universal character of a_0 . Milgrom & Sanders (2003) counter-argued that there were discrepancies between Gerhard et al.'s analysis and that of Romanowsky et al. (2003), indicating that the last word has not been spoken yet. Therefore, it is interesting to look at the MOND rotation curve of NGC 4636 expected from the luminosity density profile and a certain M/L -ratio.

Figure 17 shows the ratio of the MOND acceleration to a_0 and its dependence on radial distance (for the "standard" interpolation function mentioned hereafter). An M/L_R -ratio of 6.8 has been adopted. The graph shows that giant elliptical galaxies like NGC 4636 are nowhere in the deep MOND regime. Thus, it is clear that the interpolation function plays a dominant role, and the dynamics at small radii do not tell anything about MOND without knowledge of the transition behavior at high accelerations (for which there is no theory). A formula that has been widely used in the case of spiral galaxies is $\mu(x) = \frac{x}{\sqrt{1+x^2}}$ (Begeman et al. 1991).

However, Famaey & Binney (2005) find that the above interpolation does not fit the Galactic rotation curve well and propose $\mu = x/(1+x)$ (but see Famaey & Binney for more detailed

Fig. 17. This graph shows the ratio of the MONDian acceleration to a_0 as a function of galactocentric radius. Equality is reached at about 30 kpc, which already is the limit of our investigation. This means that the deep MOND regime cannot be reached by dynamical tracers and that the scheme of interpolating between the MONDian and the Newtonian regime dominates the analysis. A stellar mass-to-light ratio of $M/L_R = 6.8$ was assumed.

remarks on the shortcomings). This formula gives a smoother transition to the MOND regime, i.e., MOND effects appear earlier. These two formulas have no physical motivation other than giving satisfactory results.

Bekenstein (2004), in his relativistic TeVeS theory of gravitation, which includes the MOND phenomenology in the limit of small accelerations, develops the interpolation $\mu(x) = \frac{\sqrt{1+4x}-1}{\sqrt{1+4x}+1}$ for spherical symmetry. This interpolation is only valid for small and intermediate accelerations and may not be valid for the full range of acceleration with which we are dealing.

The results are shown in Fig. 18. We again adopted $M/L_R = 6.8$ (an M/L_R of 4.3 would, in any case, not be compatible with MOND). The dashed lines are the circular velocities derived from GCs with their anisotropies indicated. The dotted line is the Newtonian circular velocity due to the luminous component alone. The solid lines represent the MOND circular velocities with the uppermost one being the interpolation of Bekenstein, the middle one Famaey & Binney's, and the lower one the "standard" interpolation. Apparently, MOND reproduces the circular velocities derived from GC kinematics quite well within the uncertainties. The minimum conclusion is that NGC 4636 does not provide a counterargument for MOND. The shape of Bekenstein's interpolation at small radii is probably irrelevant, but at large radii the deviation from our mass models is also quite large and becomes larger with declining M/L . The interpolation of Famaey & Binney works seemingly better than the "standard" formula, however, the existent data are not sufficient to perform a critical test. A case against MOND could perhaps emerge (it only can be falsified, not verified), if the suspected drop of the velocity dispersion were to be confirmed in combination with a clear tangential bias. The necessary data set must then allow also the measurement of higher moments of the velocity dispersion. NGC 4636 has already a rich cluster system, is more or less spherical, and has a relatively isolated location. Thus, one may conclude that critical tests are difficult to perform with elliptical galaxies.

However, it is worth mentioning that, so far, one of the most interesting arguments comes from X-rays. Buote et al. (2002)

Fig. 18. MOND rotation curves for different interpolation schemes are shown for a stellar M/L_R ratio of 6.8 (solid lines). The upper solid line is derived from Bekenstein's interpolation, the middle one from Famaey & Binney's, and the lower one from the "standard" interpolation (see text for explanation). The dashed lines indicate the derived circular velocities from GCs for the given anisotropy parameters (models 3, 4, and 5). The dotted line is the stellar component alone with an adopted $M/L_R = 6.8$. The Famaey & Binney interpolation apparently works best.

note that the ellipticities of the X-ray isophotes around NGC 720 at larger radii are larger than those expected from the equipotential surfaces calculated from the visible mass distributions. This holds for both the Newtonian and the MOND case.

10. Conclusions

This is the first dynamical study of the globular cluster system of the giant elliptical galaxy NGC 4636. Several hundred medium resolution spectra were acquired at the VLT with FORS 2/MXU. We obtained velocities for 174 globular clusters in the radial range $0.90 < R < 15.5$, or $0.5-9 R_e$, in units of effective radius. Assuming a distance of 15 Mpc, this corresponds to projected galactocentric distances in the range of 4 to 70 kpc. Due to the sharp decrease in the GC radial number density at $7'-9'$, about 90 percent of our clusters are found in the range $1' < R < 7.5'$, i.e., within 4.5 effective radii. This implies that the dynamics beyond this radius cannot be determined with the current data set. Within this radius, however, we find a roughly constant velocity dispersion for the blue clusters. The red clusters are found to have a distinctly different behavior: at a radius of about $3'$, the velocity dispersion drops by $\sim 50 \text{ km s}^{-1}$ to about 170 km s^{-1} , which then remains constant out to a radius of $7'$. The cause might be the steepening of the number density profile at $\sim 3'$ observed for the red clusters. Following this line of thought, one would expect a dramatic drop in the velocity dispersion for both red and blue clusters at $7'-9'$, corresponding to the observed change in the power-law exponent of the GC number density. The observational difficulty will be to pick up sufficient clusters in this region of low surface density. To derive a mass profile, we perform a spherical Jeans analysis. For a given stellar mass-to-light ratio, a model dark matter halo, and an orbital anisotropy, we calculate the projected velocity dispersion and choose those halos that minimize the residuals to the observational data. The uncertain outermost data bin is an important obstacle, which permits a large variety of halos to fit. Generally, slightly tangential models fit better than radial ones. Adopting the high stellar M/L value of Kronawitter et al. (2000) ($M/L_R = 6.8$), we find an M/L_R -value of 12 within 30 kpc for $\beta = -0.5$, corresponding to a dark matter fraction of 27%. That being said, values

