KINEMATIC STUDY OF THE DISRUPTING GLOBULAR CLUSTER PALOMAR 5 USING VLT SPECTRA

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ABSTRACT

Wide-field photometric data from the Sloan Digital Sky Survey have recently revealed that the Galactic globular cluster Palomar 5 is in the process of being tidally disrupted. Here we investigate the kinematics of this sparse remote star cluster using high-resolution spectra from the Very Large Telescope (VLT). Twenty candidate cluster giants located within 6' of the cluster center have been observed with the UV-Visible Echelle Spectrograph on VLT-UT2. The spectra provide radial velocities with a typical accuracy of 0.15 km s^{-1}. We find that the sample contains 17 certain cluster members with very coherent kinematics, two unrelated field dwarfs, and one giant with a deviant velocity, which is most likely a cluster binary showing fast orbital motion. From the confirmed members we determine the heliocentric velocity of the cluster as $-58.7 \pm 0.2$ km s^{-1}. The total line-of-sight velocity dispersion of the cluster stars is $1.1 \pm 0.2$ km s^{-1} (all members) or $0.9 \pm 0.2$ km s^{-1} (stars on the red giant branch only). This is the lowest velocity dispersion that has so far been measured for a stellar system classified as a globular cluster. The shape of the velocity distribution suggests that there is a significant contribution from orbital motions of binaries and that the dynamical part of the velocity dispersion is therefore still substantially smaller than the total dispersion. Comparing the observations with the results of Monte Carlo simulations of binaries we find that the frequency of binaries in Pal 5 is most likely between 24% and 63% and that the dynamical line-of-sight velocity dispersion of the cluster must be smaller than 0.7 km s^{-1} (90% confidence upper limit). The most probable values of the dynamical dispersion lie in the range $0.12 < \sigma_{\text{v}} / \text{km s}^{-1} < 0.41$ (68% confidence). Pal 5 thus turns out to be a dynamically very cold system. Our results are compatible with an equilibrium system. We find that the luminosity of the cluster implies a total mass of only $4.5 \times 10^5 M_\odot$. We further show that a dynamical line-of-sight velocity dispersion of $0.32$ to $0.37$ km s^{-1} admits a King model that fits the observed surface density profile of Pal 5 (with $W_0 = 2.9$ and $r_1 = 16.1'$) and its mass.

Key words: globular clusters: individual (Palomar 5) — stars: kinematics

1. INTRODUCTION

The globular cluster Palomar 5, an old halo cluster located at a distance of about 23 kpc from the Sun and 18.5 kpc from the Galactic center (see Harris 1996), stands out through a number of unusual and extreme properties. These make it particularly interesting from the viewpoint of dynamics, cluster evolution, and galactic structure. First of all, Pal 5 is extraordinarily sparse and faint. Its total luminosity of $M_V \approx -5.0$ (Sandage & Hartwick 1977, hereafter SH77) places it among the least luminous globular clusters that we currently know to exist in our Galaxy. Assuming a mass-to-light ratio typical of other globular clusters this luminosity corresponds to a stellar mass of about $1.3 \times 10^4 M_\odot$ (SH77) or $0.8 \times 10^4 M_\odot$ (Mandushev, Spassova, & Staneva 1991), which lies a factor of 30 below the median mass of Galactic globulars. Further, Pal 5 has a very extended core and a low central concentration (see, e.g., Trager, King, & Djorgovski 1995). Finally, the faint part of the luminosity function of Pal 5 is unusually flat (Smith et al. 1986; Grillmair & Smith 2001), i.e., the fraction of low-mass stars in Pal 5 is much smaller than in other Galactic globulars. These peculiarities suggest that Pal 5 has undergone strong dynamical evolution and mass loss and that it may be close to complete disruption. The hypothesis of ongoing dissolution was recently confirmed by the discovery of two massive tails of unbound former cluster members, which spread from the cluster in opposite directions over an arc of several degrees (Odenkirchen et al. 2001). The stars observed in the tails make up at least 35% of the total mass of cluster members and thus provide direct evidence for heavy mass loss from a strong tidal perturbation. Currently, Pal 5 is therefore the best-known example of a tidally disrupting globular cluster and is ideally suited for studying this phenomenon in situ.

In order to reconstruct the mass-loss history of Pal 5 and to understand and interpret the density structures that are visible in its tidal tails, one needs to simulate the cluster’s dynamics with numerical methods. The present-day velocity distribution in the cluster, in particular the velocity dispersion, provides an important boundary condition for such simulations and is indispensable for deriving a realistic numerical model of the cluster’s evolution in the tidal field of the Milky Way. However, the internal stellar velocities in Pal 5 have not been measured to date. The only published measurements of radial velocities of stars in Pal 5 are by Peterson (1985) and by Smith (1985). The spectral resolution of these measurements is sufficient to estimate the radial velocity of the cluster as a whole, but clearly too low to resolve the internal kinematics in the cluster. The results of Smith (1985) yield an upper limit of $4$ km s^{-1} on the velocity dispersion in the cluster. Assuming that the cluster is in virial equilibrium the mass of $1.3 \times 10^4 M_\odot$ estimated by SH77 and a typical radius of about 20 pc imply a velocity dispersion of the order of $1$ km s^{-1}. On the other hand, since...
Pal 5 has undergone tidal perturbations and is surrounded by a massive population of extratidal stars, it would be conceivable that the above equilibrium model is not valid. Hence any such prediction of the velocity dispersion in the cluster can only be a rough guideline. The goal of this paper is to determine the internal kinematics of Pal 5 directly from observation. We thus set out to obtain high-resolution spectra for a number of cluster members to derive very precise radial velocities. Due to the rather large distance of the cluster, its deficiency in bright giants, and the need for high spectral resolution, this project required an 8 m class telescope.

In §2 we provide details on the observations and the reduction and analysis of the spectra. In §3 we then analyze the observed radial velocities, determine the cluster’s velocity and the overall velocity dispersion along the line of sight and compare the observed velocity distribution with a Gaussian model. In §4 we investigate the influence of binaries and derive constraints on the dynamical velocity dispersion of the cluster. In §5 we rederive the structural parameters and the total luminosity of the cluster from new photometric data and compare these parameters with the kinematics of the cluster in the framework of an equilibrium cluster model. In §6 we summarize and discuss our results.

2. OBSERVATIONS AND DATA REDUCTION

The stars that are used to probe the kinematics of Pal 5 were selected with the help of multiband photometry from the Sloan Digital Sky Survey (SDSS, see Stoughton et al. 2002 and York et al. 2000 for overviews and Smith et al. 2002; Pier et al. 2002; Hogg et al. 2001; Gunn et al. 1998; Fukugita et al. 1996 for different technical aspects of the project). We defined a sample of 20 program stars located within a radius of 6′ around the center of Pal 5, that have magnitudes in the range $15.0 < i^* < 17.7$ and appear as likely cluster giants according to their magnitude and colors (see Odenkirchen et al. 2001). The target sample is presented in Table 1 and its properties are shown in Figures 1 and 2. These stars were observed with the UV-Visual Echelle Spec-

![Figure 1](image-url)
The reduction of the spectra (i.e., bias and background subtraction, flat fielding, order extraction, sky subtraction, wavelength calibration, rebinning, and order merging) was carried out with ESO’s dedicated UVES reduction pipeline. The spectra were wavelength-calibrated using the attached ThAr spectra and were rebinned to a linear wavelength scale of 0.030 Å pixel$^{-1}$ (blue part) and 0.035 Å pixel$^{-1}$ (red part). Examples of the reduced and calibrated spectra are shown in Figure 3.

