IS THE DISTANT GLOBULAR CLUSTER Pal 14 IN A DEEP FREEZE?

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ABSTRACT

We investigate the velocity dispersion of Pal 14, an outer Milky Way globular cluster at a Galactocentric distance of 71 kpc with a very low stellar density (central density 0.1–0.2 $M_\odot$ pc$^{-3}$). Due to this low stellar density the binary population of Pal 14 is likely to be close to the primordial binary population. Artificial clusters are generated with the observed properties of Pal 14, and the velocity dispersion within these clusters is measured as Jordi et al. have done with 17 observed stars of Pal 14. We discuss the effect of the binary population on these measurements and find that the small velocity dispersion of 0.38 km s$^{-1}$, which has been found by Jordi et al., would imply a binary fraction of less than 0.1, even though from the stellar density of Pal 14 we would expect a binary fraction of more than 0.5. We also discuss the effect of mass segregation on the velocity dispersion as a possible explanation for this discrepancy, but find that it would increase the velocity dispersion further. Thus, either Pal 14 has a very unusual stellar population and its birth process was significantly different than we see in today’s star-forming regions, or the binary population is regular and we would have to correct the observed 0.38 km s$^{-1}$ for binarity. In this case, the true velocity dispersion of Pal 14 would be much smaller than this value and the cluster would have to be considered as “kinematically frigid,” thereby possibly posing a challenge for Newtonian dynamics but in the opposite sense to modified Newtonian dynamics.

Key words: binaries: general – globular clusters: general – globular clusters: individual (Palomar 14)

Online-only material: color figures

1. INTRODUCTION

Stellar populations with densities less than about 10$^2$ stars pc$^{-3}$ have a binary fraction,

$$f_{\text{bin}} = \frac{N_{\text{bin}}}{N_{\text{bin}} + N_{\text{sing}}},$$

of at least 50%. For example, in the solar neighborhood (density 1 star pc$^{-3}$) $f_{\text{bin}} \approx 0.6$ (Duquennoy & Mayor 1991), or in OB associations (density $<0.1$ star pc$^{-3}$) $f_{\text{bin}} > 0.7$ (Kouwenhoven et al. 2007). In star-forming regions the binary fractions can be even higher, such as in the Taurus-Auriga groups (density about 10 stars pc$^{-3}$) where the fraction is near 100% (e.g., Kroupa & Bouvier 2003). But even in high-density star-forming regions, such as the 1 Myr old Orion Nebula cluster which has a density of 10$^4$ stars pc$^{-3}$ (Hillenbrand & Hartmann 1998), the binary fraction is near 50% (Kohler et al. 2006). Stellar-dynamical models have demonstrated that the Orion Nebula cluster must be expanding and that consequently further destruction of binary systems has mostly ceased (Kroupa et al. 2001). Only in globular clusters, which are dense ($>10^5$ stars pc$^{-3}$) and which have a long dynamical history over a Hubble time, are binary fractions observed to be less than 10%–20% (Hut et al. 1992). But this is probably understandable as a result of the destruction of binary systems, first in the very dense initial configuration which these objects typically formed with (Marks et al. 2008; Marks & Kroupa 2010), followed by long-term binary-star burning.

Pal 14 was discovered by Sidney van den Bergh in 1958 as a faint smudge on the Palomar Sky Survey prints (Arp & van den Bergh 1960). It is an old globular cluster with a mass of about 10$^6$ $M_\odot$, a (three-dimensional) half-light radius of 34 pc, and is located at a distance of 71 kpc from the Galactic center (Hilker 2006; Jordi et al. 2009). It has a low density (0.1–0.2 stars pc$^{-3}$) and so conformity with known stellar populations would imply it to have $f_{\text{bin}} \approx 0.5$. Measurements of $f_{\text{bin}}$ would thus allow testing the dependence of the binary population on the physical conditions during star formation, as Pal 14 is a low-metallicity population that formed nearly a Hubble time ago (Jordi et al. 2009). Furthermore, Jordi et al. (2009) suggest that Pal 14 may be significantly mass segregated. How mass segregation can affect a velocity dispersion measurement has not been investigated though.