as high as 26 cannot be ruled out with certainty, depending on the treatment of the last bin. When a lower stellar M/L value is used (Loewenstein et al. 2003) ($M/L_R = 4.3$), the amount of dark matter that is needed to explain the observed circular velocities increases correspondingly. Massive dark matter halos (up to 76% dark matter) can be required, and neither of the models can be ruled out. An important source of uncertainty is the sparse data at the outer radius. However, for most of the reasonable models, we found either less dark matter than X-ray studies with ROSAT at small radii or the halos are so concentrated that the total mass is distinctly smaller. One should consider that the claim for the very high dark matter fraction is based upon X-ray luminosities that arise in a region suspected to be out of hydrostatic equilibrium, so one must proceed with caution. The flattening of the ASCA mass profile cannot be seen. It seems that the dark matter problem in NGC 4636 also depends, to a large extent, on the uncertain M/L value of the luminous matter. A dynamical re-investigation of the inner stellar region would therefore be worthwhile. Furthermore, it would be of great interest to obtain more spectra for globular clusters in the radial range beyond $7'$ to see whether the suspected decline in the velocity dispersion can be confirmed. To answer the question whether the NGC 4636 globular cluster systems rotates, it is desirable to obtain a more uniform angular coverage. We also investigated whether the dynamics are consistent with MOND and answer that positively. The difficulty is that the deep MOND regime is beyond our radial coverage. Because MOND does not predict the behavior of the circular velocity in the transition region, one has to apply physically unmotivated interpolation formulae. The interpolation given by Famaey & Binney (2005) seems to work best.

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Online Material

Appendix A: Velocities

The appendix lists the heliocentric velocities of globular clusters and foreground stars. The object identification follows the scheme #field.#mask#slit. The coordinates are for equinox 2000. The colors and magnitudes are from Dirsch et al. (2005).

Table A.1. Globular cluster data.

ID	RA	Dec	$C - R$	m_R	v (km s ⁻¹)
1.1 7	12 42 52.05	2 36 18.8	1.83 ± 0.02	21.22 ± 0.008	1032 ± 22
1.1 8	12 42 49.92	2 36 23.4	1.80 ± 0.02	21.20 ± 0.011	682 ± 42
1.1 9	12 42 45.17	2 36 27.6	1.34 ± 0.02	20.91 ± 0.018	663 ± 30
1.1 16	12 42 53.54	2 36 55.2	1.76 ± 0.03	21.29 ± 0.011	968 ± 30
1.1 27	12 42 45.50	2 37 36.7	1.86 ± 0.02	21.31 ± 0.009	682 ± 22
1.1 28	12 42 54.08	2 37 41.9	1.19 ± 0.01	21.03 ± 0.007	968 ± 45
1.1 32	12 42 44.81	2 37 58.1	1.56 ± 0.01	19.93 ± 0.009	852 ± 23
1.1 33	12 42 49.79	2 38 00.4	1.44 ± 0.03	21.41 ± 0.017	880 ± 32
1.1 34	12 42 56.55	2 38 04.9	1.12 ± 0.01	20.57 ± 0.008	895 ± 45
1.1 36	12 42 44.36	2 38 13.0	1.45 ± 0.01	20.16 ± 0.004	666 ± 24
1.1 39	12 42 53.93	2 38 25.9	1.33 ± 0.02	21.50 ± 0.010	991 ± 36
1.1 40	12 42 43.41	2 38 29.7	1.38 ± 0.02	21.06 ± 0.008	586 ± 26