Radial velocities were determined by cross-correlating the spectra of the program stars with those of the two velocity standards. This was done using the routine FXCOR in the software package IRAF. We calculated separate cross-correlation functions in five distinct wavelength intervals, i.e., at 4910–5210, 5210–5460, 5460–5750, 5850–6320, and 6320–6790 Å. Hereby we obtained, for each pair of a program star and a standard star, five independent velocity measurements of nearly equal accuracy. The velocity shift between program star and template was determined by fitting a Lorentzian curve to the cross-correlation function in a range of $\pm 12.5$ km s$^{-1}$ (i.e., 15 data points) around its highest peak. The results from the five wavelength intervals were averaged to define the relative velocity of each program star with respect to the standard star. The rms deviation of the individual results from the mean was used to derive an empirical estimate of the random error of the velocity. Heliocentric corrections for the program stars and the templates, depending on their position and the time of their observation, were calculated with the routine

Fig. 2.—Digitized Sky Survey image of Pal 5 (DSS2) showing the positions of our spectroscopic targets (size $12' \times 10'$; north is up, east to the left). The region of the cluster core is marked by the dashed circle ($r = 3.6$, core radius of the best-fitting King model; see § 5.1).
Fig. 3.—Examples of the UVES spectra for program stars of different magnitude and for one of the standard stars. The plot shows a 100 Å wide section from the blue part of the spectrum, i.e., about 5% of the full wavelength range covered by the spectra. The left side of the plot contains the Mg I b triplet feature. Note the broad line profiles of stars 4 and 12, which indicate that they are dwarfs.

RVCORRECT in IRAF. Applying these corrections and adding the known absolute velocities of the template stars, the measured velocities were transformed to the heliocentric absolute system.

The results of this procedure are presented in Table 2. The velocities are found to have accuracies between 0.05 and 0.25 km s\(^{-1}\). In most cases the random error is below 0.15 km s\(^{-1}\). The results obtained with the two different velocity standards (see cols. [4] and [6] of Table 2) are in good agreement with each other. There is a small mean offset of 0.14 km s\(^{-1}\) between the two sets of absolute velocities. When removing this offset, the remaining rms deviation is less than 0.03 km s\(^{-1}\). Cross-correlation of the spectra of the two standard stars with one another yields velocities that differ from the nominal values by 0.14 km s\(^{-1}\). The difference agrees with the mean offset in the results for the program stars and shows that the zero point of our absolute velocities has an uncertainty of this order. We take for each program star the mean of the results obtained with either of the two standards as the best estimate of its absolute velocity. Note, however, that the uncertainty of velocity differences is given by the individual random errors only.

The last two columns of Table 2 give the velocities obtained by Smith (1985) and by Peterson (1985) for stars in common with those in our sample. The differences between

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### Table 2: Results from Spectroscopy

| Star (1) | Stellar Type | MJD of Obs. (3) | \(v_r\) \(^a\) \(\epsilon\) | \(v_r\) \(^b\) \(\epsilon\) | \(v_r\) \(^S85\) | \(v_r\) \(^P85\) |
|----------|--------------|-----------------|-----------------|-----------------|------------|------------|
| 1........... | RGB | 52,033.168 | -58.51 0.05 | -58.66 0.05 | -54 | ... |
| 2........... | RGB | 52,033.178 | -58.31 0.05 | -58.47 0.05 | -51 | ... |
| 3........... | AGB | 52,033.187 | -61.16 0.06 | -61.30 0.05 | -61 | ... |
| 4........... | MS | 52,033.197 | -23.44 0.06 | -23.62 0.06 | -23 | ... |
| 5........... | AGB | 52,033.210 | -56.92 0.07 | -57.06 0.05 | -53 | -46 |
| 6........... | RGB | 52,039.069 | -58.72 0.09 | -58.87 0.11 | -61 | ... |
| 7........... | RGB | 52,039.082 | -58.79 0.10 | -58.93 0.12 | -59 | ... |
| 8........... | AGB | 52,039.096 | -58.98 0.05 | -59.14 0.05 | ... | ... |
| 9........... | AGB | 52,039.110 | -57.35 0.15 | -57.49 0.15 | -57 | -55 |
| 10.......... | RGB | 52,039.124 | -60.10 0.14 | -60.24 0.14 | -52 | ... |
| 11.......... | RGB | 52,039.138 | -58.90 0.09 | -59.06 0.07 | ... | -58 |
| 12.......... | MS | 52,039.162 | -52.97 0.12 | -53.13 0.12 | ... | ... |
| 13.......... | RGB | 52,032.268 | -58.94 0.08 | -59.10 0.06 | ... | ... |
| 14.......... | RGB | 52,033.222 | -61.07 0.17 | -61.19 0.19 | ... | ... |
| 15.......... | RGB | 52,033.251 | -44.67 0.12 | -44.73 0.09 | ... | ... |
| 16.......... | RGB | 52,040.248 | -58.33 0.15 | -58.50 0.16 | ... | ... |
| 17.......... | RGB | 52,083.033 | -58.54 0.06 | -58.67 0.04 | ... | ... |
| 18.......... | RGB | 52,078.169 | -58.42 0.25 | -58.55 0.22 | ... | ... |
| 19.......... | RGB | 52,078.130 | -59.48 0.22 | -59.60 0.20 | ... | ... |
| 20.......... | RGB | 52,079.064 | -57.27 0.06 | -57.40 0.05 | ... | ... |
| HD 107328..... | ... | 52,033.163 | +36.26 0.03 | ... | ... | ... |
| HD 157457..... | ... | 52,032.438 | +17.94 0.03 | ... | ... | ... |

Notes.—RGB = red giant branch; AGB = asymptotic giant branch; MS = main-sequence star; \(\epsilon\) = random error of the radial velocity measurement; S85 = Smith 1985; P85 = Peterson 1985.

\(^a\) By cross-correlation with HD 107328.

\(^b\) By cross-correlation with HD 157457.
our results and the previous ones are of the order of a few kilometers per second. It is easily seen that our results for different stars are in much closer agreement with each other than the previous measurements. This suggests that the differences between the previous results and ours are largely due to the lower precision of the previous measurements (and perhaps differences in the absolute calibration) and in general do not reflect true variations in the radial velocities of these stars. Variations from binaries are expected to occur mostly with smaller velocity amplitudes (see § 4).

3. ANALYSIS OF THE KINEMATICS

3.1. Cluster Membership

The spectroscopic observations show that most of the stars in our target sample are indeed giants and that many of them have almost identical velocities. Figure 4 shows the distribution of the observed velocities. Seventeen of the 20 measured stars have radial velocities in the range between $-61.2$ and $-56.9 \text{ km s}^{-1}$. These are undoubtedly all members of the cluster. Ten stars in this group stand out by having particularly coherent velocities that lie in an interval of only 1 km s$^{-1}$. This can be seen by the pronounced peak in Figure 4a and by the corresponding steep rise of the cumulative number counts shown in Figure 4b. Only three stars appear to be kinematically distinct from the cluster. Their velocities deviate from the rest of the sample by about 6, 14, and 35 km s$^{-1}$, respectively. Two of these stars turn out to be foreground dwarfs on the basis of a much larger width of their spectral lines (stars 4 and 12; see Fig. 3). They definitely do not belong to the cluster and are discarded from the subsequent analysis. The only doubtful case is star 15, which has the spectrum of a giant resembling those of other cluster members, but is set off from the cluster by about 14 km s$^{-1}$ in radial velocity. Its location at less than 2' angular distance from the center of the cluster suggests that it is a member of Pal 5 rather than an unrelated field giant at about the same spatial distance as the cluster. From the surface density of field stars with magnitude and color similar to star 15 (i.e., $\pm 0.15 \text{ mag}$ in magnitude and $\pm 0.05 \text{ mag}$ in color) it follows that the expected number of such field stars within 2' from the cluster center is 0.1, while the expected number of cluster stars is 3.5. Since we have observed three stars in this range of position, color, and magnitude, the probability that (at least) one of them is a field star is only $1 - (3.5/3.6)^3 = 0.08$.