However, Pal 14 is also interesting for testing gravitational theories. The fact that binaries can affect the dynamical mass estimate of stellar populations has already been studied in the context of dwarf-spheroidal satellite galaxies by Hargreaves et al. (1996) and has recently been re-addressed by Kouwenhoven & de Grijs (2008) and Gieles et al. (2010) for star clusters in the Milky Way disk. The measured (one-dimensional) velocity dispersion of Pal 14 is (0.64 ± 0.15) km s$^{-1}$ or (0.38 ± 0.12) km s$^{-1}$ depending on whether the outlying “star 15” of a sample investigated by Jordi et al. (2009) is included or not, respectively. Now, if Pal 14 has a binary fraction of 50% or more, then the velocity dispersion measured from a single spectroscopic snapshot may be significantly contaminated, i.e., inflated, because of the binary-star orbital motions of the tracer stars. A potential problem arising here is that the dynamical velocity dispersion of the cluster must be about 0.5 km s$^{-1}$ for Newtonian dynamics to hold. So there is not much room for a binary-star contribution to the measured velocity dispersion. Alternatively, if the binary population is normal (i.e., canonical), then the true (binary corrected) velocity dispersion of the virialized cluster may be much smaller than the Newtonian value. If this were the case, then a Newtonian crisis would emerge, such that Pal 14 would be “kinematically frigid,” a situation which is not expected from current theoretical dynamics. A third
possibility is given by the unreliability of low-number statistics in such systems, i.e., a sample of about 17 stars may simply be insufficient to determine the velocity dispersion of such a stellar system.

Thus, either Pal 14 is in virial equilibrium, such that its stellar population would be non-canonical (a binary fraction much lower than all other known populations) or the cluster has a canonical stellar population, but is then kinematically frigid, in violation of Newtonian dynamics. This would not be remedied by modified Newtonian dynamics (MOND), because according to MOND the cluster ought to have an even larger velocity dispersion than the Newtonian value (Baumgardt et al. 2005).

The third explanation, of low-number statistics, would imply that velocity dispersion measurements of low-velocity stellar systems would have to be taken with much more caution than is done in practice nowadays.

With this contribution, we assess the expected velocity dispersion of Pal 14 assuming various binary fractions and Newtonian dynamics to be valid (Section 2). These numerical experiments are compared to the observed velocities in the cluster in Section 3. The conclusions are contained in Section 4.

2. VELOCITY DISPERSIONS

For the purpose of testing the observed velocity dispersion of Pal 14, we create artificial star clusters with the observed properties of Pal 14 and measure the velocity dispersion in these clusters. Therefore, we use the code MCCLUSTER3 (A. H. W. Küpper et al. 2010, in preparation), an open-source project developed at AlFA Bonn to set up clusters for N-body computations, especially for NaoPy6 (Aarseth 2003). We use this software to conveniently generate 300 renditions of Pal 14 with various properties for taking out mock observations and testing the findings of Jordi et al. (2009) on their conclusiveness.

We take the parameters for the artificial clusters from Jordi et al. (2009) and Hilker (2006). The most important quantity in this respect is the total mass of the cluster and its velocity dispersion in the assumed case of the cluster being in virial equilibrium. Using star counts, Jordi et al. (2009) find a mass for Pal 14 between 6000 and 12,000 $M_\odot$ without taking into account compact remnants, and depending on the assumed mass function within the cluster. Assuming additional 15%–20% mass in stellar remnants (Dabringhausen et al. 2009; J. Dabringhausen 2010, private communication) yields a mass range for Pal 14 of 7000–14,000 $M_\odot$. We therefore concentrate on the two cases of 7000 $M_\odot$ and 14,000 $M_\odot$, respectively.