1.1 44	12 42 53.28	2 38 44.0	1.18 ± 0.03	19.64 ± 0.022	1210 ± 25
1.1 46	12 42 48.19	2 39 00.7	1.46 ± 0.02	20.23 ± 0.012	890 ± 18
1.1 47	12 42 44.72	2 39 05.1	1.85 ± 0.01	20.30 ± 0.007	1092 ± 21
1.1 52	12 42 49.91	2 39 22.1	1.59 ± 0.01	20.40 ± 0.004	1217 ± 20
1.1 53	12 42 44.17	2 39 27.1	1.33 ± 0.03	19.80 ± 0.020	1210 ± 18
1.1 56	12 42 42.20	2 39 36.7	1.64 ± 0.03	19.74 ± 0.024	1112 ± 17
1.1 62	12 42 47.53	2 40 00.4	1.45 ± 0.02	20.87 ± 0.010	764 ± 17
1.1 63	12 42 52.33	2 40 04.3	1.62 ± 0.02	19.11 ± 0.016	725 ± 17
1.1 71	12 42 42.58	2 40 32.0	1.55 ± 0.01	20.06 ± 0.006	902 ± 14
1.1 87	12 42 44.81	2 41 24.1	1.55 ± 0.01	20.32 ± 0.004	502 ± 17
1.1 91	12 42 53.62	2 41 38.2	1.62 ± 0.01	20.22 ± 0.006	1051 ± 20
1.1 93	12 42 43.16	2 41 46.6	1.45 ± 0.02	20.52 ± 0.010	991 ± 19
1.1 102	12 42 42.78	2 42 17.5	1.83 ± 0.02	20.39 ± 0.006	1252 ± 19
1.1 103	12 42 49.89	2 42 20.3	1.18 ± 0.02	20.76 ± 0.009	968 ± 31
1.1 106	12 42 46.82	2 42 32.4	1.06 ± 0.02	20.90 ± 0.009	530 ± 43
1.2 1	12 42 43.99	2 35 52.0	1.20 ± 0.02	21.05 ± 0.019	1230 ± 64
1.2 2	12 42 42.47	2 35 55.8	1.16 ± 0.02	22.13 ± 0.011	1040 ± 60
1.2 6	12 42 45.91	2 36 14.1	1.46 ± 0.02	20.66 ± 0.014	860 ± 17
1.2 9	12 42 42.55	2 36 23.7	1.55 ± 0.02	21.81 ± 0.007	1198 ± 52
1.2 11	12 42 44.49	2 36 31.7	1.19 ± 0.02	22.24 ± 0.011	888 ± 86
1.2 15	12 42 41.23	2 36 51.1	1.70 ± 0.03	21.61 ± 0.030	392 ± 38
1.2 18	12 42 52.63	2 37 05.3	1.78 ± 0.04	22.27 ± 0.019	787 ± 29
1.2 20	12 42 42.09	2 37 14.4	1.67 ± 0.03	21.77 ± 0.016	904 ± 33
1.2 23	12 42 47.62	2 37 22.6	1.50 ± 0.01	20.15 ± 0.006	1112 ± 15
1.2 25	12 42 51.66	2 37 30.7	1.81 ± 0.02	20.83 ± 0.008	746 ± 31
1.2 27	12 42 42.78	2 37 36.5	1.16 ± 0.03	20.73 ± 0.028	730 ± 62
1.2 33	12 42 47.94	2 38 02.3	1.91 ± 0.05	22.63 ± 0.024	909 ± 32
1.2 35	12 42 50.71	2 38 10.3	1.37 ± 0.02	21.67 ± 0.007	1121 ± 42
1.2 36	12 42 49.50	2 38 14.4	1.96 ± 0.02	21.69 ± 0.008	840 ± 43
1.2 38	12 42 43.37	2 38 22.2	1.67 ± 0.02	21.67 ± 0.010	870 ± 30
1.2 40	12 42 44.71	2 38 30.3	1.58 ± 0.02	21.49 ± 0.010	816 ± 26
1.2 41	12 42 51.23	2 38 33.8	1.71 ± 0.02	21.51 ± 0.010	626 ± 22
1.2 42	12 42 42.28	2 38 36.7	1.74 ± 0.03	22.12 ± 0.011	1040 ± 43
1.2 49	12 42 52.19	2 39 26.0	1.54 ± 0.08	22.34 ± 0.064	901 ± 28
1.2 55	12 42 51.61	2 39 46.5	1.21 ± 0.02	20.34 ± 0.011	718 ± 21
1.2 57	12 42 45.51	2 39 53.2	1.64 ± 0.02	19.50 ± 0.020	682 ± 15
1.2 58	12 42 45.67	2 39 57.0	1.36 ± 0.01	19.88 ± 0.010	670 ± 14
1.2 61	12 42 40.47	2 40 09.1	1.30 ± 0.02	21.68 ± 0.013	832 ± 26
1.2 62	12 42 46.55	2 40 12.8	1.19 ± 0.02	20.78 ± 0.008	848 ± 49
1.2 65	12 42 43.55	2 40 29.6	1.52 ± 0.03	21.45 ± 0.008	858 ± 31
1.2 67	12 42 44.83	2 40 42.4	1.61 ± 0.02	20.69 ± 0.008	720 ± 33
1.2 69	12 42 42.83	2 40 47.1	1.60 ± 0.03	21.87 ± 0.007	1159 ± 22
1.2 71	12 42 41.09	2 40 56.7	1.59 ± 0.04	21.92 ± 0.012	1010 ± 28
1.2 72	12 42 41.98	2 41 00.8	1.60 ± 0.02	20.01 ± 0.010	607 ± 17
1.2 75	12 42 42.35	2 41 15.1	1.63 ± 0.03	19.22 ± 0.022	1027 ± 16
1.2 76	12 42 43.71	2 41 19.0	0.98 ± 0.01	20.80 ± 0.007	1187 ± 36
1.2 77	12 42 42.00	2 41 22.9	1.31 ± 0.02	20.82 ± 0.009	958 ± 23
1.2 78	12 42 42.40	2 41 26.3	1.70 ± 0.02	20.75 ± 0.005	933 ± 17