The cluster membership of all but stars 4 and 12 of our sample is independently confirmed in a proper-motion study carried out by Cudworth, Schweitzer, & Majewski (2002). This study determines proper motions of about 500 stars in the field of Pal 5 using microdensitometer scans of 25 plates from large reflectors ranging in epoch from 1949 to 1991. From the preliminary results of this work membership probabilities for our stars were derived in the way described in Dinescu et al. (1996). The probabilities are presented in Table 3. While stars 4 and 12 again prove to be nonmembers, the other stars have membership probabilities between 72% and 99% and thus qualify as cluster members. In particular, star 15 has a proper-motion membership probability of 73%, which is comparable to that of other stars with radial velocities close to the cluster mean, thus supporting its membership.

The most plausible explanation, then, is that star 15 is a binary member of Pal 5 and that the observed offset of its radial velocity (actually that of the primary component) is the result of temporal variations due to rapid orbital motion. For a binary in a circular orbit the orbital period $T$ is related to the orbital velocity $v_1$ of the primary by

$$\frac{T}{\text{yr}} = \left(\frac{30 \text{ km s}^{-1}}{v_1 M_2}{\frac{M_2}{M_1 + M_2}}\right)^{3} \frac{M_1 + M_2}{M_\odot} \quad (1)$$

Assuming a mass of 0.8 $M_\odot$ for the primary, one finds that the orbital period of star 15 can at most be 2 yr ($M_2 = M_1$) and that it is likely to be of the order of a few months because the companion mass is probably smaller.
TABLE 3

Membership Probabilities from Proper Motion

| Star | SH77 ID | CSM ID | Probability (%) |
|------|---------|--------|-----------------|
| 1.... | F       | ...    | 78              |
| 2.... | G       | ...    | 73              |
| 3.... |         | 174    | 88              |
| 4.... | I       | ...    | 0               |
| 5.... | H       | ...    | 92              |
| 6.... | K       | ...    | 88              |
| 7.... | L       | ...    | 86              |
| 8.... |         | 32     | 72              |
| 9.... | J       | ...    | 80              |
| 10... | N       | ...    | 98              |
| 11... | U       | ...    | 95              |
| 12... |         | 593    | 0               |
| 13... | 6       | ...    | 98              |
| 14... | 19      | ...    | 99              |
| 15... | 27      | ...    | 73              |
| 16... | AB      | ...    | 80              |
| 17... | 35      | ...    | 89              |
| 18... | 26      | ...    | 97              |
| 19... |         | 142    | 99              |
| 20... | 5       | ...    | 97              |

Notes.—SH77 = Sandage & Hartwick 1977; CSM = Cudworth et al. 2002.

* Probabilities from CSM.

than that of the primary and because the projection on the line of sight has to be taken into account. Therefore, even only one additional precise measurement of the radial velocity of this star should immediately reveal whether it is indeed a binary member of Pal 5. For the present paper we take its occurrence as an indication of the likely existence of binaries. For the present paper we take its occurrence as an indication of the likely existence of binaries. For the present paper we take its occurrence as an indication of the likely existence of binaries. For the present paper we take its occurrence as an indication of the likely existence of binaries.

3.2. Mean Velocity and Dispersion

The median of the velocities of the 17 certain members of Pal 5 is $-58.8 \pm 0.3$ km s$^{-1}$, the arithmetic mean $-58.9 \pm 0.3$ km s$^{-1}$. By successive omission of those stars that deviate most strongly from the median of the sample, one obtains mean velocities between $-58.6$ and $-58.8$ km s$^{-1}$. The particular subgroup of 10 stars whose velocities coincide within 1 km s$^{-1}$ has a mean velocity of $-58.7 \pm 0.1$ km s$^{-1}$. Combining these results with the uncertainty of the zero point of the absolute velocity scale, we adopt the heliocentric velocity of the cluster $v_{\odot}$ as $-58.7 \pm 0.2$ km s$^{-1}$. The rms dispersion of the individual velocities of the 17 cluster members with respect to this cluster mean is $1.14 \pm 0.1$ km s$^{-1}$. The individual measurement errors are much smaller, and their contribution to this dispersion can be neglected.

The colors and magnitudes of the stars reveal that the set of confirmed members consists of 13 normal red giants (RGB stars) and four asymptotic giant branch (AGB) stars (see Fig. 1). Comparing the velocities of the RGB and AGB stars, we find that three of the four AGB stars have radial velocities that differ from the above cluster mean by more than 1 km s$^{-1}$. Among the RGB stars only three out of 13 have velocities beyond this limit. This suggests either that the two types of giants are somehow kinematically different or that the measurements of the AGB stars are affected by some kind of pulsational variations in their extended atmospheres.

3.3. Dependence on Magnitude and Position

In Figure 5 the individual radial velocities are plotted versus magnitude, angular distance from the cluster center ($r = 15^h 16^m 04^s.5, \delta = -00^\circ 07' 16'', J2000.0$), and position angle $\varphi$ (measured from north over east). Figure 5a shows that the mean velocity of the cluster members does not depend on the magnitude of the stars. Note that we also find no sign of a dependence of the measured velocities on the epoch of observation. We thus can eliminate substantial systematic measuring errors as a function of brightness or epoch. Figure 5a also demonstrates that, while there may be velocity jitter in the AGB stars, there is clearly no sign for corresponding jitter in the brightest red giants of the sample, since the velocities of these stars are in extremely close agreement with each other.

Figure 5b gives the impression that subgroups of stars at different angular distance from the center have very different velocity dispersions. This is partly, but not entirely, due to the AGB stars, which are all located at $r > 2.5$ and hence differ from the spatial distribution of the normal giants. An $f$-test shows that the very low dispersion of $0.21$ km s$^{-1}$ for the subgroup of the four innermost stars ($r \leq 1.5$) is indeed significantly smaller (99% significance) than the dispersion for the remaining sample, even if the AGB stars are excluded. On the other hand, it turns out that the somewhat lower dispersion of the outermost stars ($r > 4$), as compared with the dispersion at medium distances from the center, is not a statistically significant effect.

In Figure 5c one finds weak indications that the observed velocities may contain azimuthal variations. Such variations could result from a rotation of the cluster. However, there remains almost no evidence for such an effect if one leaves out the AGB stars. Because of the limited number of data points the question of rotation cannot be investigated beyond the simple case of solid-body rotation. By least-squares adjustment we find that if the velocities contain a solid-body rotation component the angular velocity of the rotation and the position angle of the rotation axis would be $\omega = 0.25 \pm 0.12$ km s$^{-1}$ arcmin$^{-1}$ and $P.A. = +15 \pm 31^\circ$, respectively. When subtracting this hypothetical rotation from the observed velocities, the velocity dispersion of the $n = 17$ sample reduces only slightly (from 1.14 to 1.08 km s$^{-1}$). For the subsample without AGB stars we likewise obtain $\omega = 0.17 \pm 0.16$ km s$^{-1}$ arcmin$^{-1}$; i.e., the rotation velocity is at the border of statistical significance, and the rotation model yields no reduction of the velocity dispersion. Therefore we conclude that rotation is not clearly detectable and that it does not provide an important contri-
bution to the kinematics of the cluster. This conclusion also holds for the possibility of an expansion of the cluster along a preferred spatial direction since, from the observational point of view, such an effect is equivalent to a rotation.

3.4. Comparison with an Isothermal System

If the cluster maintains a state of dynamical quasi equilibrium one expects the kinematics in its inner region to be isothermal, which means that the line-of-sight velocity distribution of objects with approximately equal masses must (in the absence of other effects) be Gaussian. Many stellar systems do indeed show velocity distributions that are approximately Gaussian. However, in the case of a cluster with low velocity dispersion it may happen that contributions from atmospherically induced variations and from orbital motion of binaries are of nonnegligible size and that the observed line-of-sight velocities are hence not completely dominated by the dynamics of the cluster. Concerning contributions from binaries, it may also be relevant that a small velocity dispersion in the cluster is favorable to the survival of binaries during the cluster’s dynamical evolution. The impact of velocity anomalies in the AGB stars, possibly caused by atmospheric jitter, was discussed in § 3.3.

In order to find out whether binaries play a significant role in Pal 5, we compare the observed velocities with a simple Gaussian representing an isothermal system of single stars. The Gaussian that best fits the observations can be found by the method of maximum likelihood. When observational errors are neglected, the dispersion parameter $\sigma$ of the best-fit Gaussian is simply given by the rms dispersion of the observed velocities. In the general case, with observations $v_i$ and errors $\varepsilon_i$, one calculates the probabilities $p_i$ of the observations by convolving the Gaussian model $\Phi_\sigma$ with the error distributions $\Phi_\varepsilon$, i.e., $p_i = (\Phi_\sigma * \Phi_\varepsilon)(v_i)$, and maximizes the total probability (or likelihood) $L = \prod p_i$ as a function of the parameter $\sigma$. For the complete sample of $n = 17$ stars the solution is $\sigma = 1.14$ km s$^{-1}$, with uncertainties of $+0.24$ and $-0.18$ km s$^{-1}$. For the $n = 13$ subsample of RGB stars we obtained $\sigma = 0.91$ km s$^{-1}$, with uncertainties of $+0.23$ and $-0.18$ km s$^{-1}$. The given uncertainties describe the interval around the maximum of $L$ that contains 68.3% of the likelihood integral $\int L \, d\sigma$.

To test the agreement between the maximum likelihood Gaussian model and the observations, we generated a large number of artificial samples of $n$ velocities based on the best-fit $\sigma$ and the observational errors and compared the likelihood of the observed velocities with the likelihood of the simulated velocities. The experiment reveals that the likelihood values of the observed samples fall close to the median of the likelihood distribution of the corresponding simulated samples, i.e., 47% (for $n = 17$) or 45% (for $n = 13$) of the simulated samples have likelihood values that are smaller than the likelihoods of the observed samples. This means that, from the viewpoint of likelihood statistics, the best-fit Gaussian is an acceptable model for the observed velocities. It would, however, be wrong to conclude that a purely Gaussian model provides an optimal description of the data.

In Figure 6 the data and the best-fit Gaussian models are compared by plotting their cumulative distributions. Here it is seen that the agreement between the data and the models is in fact less than satisfactory. For both samples there are clear systematic differences between the data and the model. The observational data are characterized by a steep rise at small velocities and a flat tail extending from 0.3 to 2.4 km s$^{-1}$. A Gaussian distribution is unable to approximate this shape in an appropriate way. In order to maintain the idea of isothermal cluster kinematics we thus need to assume the existence of an additional velocity component.

This suggests that there are indeed significant contributions from orbital motion of binaries. These binaries may either be primordial (as in young open clusters and the field) or may have formed by close stellar encounters during the evolution of the cluster. Recent searches for binaries in other Galactic globulars have revealed that globular clusters
are not generally deficient in binaries, as compared with the local population of field stars, and that clusters with low central density and/or indications of strong tidal mass loss tend to have enhanced binary frequencies (see McMillan, Pryor, & Phinney 1998 and references therein). Moreover, star 15 provides a direct hint that the existence of binaries in our sample is likely (see § 3.1). If this object is indeed a binary member of Pal 5 with a relatively short period of a few months, as assumed in § 3.1, then it is natural to expect that the sample also contains binaries with longer orbital periods of up to several decades. Such systems will typically produce shifts of the order of 1 km s\(^{-1}\) in the observed distribution but fails in the outer part. (b) Subsample of 13 RGB stars and best-fit model with \(\sigma = 0.91\) km s\(^{-1}\).

4. SIMULATION OF BINARIES

Since the binarity of the observed objects and their orbital motions are not individually known, one may assume that each object has a probability \(x_b\) of being a binary and consider a variety of possible systems with statistically distributed orbital parameters. If the distribution functions of the orbital parameters of the binary population are known, then the statistical impact of their orbital motions on the radial velocity of the primaries and the resulting distribution of observable velocities can be determined by a Monte Carlo simulation. For binaries in globular clusters one faces the problem that specific information on the distributions of their parameters is lacking. Hence one must either work with plausible general assumptions or refer to the empirical parameter distributions for field binaries in the local neighborhood, hoping that these are not prohibitively wrong for cluster binaries. We decided to try both ways and thus generated different sets of artificial binary populations in the following way.

The mass of the primary component was chosen as \(M_1 = 0.8\ M_\odot\) for normal red giants and \(M_1 = 0.5\ M_\odot\) for AGB stars. The mass \(M_2\) of the secondary was modeled by a log-normal mass function in the mass range \(0.1\ M_\odot \lesssim M_2 \lesssim M_1\), i.e., a Gaussian for \(\log M\), with mean \((\log (M/M_\odot)) = -0.38\) and dispersion \(\sigma_{\log(M/M_\odot)} = 0.35\). This mass function closely resembles the empirical mass distribution of secondaries around nearby solar-type stars found by Duquennoy & Mayor (1991). Alternatively, we also tried simpler choices, such as, for example, \(M_2 = M_1\), \(M_2 = 0.4\ M_\odot\), or \(M_2 = 0.2\ M_\odot\). For the semimajor axis \(a\) of the binary orbits we adopted a Gaussian in \log \((a/AU)\) with mean \((\log (a/AU)) = 1.5\) and dispersion \(\sigma_{\log(a/AU)} = 1.5\). This model is in agreement with empirical semimajor axis distributions as, e.g., given by Heintz (1969), and with the period statistics of local G and K dwarfs given by Mayor et al. (1992). We note that this distribution was used in truncated form (see below). For the orbital eccentricity \(e\) we used as standard case a flat distribution \(f(e) = \text{const}\) in the range \(0.1 \leq e \leq 0.8\) and \(e = 0\) for periods \(P < 0.3\) yr, taking into account observational results by Duquennoy & Mayor (1991), Mayor et al. (1992), and Latham et al. (1998). In addition, we also ran simulations with either \(e = 0\) (circular orbits) or \(f(e) = 2e\) (so-called thermal orbits) as extreme alternatives.