Table A.1. continued.

ID	RA	Dec	$C - R$	m_R	v (km s ⁻¹)
1.2 83	12 42 43.79	2 41 50.1	1.61 ± 0.05	21.13 ± 0.011	460 ± 30
1.2 85	12 42 43.64	2 41 59.8	1.11 ± 0.01	21.13 ± 0.007	1070 ± 27
1.2 86	12 42 47.40	2 42 05.1	1.60 ± 0.01	20.21 ± 0.009	1159 ± 14
1.2 88	12 42 50.28	2 42 11.4	1.34 ± 0.03	20.77 ± 0.006	971 ± 18
1.2 91	12 42 42.48	2 42 21.3	1.50 ± 0.01	20.22 ± 0.006	810 ± 14
1.2 93	12 42 45.67	2 42 28.0	1.39 ± 0.01	19.27 ± 0.007	1002 ± 17
1.2 95	12 42 41.65	2 42 34.3	1.08 ± 0.02	21.25 ± 0.008	943 ± 42
1.3 3	12 42 49.71	2 36 02.9	1.84 ± 0.02	20.70 ± 0.014	653 ± 29
1.3 19	12 42 53.42	2 37 01.2	1.62 ± 0.02	20.02 ± 0.012	1099 ± 15
1.3 23	12 42 53.42	2 37 01.2	1.62 ± 0.02	20.02 ± 0.012	901 ± 25
1.3 25	12 42 47.62	2 37 22.6	1.50 ± 0.01	20.15 ± 0.006	1060 ± 34
1.3 27	12 42 51.66	2 37 30.7	1.81 ± 0.02	20.83 ± 0.008	641 ± 21
1.3 31	12 42 55.12	2 37 43.8	1.65 ± 0.01	20.61 ± 0.006	875 ± 30
1.3 41	12 42 49.82	2 38 18.6	1.35 ± 0.03	21.06 ± 0.019	877 ± 60
1.3 45	12 42 53.10	2 38 33.8	1.87 ± 0.03	21.97 ± 0.021	946 ± 36
1.3 48	12 42 52.37	2 39 00.7	1.44 ± 0.01	20.58 ± 0.004	992 ± 25
1.3 52	12 42 46.04	2 39 15.9	1.84 ± 0.02	21.32 ± 0.007	750 ± 22
1.3 57	12 42 52.31	2 39 39.2	1.39 ± 0.03	20.28 ± 0.009	565 ± 16
1.3 58	12 42 55.29	2 39 48.3	1.21 ± 0.02	19.21 ± 0.017	1345 ± 15
1.3 62	12 42 55.45	2 40 05.4	1.43 ± 0.03	21.69 ± 0.013	1230 ± 30
1.3 64	12 42 56.07	2 40 11.8	1.14 ± 0.02	20.94 ± 0.012	592 ± 36
1.3 66	12 42 56.17	2 40 17.8	1.99 ± 0.05	20.19 ± 0.011	1134 ± 21
1.3 69	12 42 55.93	2 40 30.2	0.85 ± 0.01	21.79 ± 0.008	514 ± 42
1.3 72	12 42 59.20	2 40 45.4	1.79 ± 0.02	20.84 ± 0.005	808 ± 17
1.3 73	12 42 56.26	2 40 50.5	1.31 ± 0.03	20.81 ± 0.008	1021 ± 24
1.3 88	12 42 55.25	2 41 38.5	0.87 ± 0.02	21.08 ± 0.009	882 ± 36
1.3 95	12 42 55.01	2 42 04.5	1.76 ± 0.02	20.61 ± 0.006	1253 ± 22
1.3 96	12 42 54.80	2 42 08.4	1.61 ± 0.02	20.93 ± 0.007	934 ± 26
1.3 99	12 42 50.17	2 42 18.0	1.47 ± 0.02	20.63 ± 0.009	618 ± 20
1.3 104	12 42 53.27	2 42 40.5	0.97 ± 0.06	20.45 ± 0.047	1107 ± 33
2.1 77	12 42 17.62	2 39 23.6	1.71 ± 0.02	21.65 ± 0.009	946 ± 38
2.1 83	12 42 23.15	2 39 44.5	0.98 ± 0.02	21.65 ± 0.010	957 ± 36
2.1 100	12 42 17.51	2 40 52.6	1.86 ± 0.03	21.83 ± 0.013	1258 ± 46
2.2 38	12 42 17.45	2 36 35.6	1.11 ± 0.02	19.92 ± 0.015	850 ± 44
2.2 59	12 42 24.39	2 38 18.8	1.23 ± 0.01	20.85 ± 0.009	1040 ± 51
3.1 3	12 42 33.92	2 42 55.7	1.85 ± 0.02	21.21 ± 0.012	1165 ± 22
3.1 4	12 42 38.33	2 42 59.9	1.62 ± 0.02	21.43 ± 0.012	947 ± 45
3.1 8	12 42 32.14	2 43 16.9	1.36 ± 0.02	20.98 ± 0.007	1186 ± 26
3.1 9	12 42 34.76	2 43 20.8	1.60 ± 0.02	21.22 ± 0.005	950 ± 27
3.1 10	12 42 28.25	2 43 25.1	1.60 ± 0.01	19.88 ± 0.008	550 ± 30
3.1 12	12 42 30.52	2 43 30.0	1.14 ± 0.02	21.60 ± 0.009	802 ± 44
3.1 17	12 42 28.85	2 43 49.8	1.29 ± 0.02	21.36 ± 0.010	907 ± 39
3.1 19	12 42 38.60	2 43 58.4	1.77 ± 0.01	19.81 ± 0.008	692 ± 19
3.1 22	12 42 33.11	2 44 08.0	1.60 ± 0.02	21.59 ± 0.009	817 ± 35
3.1 24	12 42 31.72	2 44 14.3	1.56 ± 0.02	21.40 ± 0.008	522 ± 29
3.1 31	12 42 30.85	2 44 41.4	1.27 ± 0.01	20.69 ± 0.009	690 ± 22
3.1 38	12 42 34.96	2 45 05.9	1.18 ± 0.02	21.88 ± 0.012	541 ± 36
3.1 45	12 42 36.89	2 45 26.5	1.34 ± 0.01	19.86 ± 0.008	915 ± 26
3.1 47	12 42 34.59	2 45 33.7	1.63 ± 0.02	20.70 ± 0.008	857 ± 29
3.1 50	12 42 38.70	2 45 58.3	1.58 ± 0.03	21.70 ± 0.020	649 ± 40
3.1 52	12 42 37.27	2 46 04.1	1.65 ± 0.02	21.53 ± 0.011	1046 ± 42
3.1 57	12 42 31.61	2 46 22.1	1.28 ± 0.02	21.58 ± 0.010	972 ± 41
3.1 62	12 42 36.38	2 46 37.4	1.72 ± 0.01	19.94 ± 0.009	1027 ± 20
3.1 65	12 42 34.60	2 46 47.7	1.57 ± 0.01	20.51 ± 0.009	902 ± 21
3.1 69	12 42 34.82	2 46 59.5	1.20 ± 0.01	20.46 ± 0.006	1423 ± 25
3.1 80	12 42 32.39	2 47 43.2	1.57 ± 0.01	20.73 ± 0.010	778 ± 19
3.1 81	12 42 38.13	2 47 47.5	1.23 ± 0.02	21.12 ± 0.010	1014 ± 25
3.1 92	12 42 39.48	2 48 33.9	1.22 ± 0.01	20.72 ± 0.008	729 ± 20
3.1 112	12 42 37.98	2 49 46.8	1.17 ± 0.03	21.86 ± 0.019	691 ± 55