In a cluster environment wide binaries are unlikely to survive stellar encounters if their binding energy is less than the typical kinetic energy of relative motion between cluster members. Using a velocity dispersion of 2 to 4 km s\(^{-1}\) (as an estimate for earlier evolutionary stages of Pal 5), the formula given in equation (1) of Pryor et al. (1996) yields upper limits for the semimajor axis of 100 to 25 AU, respectively.
We thus tentatively truncated the distribution of $a$ at different values in this range and, after some testing, set the upper limit of $a$ to 50 AU. At the lower end the range of distances between the two binary components also has to be truncated because the primaries in our sample are giants and thus have large radii, which can surpass the Roche limit for mass transfer. Roche overflow would increase the separation between the components and decrease the brightness of the system (see, e.g., the discussion by Pryor et al. 1988). Therefore we calculated approximate radii for our giants using the radius-magnitude relation shown in Figure 6 of Côté et al. (1996), determined the distance of the inner Lagrange point L1 from the primary component at pericenter, and neglected all cases in which this distance was smaller than the estimated stellar radius ($10 < R/R_* < 40$). Note that this constraint precludes the existence of very hard binaries in our sample.

From each simulated set of binaries we derived a characteristic radial velocity distribution $\Phi_b$ by projecting the orbital velocities of the primary components onto isotropically distributed line-of-sight directions at randomly chosen fractions of the orbital period. Examples of such distributions are shown in Figure 7. These distributions have long high-velocity tails, which distinguish them from a Gaussian. To describe the radial velocities of a sample of binaries in a cluster with isothermal kinematics the binary radial velocity distribution $\Phi_b$ needs to be convolved with a Gaussian $\Phi_d$ that models the dynamical velocity dispersion, as in § 3.4. Furthermore, for a cluster with a fraction $x_b$ of binaries the velocity distribution must be a composite of $\Phi_d * \Phi_b$ and $\Phi_d$, namely,

$$\Phi = x_b(\Phi_d * \Phi_b) + (1 - x_b)\Phi_d.$$  

This yields an extended model $\Phi$ with adjustable parameters $\sigma$ and $x_b$, which should allow a better match with the observed velocities provided that the distributions of the orbital parameters of the binaries have been set appropriately. The model was fitted to the observations in the same way as in § 3.4, namely, by convolving it with the observational errors, calculating the individual probabilities $p_i$ of the observed velocities, and then maximizing the probability product $L$ (or actually its logarithm, $\log L = \sum \log p_i$) as a function of $\sigma$ and $x_b$. We calculated maximum likelihood solutions for a variety of choices of the binary parameters $M_2$ and $e$. The results are presented in Table 4. The upper part of the table refers to the entire sample and the lower part to the subsample of red giants. The quoted uncertainties in $\sigma$ and $x_b$ describe the parameter range that comprises 68.3% of the integrated likelihood. In addition, we provide the value of the 90% confidence upper limit of $\sigma$, which is denoted $\sigma_{90\%}$. For comparison, the first line in each part of Table 4 repeats the single star solution from § 3.4.

It turns out that most of the binary models indeed enable solutions with higher maximum likelihood than the single-star model. The only exception is the extreme case of equal-mass binary components ($M_1 = M_2$), which fails to produce an improved fit to the velocity distribution of the $n = 17$ sample and thus proves to be inadequate. Comparing the values of $\ln L$ in Table 4, it is seen that the improvements achieved with the different binary models are generally larger for the $n = 13$ subsample than for the complete $n = 17$ sample. This supports the assumption that the increased velocity dispersion of the AGB stars has a different origin (see § 3.2) and is not due to binarity. The best fit to the observed velocities is obtained with the model that is based on low-mass companions ($M_2 = 0.2 M_\odot$) and preferentially high orbital eccentricities $[f(e) = 2e]$. This holds for both samples. Our so-called standard case, which is closest to the properties of the local field binaries, is found to be less adequate. Other cases with more massive secondary components or low eccentricities are also seen to be less in agreement with the observed velocities.

![Fig. 7.—Radial velocities induced by the orbital motion of a random-generated population of binaries with parameters as described in the text and in the legend. Here $v_r$ is the radial velocity of the primary component along isotropically distributed lines of sight at random orbital phase. The so-called standard binary model assumes a log-normal mass function for the secondary and a constant distribution of ellipticities as observed in local field binaries (for further details see § 4).](image-url)
TABLE 4
MAXIMUM LIKELIHOOD SOLUTIONS FOR A GAUSSIAN MODEL PLUS BINARY COMPONENT

| Model          | Binary Parameters and Distributions | Sample | $\text{max}(\ln \mathcal{L})$ | $x_b$ | $\sigma$ (km s$^{-1}$) | $\sigma_{90\%}$ (km s$^{-1}$) |
|----------------|-------------------------------------|--------|-------------------------------|------|------------------------|-------------------------------|
| Single stars only |                                     | R+A    | $-26.38$                      | 0.0  | $1.14^{+0.24}_{-0.19}$ | 1.53                          |
| a ............ | Standard binary model | R+A    | $-25.94$                      | 0.45$^{+0.18}_{-0.26}$ | $0.24^{+0.57}_{-0.10}$ | 1.07                          |
| b ............ | $e = 0^\circ$                      | R+A    | $-26.08$                      | 0.44$^{+0.17}_{-0.27}$ | $0.24^{+0.59}_{-0.10}$ | 1.08                          |
| c ............ | $f(e) = 2e^a$                      | R+A    | $-25.57$                      | 0.50$^{+0.21}_{-0.25}$ | $0.24^{+0.51}_{-0.11}$ | 1.04                          |
| d ............ | $M_2 = M_1^a$                      | R+A    | $-26.38$                      | 0.00$^{+0.09}_{-0.08}$ | 1.06$^{+0.40}_{-0.10}$ | 1.39                          |
| e ............ | $M_2 = 0.4 M_1^a$                  | R+A    | $-25.98$                      | 0.43$^{+0.26}_{-0.28}$ | $0.24^{+0.40}_{-0.10}$ | 1.07                          |
| f ............ | $M_2 = 0.2 M_1^a$                  | R+A    | $-25.16$                      | 0.53$^{+0.21}_{-0.23}$ | $0.24^{+0.45}_{-0.12}$ | 1.02                          |
| g ............ | $M_2 = 0.2 M_1^a, e = 0^\circ$     | R+A    | $-25.32$                      | 0.52$^{+0.21}_{-0.20}$ | $0.24^{+0.47}_{-0.11}$ | 1.03                          |
| h ............ | $M_2 = 0.2 M_1^a, f(e) = 2e^a$     | R+A    | $-25.02$                      | 0.60$^{+0.22}_{-0.23}$ | $0.23^{+0.46}_{-0.13}$ | 1.01                          |
| Single stars only |                                     | R      | $-17.35$                      | 0.0  | $0.91^{+0.23}_{-0.19}$ | 1.30                          |
| a ............ | Standard binary model | R      | $-15.30$                      | 0.32$^{+0.18}_{-0.16}$ | $0.23^{+0.20}_{-0.09}$ | 0.74                          |
| b ............ | $e = 0^\circ$                      | R      | $-15.38$                      | 0.31$^{+0.17}_{-0.16}$ | $0.23^{+0.21}_{-0.09}$ | 0.75                          |
| c ............ | $f(e) = 2e^a$                      | R      | $-15.10$                      | 0.35$^{+0.19}_{-0.17}$ | $0.22^{+0.20}_{-0.09}$ | 0.72                          |
| d ............ | $M_2 = M_1^a$                      | R      | $-16.54$                      | 0.23$^{+0.14}_{-0.15}$ | $0.24^{+0.35}_{-0.09}$ | 0.89                          |
| e ............ | $M_2 = 0.4 M_1^a$                  | R      | $-15.37$                      | 0.30$^{+0.17}_{-0.15}$ | $0.23^{+0.20}_{-0.09}$ | 0.75                          |
| f ............ | $M_2 = 0.2 M_1^a$                  | R      | $-14.78$                      | 0.37$^{+0.20}_{-0.17}$ | $0.22^{+0.19}_{-0.09}$ | 0.69                          |
| g ............ | $M_2 = 0.2 M_1^a, e = 0^\circ$     | R      | $-14.87$                      | 0.36$^{+0.17}_{-0.19}$ | $0.22^{+0.19}_{-0.09}$ | 0.70                          |
| h ............ | $M_2 = 0.2 M_1^a, f(e) = 2e^a$     | R      | $-14.67$                      | 0.42$^{+0.21}_{-0.18}$ | $0.22^{+0.19}_{-0.10}$ | 0.69                          |