Table A.1. continued.

ID	RA	Dec	$C - R$	m_R	v (km s ⁻¹)
3.2 1	12 42 31.95	2 42 49.0	0.96 ± 0.01	21.59 ± 0.008	1281 ± 40
3.2 9	12 42 33.08	2 43 16.8	1.32 ± 0.02	21.69 ± 0.007	1175 ± 28
3.2 12	12 42 28.58	2 43 27.2	1.06 ± 0.02	21.33 ± 0.008	912 ± 43
3.2 20	12 42 26.23	2 43 57.8	1.23 ± 0.02	21.29 ± 0.006	860 ± 46
3.2 31	12 42 35.06	2 44 31.4	1.72 ± 0.02	21.83 ± 0.008	1092 ± 43
3.2 34	12 42 29.26	2 44 42.1	1.64 ± 0.02	21.17 ± 0.012	1002 ± 29
3.2 37	12 42 27.33	2 44 52.6	1.31 ± 0.02	20.69 ± 0.008	736 ± 22
3.2 44	12 42 30.89	2 45 15.5	1.32 ± 0.01	21.37 ± 0.006	998 ± 39
3.2 50	12 42 35.10	2 45 35.4	2.00 ± 0.03	22.05 ± 0.016	1050 ± 26
3.2 61	12 42 34.47	2 46 35.5	1.71 ± 0.02	20.70 ± 0.014	1273 ± 21
3.2 65	12 42 36.97	2 46 53.5	1.04 ± 0.01	20.95 ± 0.012	1441 ± 28
3.2 98	12 42 31.76	2 49 05.4	1.69 ± 0.10	21.88 ± 0.071	1009 ± 45
3.2 106	12 42 30.95	2 49 29.5	1.63 ± 0.01	20.82 ± 0.006	916 ± 25
4.1 16	12 42 32.21	2 50 50.1	1.81 ± 0.02	22.03 ± 0.008	869 ± 50
4.1 33	12 42 29.38	2 52 00.0	1.84 ± 0.03	21.93 ± 0.018	760 ± 64
5.1 1	12 42 54.62	2 43 20.3	...	...	1169 ± 35
5.1 9	12 43 07.45	2 43 45.5	1.11 ± 0.02	20.28 ± 0.016	791 ± 26
5.1 18	12 42 57.63	2 44 23.8	1.14 ± 0.01	20.96 ± 0.008	963 ± 23
5.1 22	12 42 55.55	2 44 39.2	1.26 ± 0.05	20.45 ± 0.054	1043 ± 48
5.1 33	12 42 59.56	2 45 13.0	1.87 ± 0.03	21.87 ± 0.014	998 ± 31
5.1 38	12 43 05.34	2 45 31.3	1.79 ± 0.02	21.86 ± 0.009	854 ± 29
5.1 43	12 43 05.46	2 45 48.7	1.30 ± 0.02	19.91 ± 0.012	928 ± 23
5.1 46	12 42 57.64	2 46 01.8	1.37 ± 0.02	21.50 ± 0.011	1102 ± 31
5.1 48	12 42 58.75	2 46 30.9	1.22 ± 0.03	19.41 ± 0.023	1085 ± 13
5.1 49	12 43 02.69	2 46 37.3	1.15 ± 0.01	20.73 ± 0.006	783 ± 23
5.1 52	12 43 08.34	2 46 49.9	1.40 ± 0.03	19.33 ± 0.029	695 ± 16
5.1 58	12 42 53.70	2 47 11.7	1.23 ± 0.01	20.72 ± 0.010	771 ± 22
5.1 60	12 43 04.55	2 47 17.4	1.14 ± 0.01	20.59 ± 0.008	661 ± 35
5.1 63	12 43 03.49	2 47 27.1	1.99 ± 0.02	20.99 ± 0.006	919 ± 17
5.1 69	12 42 56.19	2 47 50.1	1.54 ± 0.02	19.54 ± 0.015	1048 ± 15
5.1 83	12 43 03.00	2 48 54.0	1.66 ± 0.02	21.63 ± 0.013	658 ± 38
5.1 91	12 43 01.02	2 49 19.9	1.28 ± 0.01	21.39 ± 0.008	1014 ± 46
6.1 45	12 43 08.76	2 39 11.0	1.22 ± 0.03	19.85 ± 0.026	1048 ± 21
6.1 55	12 43 13.68	2 39 45.7	1.66 ± 0.01	20.59 ± 0.006	941 ± 25
6.1 57	12 43 16.86	2 39 51.8	1.34 ± 0.02	21.27 ± 0.012	762 ± 43
6.1 67	12 43 20.79	2 40 31.5	1.20 ± 0.01	21.21 ± 0.012	724 ± 43
6.1 88	12 43 08.88	2 41 55.0	1.40 ± 0.02	19.99 ± 0.012	618 ± 25
6.1 92	12 43 09.04	2 42 06.1	1.54 ± 0.02	20.02 ± 0.018	698 ± 23
6.2 16	12 43 05.96	2 36 50.6	1.18 ± 0.02	21.69 ± 0.009	868 ± 29
6.2 18	12 43 09.78	2 36 57.8	1.24 ± 0.02	21.78 ± 0.009	670 ± 37
6.2 23	12 43 08.10	2 37 14.3	...	...	1316 ± 30
6.2 30	12 43 12.02	2 37 38.4	1.49 ± 0.02	20.29 ± 0.016	924 ± 15
6.2 35	12 43 07.95	2 37 55.3	1.11 ± 0.02	21.11 ± 0.011	818 ± 33
6.2 57	12 43 17.10	2 39 24.9	1.26 ± 0.02	21.32 ± 0.013	1309 ± 62
6.2 59	12 43 09.28	2 39 33.2	1.62 ± 0.02	19.85 ± 0.015	990 ± 15
6.2 63	12 43 06.55	2 39 53.4	1.47 ± 0.02	19.76 ± 0.018	790 ± 17
6.2 65	12 43 11.42	2 40 01.3	1.18 ± 0.01	20.59 ± 0.008	940 ± 26
6.2 81	12 43 06.56	2 40 59.1	2.15 ± 0.03	22.24 ± 0.011	959 ± 37
6.2 86	12 43 14.28	2 41 20.4	1.41 ± 0.01	20.68 ± 0.007	986 ± 25
6.2 87	12 43 08.26	2 41 25.4	1.10 ± 0.01	20.64 ± 0.010	791 ± 19
6.2 95	12 43 14.68	2 41 53.6	2.08 ± 0.04	21.23 ± 0.035	614 ± 28
6.2 104	12 43 17.30	2 42 29.5	1.73 ± 0.03	21.04 ± 0.015	746 ± 21
6.2 108	12 43 06.79	2 42 43.9	1.15 ± 0.02	20.13 ± 0.013	885 ± 26
7.2 2	12 43 21.19	2 28 52.0	1.28 ± 0.02	21.80 ± 0.016	535 ± 88
7.2 23	12 43 32.17	2 30 01.0	1.15 ± 0.05	22.73 ± 0.014	1051 ± 68

Table A.2. Star data.