Notes.—R+A = RGB and AGB stars ($n = 17$); R = RGB stars only ($n = 13$); $x_b$ = best-fit binary fraction; $\sigma$ = Gaussian dispersion parameter; $\sigma_{90\%}$ = upper limit of $\sigma$ for 90% confidence.

$^a$ Other parameters same as in model a.

Fig. 8.—Likelihood distribution in the plane of the parameters $x_b$ (binary frequency) and $\sigma$ (single star velocity dispersion) and marginal distributions thereof, calculated with the RGB star sample ($n = 13$) and the binary model with $M_2 = 0.2 M_1^a$ and $f(e) = 2e$ (see case h in the lower part of Table 4). The lines in the $x_b$-$\sigma$ plane show contours of equal likelihood $\mathcal{L}$ that encircle regions with 25%, 50%, 75%, and 90% of the total integrated likelihood. The small central ellipse marks the location of the maximum of $\mathcal{L}$. Hatched areas mark the ranges of the probable values of $\sigma$ and $x_b$; i.e., the intervals around the maxima of $\sigma$ and $x_b$ that contain 68.3% of the integrated likelihood.

two of our models with binaries, namely, the standard model and the one that yields the best fits. Other than the single Gaussians shown in the analogous Figure 6, these models can (because of the inclusion of binaries) approximate both the steep inner rise and the extended tail of the observed velocity distribution. The standard model, however, is seen to be somewhat less adequate than the other model since it predicts too many stars with $|\Delta v| > 1.5$ km s$^{-1}$ in comparison with the observations.

5. VELOCITY DISPERSION VERSUS STRUCTURAL PARAMETERS, LUMINOSITY, AND MASS-TO-LIGHT RATIO

A key question in connection with the determination of the velocity dispersion is how the result compares with other fundamental parameters of the cluster. We combine the discussion of this question with a redetermination of Pal 5’s size, structure, luminosity, and mass, using the SDSS data and the HST luminosity function for main-sequence stars of Pal 5 by Grillmair & Smith (2001).

5.1. Surface Density Profile and Best-Fit King Model

The wide-field photometry from SDSS allows us to derive an improved radial density profile for Pal 5. Using the advantage of selective star counts, the cluster’s profile can be traced down to 5 times lower surface density than in former work by Trager et al. (1995). We separated cluster members from field stars through an efficient color-magnitude filter (see Odenkirchen et al. 2001) and determined the surface density of the members by counts in circular annuli out to a radius of 100’. In the outer annuli the member counts are in some places influenced by an overlap with the
tidal tails. This was taken into account by splitting the field into four 90° sectors pointing toward north, south, east, and west. The profiles obtained for the northern and southern sector and for the eastern and western sector are compared in Figure 10. Since the cluster overlaps with the tails only in the northern and southern sector, the counts obtained in the eastern and western sector yield a profile that is free of contamination by tidal tail stars and describes the true size and structure of the cluster.

Under the assumption of dynamical quasi equilibrium the density profile of the cluster should match the profile of a so-called King model, i.e., a truncated isothermal sphere (King 1966). We thus took the “clean” surface densities measured in the eastern and western sector of the field, fitted a series of King profiles by means of weighted least squares, and determined the best-fitting King (1966) model for the cluster. The best-fit model has $W_0 = 2.9$, which is equivalent to $c = 0.66$ for the concentration parameter and a limiting radius $r_1 = 16\,' 0 0\,' 0 8$. The corresponding core radius is $r_c = 3\,' 6 0\,' 0 2$. At the assumed distance of $d = 23.2$ kpc of Pal 5 this means a linear core radius of 24.0 pc. Figure 10 shows the best-fit King model (plus constant foreground density) by a solid curve. The agreement between the measurements and the model is satisfactory beyond the core radius, but the model fails to describe the constant surface density in the central 3' of Pal 5 and the subsequent abrupt decline. This may be an indication that the dynamical state of the cluster is in fact somewhat different from a King model. Nevertheless, the best-fit King model remains a useful approximation because it provides a relation between mass and velocity dispersion.

The mass of a truncated isothermal sphere with spatial parameters $r_c$ and $c$ and with a line-of-sight velocity dispersion $\sigma_{\text{los}}$ is given by

$$M = \frac{9}{4\pi G r_c \mu (\beta \sigma_{\text{los}})^2}$$

(see King 1966). Here $\mu$ denotes a normalized mass parameter that depends on $c$ and that has to be determined by numerical integration. For a model with $W_0 = 2.9$ one finds $\mu = 4.9$. The correction factor $\beta$ depends on the model and on the area within which the velocity dispersion is sampled. If $\sigma_{\text{los}}$ is determined as an average line-of-sight dispersion over a region of one core radius, as is the case with our observations, the appropriate correction factor $\beta$ for a model with $W_0 = 2.9$ is $\beta = 1.5$ (see Binney & Tremaine 1987, p. 236). Inserting these values into equation (3) we obtain the relation

$$\frac{M_{\text{Pal5}}}{M_\odot} = 4.4 \times 10^4 \left(\frac{\sigma_{\text{los}}}{\text{km s}^{-1}}\right)^2.$$  (4)
5.2. Total Luminosity and Mass

To determine the total absolute $V$-band magnitude of the cluster we integrated the flux of all SDSS stars that lie in the region of the giant and subgiant branch, horizontal branch, and main sequence of Pal 5, and within the limiting radius $r_I = 16'$ of the cluster. The integration was carried out down to a magnitude limit of $V = 21.75$. Visual magnitudes were derived from SDSS $g^*$ and $r^*$ magnitudes using the transformation $V = 0.4q^* + 0.6r^* + 0.23$. This relation was set up by comparing SDSS photometry and CCD photometry in $V$ from Smith et al. (1986) for 18 stars in the color range $-0.2 \leq g^* - r^* \leq 1.4$. We corrected the integrated flux for the contribution of residual field stars by subtracting the statistically expected luminosity of field stars as estimated in nearby fields. The resulting integrated magnitude of Pal 5 from stars down to the limit of $V = 21.75$ is $m_V = 12.24 \pm 0.07$. Using a distance modulus of $16.83 \pm 0.20$ ($d = 23.2 \pm 2.3$ kpc), the absolute magnitude of the cluster down to this limit is $M_V = -4.59 \pm 0.20$.

The missing flux of cluster stars fainter than $V = 21.75$ was estimated using the deep luminosity function (LF) of Grillmair & Smith (2001). We rescaled this LF to the SDSS star counts in the range $19.75 \leq V < 21.75$ and then integrated the predicted flux from $V = 21.75$ down to $V = 27$, where the LF is flat and the contribution to the total flux becomes negligible. This yields an additional contribution to the integrated magnitude of the cluster of 0.18 mag. Our result for the total absolute magnitude of Pal 5 is thus $M_V = -4.77 \pm 0.20$. This is marginally lower than the estimate of $M_V = -5.0$ obtained by SH77 and corresponds to a total $V$-band luminosity of $(L/L_V)_V = 7.2 \times 10^3$ (using $M_V = 4.87$ for the Sun).

One way of deriving the mass of the cluster from its luminosity is by assuming that the mass-to-light ratio of Pal 5 is not substantially different from that of other Milky Way globular clusters. According to the empirical mass-luminosity relation by Mandushev, Spassova, & Stanova (1991), which reads

$$\log(M/L_V) = -0.456M_V + 1.64$$

the mean mass-to-light ratio of Galactic globulars varies between $M/L_V = 1.1$ for faint clusters ($M_V = -6$) and $M/L_V = 1.8$ for very bright clusters ($M_V = -10$). The estimates of the masses and mass-to-light ratios of individual clusters deviate from this relation by at most a factor of two. Since the relation is calibrated with clusters that have $M_V \leq -5.6$, its application to Pal 5 involves an extrapolation toward fainter magnitudes. Equation (5) then provides an estimate of the cluster’s mass of $M/M_\odot = (6.5 \pm 1.5) \times 10^3$, corresponding to $M/L_V = 0.90 \pm 0.20$. For two reasons this estimate may not appear completely convincing by itself. First, the extrapolation to $M_V < -5.6$ is uncertain. Second, it is not a priori clear that Pal 5 fits into the above mean relation for other globular cluster because its main-sequence luminosity function is known to be flatter than that of other clusters.

Therefore we derived the mass of the cluster also in a more direct way using the luminosity function of the cluster and theoretical stellar masses from a 14 Gyr isochrone by Bergbusch & Vandenbreg (1992). Same as for the calculation of the total luminosity the luminosity function of Grillmair & Smith (2001) was rescaled to the SDSS counts for the entire cluster in the range $19.75 \leq V < 21.75$. We then multiplied in each interval of width 0.5 mag from $V = 14.75$ down to $V = 28.75$ the number of stars with the stellar mass for the mean absolute magnitude of the interval and computed the sum of these masses, i.e., the integral of the mass function. For the faintest three bins from $V = 27.25$ to $V = 28.75$, for which no star counts are available from observation, we assumed that the luminosity function at $V \geq 27$ is constant. This allowed us to extend the integral of the mass function down to $0.17 M_\odot$ and hence to be complete down to the transition from stars to brown dwarfs. The mass contribution from the faintest three bins is of the order of 10%. The total mass of the cluster according to this second approach is $(5.2 \pm 0.7) \times 10^3 M_\odot$, which corresponds to $M/L_V = 0.73 \pm 0.10$. The quoted uncertainty has been estimated by considering the changes that occur when varying the age of the isochrone, the radius of the field encircling the cluster, the transformation between SDSS and standard magnitudes, and the distance modulus of the cluster. The result shows that the extrapolation of the mean mass-luminosity relation in equation (5) down to the absolute magnitude of Pal 5 is principally correct, but that this may still slightly overestimate the mass of the cluster. We conclude that the mass of Pal 5 as revealed by its luminosity is in the range $4.5 \times 10^3 \leq M_{Pal 5}/M_\odot \leq 6.0 \times 10^3$, which corresponds to $0.63 \leq M/L_V \leq 0.83$ for the mass-to-light ratio.

5.3. Implications for the Velocity Dispersion

By putting the empirical mass limits from the end of the previous section into equation (4) we obtain the following result: a King model that fits the stellar surface density of Pal 5 and has the appropriate mass of $4.5 \times 6.0 \times 10^3 M_\odot$ requires an observable line-of-sight velocity dispersion between $\sigma_{los} = 0.32 \text{ km s}^{-1}$ and $\sigma_{los} = 0.37 \text{ km s}^{-1}$. Velocity dispersions at the level of 0.7 km s$^{-1}$ are higher are not in agreement with an appropriate King model because one would need to assume a high mass-to-light ratio of $M/L_V \geq 3$, which, from the results of § 5.2, is unrealistic. For $\sigma_{los} = 0.91 \text{ km s}^{-1}$ equation (4) leads to a predicted equilibrium cluster mass of $3.6 \times 10^4 M_\odot$. This shows that, if one denies the presence of binaries, the resulting velocity dispersion is much too high to be consistent with the mass that is revealed by the cluster’s luminosity. However, when taking the binaries into account, as is done in § 4, the estimates of the line-of-sight velocity dispersion of the cluster decrease in such a way that a consistent equilibrium model with normal $M/L$ is then viable and a velocity dispersion in excess of the equilibrium value is unlikely. More specifically, the line-of-sight velocity dispersion must lie in the upper third of the 68% confidence interval of probable values of $\sigma$ in order to enable an equilibrium model that is in agreement with the surface density profile and the mass of the cluster. Dispersion values near the point of the highest likelihood (i.e., at $\sigma \approx 0.22 \text{ km s}^{-1}$), on the other hand, are too low to be consistent with an equilibrium model of Pal 5, since this would require a very small mass-to-light ratio of $M/L_V \approx 0.3$, which again contradicts the results of § 5.2.

6. SUMMARY AND DISCUSSION

Our study has shown that the radial velocities of the giants in the cluster Pal 5 are tightly concentrated around a mean velocity of $-58.7 \text{ km s}^{-1}$ and have an overall disper-
sion of at most 1.1 km s\(^{-1}\). Only one out of a total of 18 observed giants appears as a kinematic outlier. Statistical arguments suggest that this outlier is also a member of the cluster. Its velocity offset of about 14 km s\(^{-1}\) with respect to the other cluster members leads to the conclusion that it is most likely a binary with an orbital period of a few months. This makes it a very interesting case because the occurrence of a binary with a relatively short period close to the center of Pal 5 would fit with the general idea that such binaries, if not primordial, are formed by stellar encounters in globular cluster cores during the dynamical evolution the cluster (see, e.g., Meylan & Heggie 1997). Such binaries are believed to be an important energy source that supports the evaporation of the cluster. However, the assumption that the above object is such a rapidly orbiting binary still needs to be confirmed.