ID	RA	Dec	$C - R$	m_R	v (km s ⁻¹)
1.1 4	12 42 44.29	2 36 05.8	3.3101 ± 0.028	20.87 ± 0.006	-119 ± 50
1.1 22	12 42 52.90	2 37 19.5	1.2874 ± 0.018	21.33 ± 0.013	178 ± 77
1.1 58	12 42 52.67	2 39 44.2	0.9948 ± 0.012	20.55 ± 0.007	-131 ± 22
1.1 105	12 42 48.74	2 42 28.7	0.5039 ± 0.009	18.93 ± 0.007	270 ± 45
1.2 10	12 42 40.32	2 36 28.7	0.7757 ± 0.011	20.06 ± 0.009	199 ± 154
1.2 14	12 42 51.96	2 36 43.1	0.8962 ± 0.013	19.25 ± 0.011	166 ± 21
1.2 24	12 42 41.45	2 37 28.1	0.9828 ± 0.009	20.60 ± 0.003	56 ± 70
1.2 30	12 42 50.55	2 37 50.5	1.9262 ± 0.025	21.89 ± 0.011	229 ± 38
1.3 7	12 42 52.55	2 36 16.6	2.4467 ± 0.026	21.21 ± 0.013	126 ± 54
1.3 11	12 42 53.93	2 36 30.4	1.2940 ± 0.031	19.94 ± 0.012	89 ± 48
1.3 15	12 42 48.28	2 36 44.5	0.8557 ± 0.024	21.11 ± 0.013	-181 ± 52
1.3 26	12 42 50.86	2 37 26.5	2.3316 ± 0.035	21.69 ± 0.011	252 ± 27
1.3 29	12 42 58.24	2 37 36.0	2.7239 ± 0.020	20.58 ± 0.009	-84 ± 51
1.3 33	12 42 50.55	2 37 50.5	1.9262 ± 0.025	21.89 ± 0.011	272 ± 27
1.3 37	12 42 57.94	2 38 03.4	0.8162 ± 0.017	20.67 ± 0.015	-120 ± 32
1.3 39	12 42 44.93	2 38 12.9	3.0088 ± 0.017	19.99 ± 0.005	-58 ± 52
1.3 91	12 42 58.61	2 41 52.3	0.5521 ± 0.009	18.92 ± 0.005	93 ± 88
1.3 105	12 42 48.92	2 42 43.9	0.3045 ± 0.076	18.98 ± 0.076	58 ± 66
2.1 3	12 42 21.82	2 34 04.1	1.7892 ± 0.014	21.23 ± 0.005	215 ± 51
2.1 5	12 42 24.43	2 34 15.4	0.7505 ± 0.009	19.56 ± 0.005	136 ± 28
2.1 9	12 42 19.16	2 34 34.1	3.5786 ± 0.026	20.17 ± 0.006	-34 ± 66
2.1 13	12 42 19.35	2 34 48.5	3.0800 ± 0.055	22.14 ± 0.018	198 ± 129
2.1 16	12 42 23.69	2 35 01.1	3.5337 ± 0.046	21.68 ± 0.008	-137 ± 46
2.1 18	12 42 15.61	2 35 08.4	0.8874 ± 0.016	20.85 ± 0.010	-87 ± 26
2.1 19	12 42 11.82	2 35 12.4	0.5894 ± 0.015	21.63 ± 0.010	263 ± 81
2.1 36	12 42 20.93	2 36 26.9	2.9102 ± 0.016	20.55 ± 0.004	38 ± 52
2.1 40	12 42 20.16	2 36 38.8	0.9609 ± 0.011	20.70 ± 0.004	17 ± 37
2.1 51	12 42 18.12	2 37 40.2	1.0934 ± 0.007	19.82 ± 0.004	-29 ± 27
2.1 56	12 42 14.04	2 38 04.7	2.5343 ± 0.031	22.06 ± 0.009	97 ± 72
2.1 60	12 42 20.32	2 38 15.8	3.6619 ± 0.023	20.41 ± 0.006	43 ± 60
2.1 61	12 42 16.30	2 38 18.1	0.8557 ± 0.013	21.06 ± 0.010	-40 ± 52
2.1 62	12 42 22.54	2 38 22.8	3.1841 ± 0.021	20.85 ± 0.006	-146 ± 67
2.1 64	12 42 11.24	2 38 30.2	3.1556 ± 0.065	22.13 ± 0.012	4 ± 60
2.1 65	12 42 18.90	2 38 34.5	1.2666 ± 0.009	19.96 ± 0.005	-52 ± 27
2.1 67	12 42 24.58	2 38 42.3	2.1881 ± 0.037	22.09 ± 0.017	-132 ± 51
2.1 69	12 42 18.30	2 38 50.3	-1.2164 ± 0.123	18.57 ± 0.094	-88 ± 18
2.1 71	12 42 17.77	2 39 01.1	1.7575 ± 0.119	18.54 ± 0.119	-15 ± 36
2.1 82	12 42 22.07	2 39 39.4	0.7231 ± 0.009	20.68 ± 0.005	150 ± 39
2.1 85	12 42 13.56	2 39 53.6	1.5230 ± 0.015	21.69 ± 0.008	250 ± 61
2.1 87	12 42 19.92	2 40 01.2	1.4222 ± 0.021	21.73 ± 0.007	217 ± 140
2.2 5	12 42 27.20	2 34 17.1	3.6432 ± 0.024	20.16 ± 0.005	-74 ± 57
2.2 16	12 42 22.19	2 35 09.6	3.6641 ± 0.024	20.64 ± 0.007	-121 ± 187
2.2 26	12 42 28.48	2 35 50.0	2.3218 ± 0.027	21.05 ± 0.009	-170 ± 45
2.2 27	12 42 21.60	2 35 53.8	2.7568 ± 0.023	20.39 ± 0.005	-110 ± 55
2.2 35	12 42 30.11	2 36 23.6	1.3203 ± 0.012	19.88 ± 0.007	-138 ± 45
2.2 50	12 42 16.37	2 37 34.8	0.9280 ± 0.094	19.08 ± 0.094	-42 ± 40
2.2 53	12 42 19.87	2 37 48.9	4.2985 ± 0.028	19.80 ± 0.011	-48 ± 85
2.2 55	12 42 18.69	2 38 02.2	0.5357 ± 0.090	18.49 ± 0.090	-67 ± 26
2.2 66	12 42 29.58	2 38 46.8	3.0800 ± 0.045	21.15 ± 0.011	-188 ± 65
2.2 68	12 42 21.32	2 38 54.0	1.1438 ± 0.008	20.17 ± 0.004	237 ± 22
2.2 75	12 42 28.04	2 39 23.6	3.3649 ± 0.015	19.97 ± 0.009	-31 ± 47
2.2 76	12 42 29.86	2 39 27.1	1.4013 ± 0.020	21.90 ± 0.010	240 ± 39
2.2 78	12 42 29.35	2 39 35.7	0.3330 ± 0.109	18.64 ± 0.109	-97 ± 28
2.2 89	12 42 23.99	2 40 17.6	0.7527 ± 0.025	21.69 ± 0.017	-236 ± 38
2.2 95	12 42 31.08	2 40 36.4	2.5190 ± 0.018	20.36 ± 0.008	34 ± 42
2.2 96	12 42 29.83	2 40 40.3	3.2389 ± 0.021	20.61 ± 0.005	-17 ± 44
2.2 97	12 42 29.01	2 40 44.1	1.7772 ± 0.025	20.98 ± 0.013	9 ± 30
3.1 7	12 42 27.12	2 43 13.9	0.0021 ± 0.087	18.53 ± 0.087	178 ± 48
3.1 20	12 42 34.62	2 44 02.3	1.7038 ± 0.011	19.19 ± 0.008	1 ± 43
3.1 27	12 42 41.93	2 44 25.9	1.7991 ± 0.102	18.31 ± 0.102	-51 ± 38
3.1 42	12 42 31.26	2 45 18.7	1.9306 ± 0.015	20.10 ± 0.007	-4 ± 40
3.1 49	12 42 33.86	2 45 39.9	1.6654 ± 0.023	21.99 ± 0.008	-47 ± 54
3.1 60	12 42 29.22	2 46 31.7	2.5574 ± 0.011	19.47 ± 0.005	-97 ± 47

Table A.2. continued.