A peculiar feature in our velocity data is that the few AGB stars in the sample show a significantly higher velocity dispersion than the stars on the RGB. In principle, such a difference could result from the lower mass of the AGB stars. In practice, however, the mass ratio of about 0.5:0.8 between AGB and RGB stars is by far not small enough to explain the observed kinematic differences. The possibility that binarity causes the enhanced velocity dispersion of the AGB stars is also unlikely, because there is no reason to believe that AGB stars should have a much higher frequency of binaries than RGB stars. We thus tend to believe that the enhanced velocity dispersion among the AGB stars is due to so-called atmospheric jitter, i.e., due to pulsations in the extended atmospheres of these evolved stars. This assumption is motivated by the fact that very luminous RGB and AGB stars in other globular clusters and in the field often exhibit photometric and spectroscopic variations due to pulsating atmospheres. A possible caveat, however, is that the stars in our sample do not belong to those most luminous types of giants, since they are more than 1 mag fainter than the tip of the red giant branch. Moreover, the RGB stars in our sample that have the same brightness as the AGB stars show a very small velocity dispersion that leaves no room for any jitter. It will therefore be necessary to check the hypothesis of atmospheric pulsation by collecting further observations of these stars. As long as the nature of the enhanced velocity dispersion of the AGB stars is not clear, one must conclude that these stars are not useful for investigating the dynamics of the cluster.

Without the AGB stars (and the above outlier, of course) the observations yield an overall line-of-sight velocity dispersion of 0.9 km s\(^{-1}\). This value sets a strict upper limit on the dynamical line-of-sight velocity dispersion of the cluster. However, by further analysis of the data we saw that this limit overestimates the dynamical velocity dispersion substantially, because orbital motions of (long-period) binaries have an important influence that cannot be neglected. The fact that the distribution of the binary-induced velocities is different from the Gaussian distribution for an isothermal cluster allowed us to distinguish the two velocity components and to estimate the fraction of binaries \(x_b\) and the dynamical line-of-sight velocity dispersion \(\sigma\). Using Monte Carlo simulations, we constructed synthetic velocity distributions for different types of binary populations, combined them with the Gaussian model of the cluster kinematics, and fitted these composite models to the observed velocity distribution. The results of this procedure suggest that the binaries in our sample have low-mass companions of about 0.2 \(M_\odot\) and orbits of very high eccentricity. Interestingly, a binary population with the orbital characteristics of local field binaries is less in agreement with the observed velocity distribution. This might be an indication of differences between cluster binaries and field binaries, which arise from the special cluster environment and the dynamical evolution in the cluster. On the other hand, the details of the different binary models turned out to be rather unimportant for the determination of the parameters \(x_b\) and \(\sigma\), since all models with a substantial fraction of secondary masses \(\lesssim 0.4 \, M_\odot\) led to similar estimates. We thus arrived at the conclusion that, with 68% confidence, the frequency of binaries in our sample of giants is in the range from 0.24 to 0.63 and that, with the same confidence level, the dynamical velocity dispersion of the cluster lies between 0.12 km s\(^{-1}\) and 0.41 km s\(^{-1}\). The latter means that the dynamical line-of-sight velocity dispersion is by at least a factor of 2 smaller than the overall velocity dispersion and that the contribution from binaries accounts for more than 50% of the overall dispersion.

Are these results credible? The binary frequency of roughly 40% \(\pm 20\%\) is consistent with results from systematic searches for spectroscopic binaries in other Galactic globular clusters. For normal clusters such studies have reported binary frequencies of about 5% to 15% per decade of period or estimates of overall binary frequencies of about 20% to 30% (see the reviews by Meylan & Heggie 1997 and McMillan et al. 1998). Moreover, there is evidence that clusters with low density and/or strong tidal mass loss can have 2 to 3 times higher binary frequencies than normal clusters (see, e.g., Pryor, Schommer, & Olszewski 1991 and Yan & Cohen 1996). If we take \(x_b = 0.24\) from the low end of our 68% confidence interval as a conservative estimate, this corresponds to three binaries in the sample of 13 RGB stars. Assuming that at least one of these binaries, but perhaps two or even all three of them, is responsible for the most deviant velocities in the sample, we can successively omit those three stars that have the highest absolute velocities with respect to the cluster mean and calculate the velocity dispersion of the remaining subsample. Hereby we obtain velocity dispersions of 0.64, 0.51, and 0.32 km s\(^{-1}\) (corrected for measurement errors), respectively. This simple test illustrates that even modest assumptions on the frequency and influence of binaries result in a substantial reduction of the velocity dispersion and easily bring it down to the level of 0.5 km s\(^{-1}\). By successive omission of the three most deviant velocities the velocity distribution also becomes progressively more consistent with an isothermal distribution. The differences between the empirical distribution and the corresponding Gaussian model then have Kolmogorov-Smirnov significance levels of 48%, 15%, and 10%, respectively, while the significance of the differences is 78% for the original sample.

Another interesting question is the following: Does the observed velocity dispersion admit an equilibrium cluster model that is consistent with other fundamental parameters of Pal 5? To investigate this point, we derived the surface density profile and the total luminosity of the cluster from recent photometric data and determined the King model that best fits the density profile. The parameters of the best-fit King profile are \(W_0 = 2.9\), \(r_i = 16.1\)\'. According to its absolute magnitude, which we found to be \(M_V = -4.77 \pm 0.20\), and by extrapolation with a general globular cluster mass-luminosity relation, Pal 5 has a mass in the range \(5 \times 10^3\) to \(8 \times 10^3\) \(M_\odot\), equivalent to a mass-to-light
ratio between 0.7 and 1.1. A direct determination of the mass using the cluster’s luminosity function and theoretical stellar masses along a 14 Gyr isochrone gave a similar result, namely, a total mass between $4.5 \times 10^3$ and $6.0 \times 10^3 M_\odot$. We showed that the best-fitting King model comes into agreement with this mass if the line-of-sight velocity dispersion is between 0.32 and 0.39 km s$^{-1}$. Therefore, a line-of-sight velocity dispersion that lies in the upper third of our 68% confidence interval for $\sigma$ does indeed admit a consistent equilibrium model for Pal 5.

By testing a variety of binary models we saw that the range of probable values of $\sigma$ does not critically depend on the choice of the orbital parameters of the binaries. In order to arrive at probable velocity dispersions that significantly exceed the equilibrium dispersion of the cluster one would thus need to assume that the cluster has only a small fraction of binaries. This case cannot be strictly ruled out, but it appears unlikely and is not supported by the solutions obtained in § 4. Based on the more plausible alternative assumption, that binaries are not rare in Pal 5, we draw the conclusion that, although the cluster has obviously experienced strong tidal perturbation and heavy mass loss, the remaining central body still presents a bound stellar system that is close to a state of dynamical quasi equilibrium.

This conclusion is in agreement with results that we recently obtained by simulating the dynamics of Pal 5 in the tidal field of the Milky Way with an $N$-body code (Dehnen et al. 2002). These simulations suggest that only shortly after a tidal shock from a disk crossing the velocity dispersion in the cluster rises above the equilibrium dispersion, whereas in other phases of the orbit the dispersion is settled down at the equilibrium level. Moreover, the numerical models confirm that, at the cluster’s present location near the apogalacticon of the orbit, the line-of-sight velocity distribution should be nearly Gaussian. The observed departure from a Gaussian distribution must therefore indeed be due to binaries, as we assumed above.

The resulting very low dynamical velocity dispersion inside the cluster suggests that the velocities of the extratidal stars may locally also be very coherent. The narrow spatial confinement of the tidal tails, which is one of the reasons that led to their detection, is probably to some extent due to this kinematical coherence. We are currently conducting a similar kinematic study using the same instrumental equipment to investigate the velocities in the tidal tails of the cluster. Hereby we aim at measuring the velocity dispersion among the extratidal stars and the radial velocity gradient along the tails and hence along the orbit of the cluster.

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