ID	RA	Dec	$C - R$	m_R	v (km s ⁻¹)
3.1 87	12 42 33.21	2 48 10.9	2.7688 ± 0.011	20.21 ± 0.003	-30 ± 51
3.1 88	12 42 28.92	2 48 16.8	1.8144 ± 0.060	18.74 ± 0.059	-17 ± 38
3.1 97	12 42 36.77	2 48 51.1	1.8429 ± 0.025	22.09 ± 0.011	-163 ± 32
3.1 107	12 42 32.75	2 49 29.6	0.8798 ± 0.043	18.87 ± 0.042	-134 ± 22
3.2 2	12 42 22.18	2 42 52.2	2.7425 ± 0.067	18.61 ± 0.066	20 ± 46
3.2 17	12 42 25.06	2 43 47.8	3.2915 ± 0.029	20.68 ± 0.014	-69 ± 58
3.2 21	12 42 36.98	2 44 02.4	3.3627 ± 0.037	21.42 ± 0.007	-2 ± 46
3.2 26	12 42 37.20	2 44 16.7	3.1874 ± 0.027	20.52 ± 0.009	19 ± 58
3.2 27	12 42 34.38	2 44 19.9	3.5479 ± 0.023	20.42 ± 0.007	47 ± 56
3.2 40	12 42 23.10	2 45 03.8	2.7250 ± 0.040	21.63 ± 0.009	-3 ± 72
3.2 46	12 42 28.90	2 45 21.4	2.9058 ± 0.024	20.90 ± 0.006	-14 ± 64
3.2 66	12 42 30.27	2 46 59.0	2.8872 ± 0.045	21.80 ± 0.006	63 ± 60
3.2 71	12 42 28.95	2 47 19.4	-0.1327 ± 0.313	19.92 ± 0.313	-5 ± 58
3.2 75	12 42 21.53	2 47 40.0	0.9904 ± 0.025	22.22 ± 0.015	-18 ± 44
3.2 82	12 42 33.21	2 48 10.9	2.7688 ± 0.011	20.21 ± 0.003	-42 ± 51
3.2 89	12 42 26.36	2 48 34.7	3.4076 ± 0.030	21.08 ± 0.011	0 ± 101
3.2 92	12 42 37.45	2 48 43.0	3.3189 ± 0.010	19.36 ± 0.003	-56 ± 41
3.2 109	12 42 27.43	2 49 38.4	1.1143 ± 0.015	20.39 ± 0.007	-25 ± 23
4.1 5	12 42 32.99	2 50 14.3	2.4346 ± 0.012	20.59 ± 0.005	-5 ± 46
4.1 11	12 42 35.60	2 50 31.9	0.6792 ± 0.018	21.43 ± 0.009	-5 ± 53
4.1 37	12 42 25.94	2 52 22.0	0.6354 ± 0.020	21.37 ± 0.010	-180 ± 47
4.1 38	12 42 31.44	2 52 24.5	0.5817 ± 0.013	20.71 ± 0.010	142 ± 62
4.1 42	12 42 29.92	2 52 41.2	0.4667 ± 0.111	18.85 ± 0.111	192 ± 23
4.1 46	12 42 29.31	2 53 11.5	0.9576 ± 0.015	20.88 ± 0.011	60 ± 59
4.1 49	12 42 25.09	2 53 23.4	2.9398 ± 0.019	20.37 ± 0.006	23 ± 48
4.1 52	12 42 34.49	2 53 34.0	0.7691 ± 0.014	20.66 ± 0.009	85 ± 34
4.1 56	12 42 23.64	2 53 49.1	3.5643 ± 0.080	21.74 ± 0.008	-102 ± 48
4.1 58	12 42 34.75	2 53 58.1	1.6753 ± 0.015	18.81 ± 0.008	-92 ± 75
4.1 60	12 42 28.19	2 54 05.5	3.6695 ± 0.028	20.67 ± 0.014	113 ± 51
4.1 65	12 42 25.97	2 54 24.2	3.1808 ± 0.029	21.10 ± 0.008	-37 ± 46
4.1 69	12 42 24.71	2 54 44.7	2.4083 ± 0.072	18.66 ± 0.072	83 ± 52
4.1 74	12 42 28.16	2 55 07.5	3.1512 ± 0.019	20.42 ± 0.009	-16 ± 53
4.1 77	12 42 29.12	2 55 25.5	3.4044 ± 0.017	19.49 ± 0.009	-61 ± 44
4.1 86	12 42 35.13	2 56 03.8	2.4456 ± 0.016	20.40 ± 0.009	-82 ± 56
4.1 88	12 42 28.50	2 56 16.6	1.5153 ± 0.016	20.81 ± 0.009	224 ± 32
4.1 90	12 42 27.43	2 56 22.4	3.8054 ± 0.035	21.16 ± 0.011	-103 ± 41
4.1 97	12 42 30.92	2 56 46.0	0.8951 ± 0.082	18.42 ± 0.082	20 ± 22
5.1 4	12 42 58.16	2 43 31.9	3.0143 ± 0.034	21.21 ± 0.006	133 ± 26
5.1 11	12 42 55.57	2 43 53.1	1.4671 ± 0.063	18.44 ± 0.063	19 ± 29
5.1 13	12 43 05.04	2 44 03.4	2.2659 ± 0.014	18.88 ± 0.011	-70 ± 44
5.1 14	12 42 57.95	2 44 09.5	2.9836 ± 0.049	21.71 ± 0.012	70 ± 34
5.1 42	12 43 02.91	2 45 45.0	3.0548 ± 0.043	21.35 ± 0.007	24 ± 51
5.1 51	12 43 07.15	2 46 45.7	3.7923 ± 0.017	20.07 ± 0.003	-22 ± 55
5.1 57	12 42 58.92	2 47 08.1	0.8710 ± 0.014	21.19 ± 0.006	35 ± 30
5.1 75	12 43 00.47	2 48 15.3	2.7250 ± 0.014	20.06 ± 0.009	13 ± 49
5.1 77	12 43 09.11	2 48 28.0	-0.1886 ± 0.096	18.24 ± 0.096	129 ± 21
5.1 81	12 42 54.00	2 48 46.6	0.9751 ± 0.025	22.26 ± 0.010	170 ± 52
5.1 88	12 42 53.65	2 49 09.4	3.5939 ± 0.016	19.68 ± 0.008	-57 ± 42
5.1 96	12 43 05.91	2 49 41.8	3.1359 ± 0.022	19.82 ± 0.008	-38 ± 51
5.1 99	12 42 57.99	2 49 52.2	0.5379 ± 0.009	20.07 ± 0.004	103 ± 52
5.1 104	12 42 59.57	2 50 12.9	0.7691 ± 0.018	21.53 ± 0.005	36 ± 65
6.1 2	12 43 07.52	2 36 03.7	2.5639 ± 0.040	21.60 ± 0.009	203 ± 43
6.1 5	12 43 21.31	2 36 14.5	3.3507 ± 0.013	19.62 ± 0.007	-32 ± 38
6.1 13	12 43 22.41	2 36 49.6	0.8896 ± 0.006	19.49 ± 0.003	-166 ± 60
6.1 18	12 43 23.80	2 37 08.3	3.0943 ± 0.041	21.37 ± 0.010	-51 ± 46
6.1 22	12 43 08.03	2 37 27.6	3.3375 ± 0.012	19.32 ± 0.004	91 ± 60
6.1 35	12 43 17.86	2 38 21.7	3.3824 ± 0.036	21.03 ± 0.009	-91 ± 77
6.1 37	12 43 20.65	2 38 28.2	0.9915 ± 0.100	18.35 ± 0.100	36 ± 35
6.1 38	12 43 10.14	2 38 33.7	0.8217 ± 0.026	19.45 ± 0.024	-166 ± 32
6.1 42	12 43 12.60	2 38 45.8	0.5609 ± 0.013	20.17 ± 0.004	-30 ± 81
6.1 50	12 43 08.48	2 39 24.9	0.6760 ± 0.008	20.21 ± 0.004	-177 ± 38

Table A.2. continued.

ID	RA	Dec	$C - R$	m_R	v (km s ⁻¹)
6.1 53	12 43 12.96	2 39 35.5	1.1427 ± 0.019	20.47 ± 0.005	-72 ± 64
6.1 62	12 43 07.91	2 40 06.8	0.7866 ± 0.018	21.01 ± 0.013	-179 ± 61
6.1 69	12 43 19.01	2 40 38.0	3.3824 ± 0.026	20.83 ± 0.005	-15 ± 54
6.1 69	12 43 20.79	2 40 31.5	1.1997 ± 0.015	21.21 ± 0.012	-15 ± 54
6.1 75	12 43 21.70	2 41 04.1	3.0614 ± 0.038	21.31 ± 0.007	-108 ± 62
6.1 86	12 43 16.71	2 41 48.0	3.3266 ± 0.034	21.13 ± 0.009	53 ± 72
6.1 87	12 43 13.14	2 41 51.3	3.3222 ± 0.024	20.53 ± 0.007	-16 ± 43
6.1 99	12 43 09.88	2 42 30.8	3.9336 ± 0.084	21.52 ± 0.005	-77 ± 37
6.1 100	12 43 14.80	2 42 33.8	3.2608 ± 0.064	22.00 ± 0.008	-248 ± 28
6.2 6	12 43 17.11	2 36 14.9	0.7253 ± 0.016	21.89 ± 0.009	3 ± 157
6.2 7	12 43 14.85	2 36 19.7	1.0080 ± 0.015	21.81 ± 0.005	-120 ± 19
6.2 9	12 43 10.05	2 36 25.4	1.2359 ± 0.061	18.55 ± 0.060	-59 ± 16
6.2 26	12 43 09.69	2 37 24.8	3.3189 ± 0.059	21.81 ± 0.011	44 ± 58
6.2 27	12 43 09.32	2 37 28.1	2.0402 ± 0.036	21.88 ± 0.011	-137 ± 42
6.2 50	12 43 12.60	2 38 45.8	0.5609 ± 0.013	20.17 ± 0.004	-130 ± 45
6.2 53	12 43 12.72	2 39 07.7	2.6801 ± 0.024	21.29 ± 0.005	23 ± 50
6.2 66	12 43 06.26	2 40 05.8	1.6556 ± 0.014	21.43 ± 0.006	-86 ± 62
6.2 67	12 43 06.04	2 40 07.7	2.4149 ± 0.100	18.54 ± 0.100	48 ± 81
6.2 77	12 43 07.65	2 40 45.3	2.9518 ± 0.015	19.13 ± 0.008	-30 ± 48
6.2 79	12 43 08.09	2 40 51.6	0.7910 ± 0.012	19.82 ± 0.005	-193 ± 22
6.2 84	12 43 15.79	2 41 12.5	1.3970 ± 0.016	20.85 ± 0.011	35 ± 32
6.2 93	12 43 18.55	2 41 48.1	3.6542 ± 0.049	21.33 ± 0.011	-107 ± 46
6.2 102	12 43 09.33	2 42 21.7	1.1197 ± 0.007	19.24 ± 0.004	89 ± 22
7.1 6	12 43 35.38	2 28 57.5	3.4471 ± 0.046	21.44 ± 0.024	-47 ± 48
7.1 7	12 43 40.85	2 29 02.7	3.8547 ± 0.040	20.80 ± 0.005	-29 ± 48
7.1 11	12 43 35.58	2 29 16.4	0.5565 ± 0.070	18.65 ± 0.069	-20 ± 22
7.1 15	12 43 26.31	2 29 31.8	0.9543 ± 0.006	19.83 ± 0.005	313 ± 20
7.1 19	12 43 41.26	2 29 46.6	4.0969 ± 0.091	21.91 ± 0.007	-31 ± 40
7.1 20	12 43 35.45	2 29 49.1	1.4945 ± 0.009	20.52 ± 0.006	256 ± 27
7.1 30	12 43 41.27	2 30 29.1	1.9602 ± 0.017	20.42 ± 0.009	33 ± 34
7.1 31	12 43 29.12	2 30 33.4	1.1515 ± 0.021	21.71 ± 0.006	131 ± 35
7.1 33	12 43 30.99	2 30 40.4	3.3912 ± 0.048	21.60 ± 0.006	-37 ± 58
7.1 36	12 43 35.87	2 30 49.5	0.5894 ± 0.026	21.92 ± 0.008	70 ± 70
7.1 41	12 43 33.03	2 31 10.1	0.7998 ± 0.007	21.03 ± 0.004	260 ± 67
7.1 43	12 43 39.10	2 31 20.7	3.0022 ± 0.064	18.54 ± 0.062	-20 ± 51
7.2 5	12 43 32.92	2 29 02.1	1.1975 ± 0.018	22.21 ± 0.011	76 ± 199
7.2 19	12 43 30.54	2 29 46.9	3.8142 ± 0.090	21.08 ± 0.056	50 ± 85
7.2 31	12 43 22.37	2 30 31.2	2.0928 ± 0.036	22.21 ± 0.012	-55 ± 50
7.2 34	12 43 30.28	2 30 40.2	1.6106 ± 0.041	22.62 ± 0.021	19 ± 61
7.2 44	12 43 25.03	2 31 12.1	1.3126 ± 0.024	22.16 ± 0.012	23 ± 42
7.2 51	12 43 26.70	2 31 51.7	0.7570 ± 0.007	20.94 ± 0.005	97 ± 60
7.2 56	12 43 33.91	2 32 09.4	3.0822 ± 0.012	19.76 ± 0.005	-8 ± 42
7.2 61	12 43 34.25	2 32 31.1	1.6391 ± 0.016	21.57 ± 0.007	-81 ± 33
7.2 62	12 43 26.58	2 32 33.5	2.9398 ± 0.015	20.01 ± 0.010	-11 ± 53
7.2 67	12 43 33.99	2 32 48.7	3.2762 ± 0.030	21.11 ± 0.005	31 ± 43
7.2 70	12 43 28.94	2 32 57.7	0.0032 ± 0.090	18.39 ± 0.089	2 ± 26
7.2 71	12 43 32.00	2 33 03.0	1.7607 ± 0.026	21.99 ± 0.012	211 ± 35
7.2 81	12 43 32.18	2 33 44.1	2.8872 ± 0.047	18.67 ± 0.047	-21 ± 55
7.2 96	12 43 24.95	2 34 33.8	0.8754 ± 0.075	18.52 ± 0.075	272 ± 11
7.2 110	12 43 22.13	2 35 22.2	2.6494 ± 0.044	22.11 ± 0.014	127 ± 70
7.2 112	12 43 21.07	2 35 27.4	0.9181 ± 0.011	21.47 ± 0.006	-38 ± 22