As the density distribution we choose a Plummer sphere with a (three-dimensional) half-mass radius of 32 pc, which corresponds to the observed half-light radius of Pal 14 of 1.28 (Hilker 2006) at the assumed distance of (71 ± 1.3) kpc (Jordi et al. 2009). Setting the half-light radius equal to the half-mass radius assumes that mass follows light, just as Jordi et al. (2009) have done in their investigation, i.e., that the cluster is not significantly mass segregated. Moreover, the infinite Plummer distribution is cut off at the Jacobi radius (≈128/156 pc for 7000/14,000 $M_\odot$) assuming a Galactic circular velocity of 220 km s$^{-1}$ at the Galactocentric radius of Pal 14.

As the mass function of the cluster stars we use the canonical initial mass function (IMF; Kroupa 2001), but cut it off at a maximum stellar mass of 1.0 $M_\odot$ as all stars above this mass should have died by stellar evolution at the expected age of Pal 14 of 11.5 Gyr (Jordi et al. 2009). Even though Jordi et al. (2009) find a shallower slope in the range of 0.5–0.8 $M_\odot$, we argue that the actual slope of the mass function is not very important in this respect as the velocities of the cluster stars get drawn independently of each other and we, in the end, only observe stars of mass above 0.7 $M_\odot$ to be consistent with Jordi et al. (2009).

For investigating the effect of a realistic binary population on the velocity dispersion, we set up the binary population following the Duquennoy & Mayor (1991) period distribution for field stars and a thermal eccentricity distribution. The binary orbital planes are distributed randomly, as are the orbital phases. We reject binaries with a semi-major axis below 100 $R_\odot$ though, as these binaries may have been destroyed in a common-envelope phase of the binary components (M. Zorotovic & M. R. Schreiber 2010, in preparation). Moreover, we use random pairing for the binary components since we are dealing with an evolved population of low-mass stars. We vary the binary fraction, $f_{\text{bin}}$, from 0 to 1 and generate 10 clusters for each binary fraction to gain better statistics.

In addition, we set up clusters with the above properties but being mass segregated. Therefore, we use the procedure defined in Šubr et al. (2008) which is implemented through PLUMIX in MCCLUSTER. Šubr et al. (2008) define the degree of mass segregation through a single parameter, $S$, which can vary from 0 (not segregated) to 1 (completely mass segregated). To keep the number of models to a minimum, we concentrate on the cluster with 7000 $M_\odot$ without binaries, and see how mass segregation affects its velocity dispersion. Again we generate 10 clusters for each value of $S$.

We measure the line-of-sight (LOS) velocity dispersion, $\sigma$, from our clusters by calculating
\[
\sigma = \sqrt{\bar{v}^2 - \bar{v}^2},
\]
where $\bar{v}$ is the mean velocity in the sample, and $\bar{v}^2$ is the mean squared velocity. We do this separately in three different directions and take each as an independent measurement.

In Figure 1, we show the mean velocity dispersions for all stars above 0.7 $M_\odot$ for 10 different binary fractions and for both cluster masses. The error bars give the standard deviation of the different cluster renditions from the mean. The clusters without binaries have a very little spread about the mean whereas a binary fraction of 0.1 already introduces such a large scatter that the two mass groups of clusters overlap within their error bars. At a binary fraction of 0.5 the two mass groups are indistinguishable as their velocity dispersion gets completely dominated by the binary population. At a binary fraction of 1.0 the velocity dispersion is about 4 times larger than in the case without binaries.

In Figure 2, we show the velocity dispersion when we draw 17 stars out of the total sample of stars above 0.7 $M_\odot$, just as Jordi et al. (2009) have done. The data points show the mean of 3,000,000 renditions out of the 10 clusters for each binary fraction. Again we took the LOS velocity dispersions independently along three different directions for each rendition. Since the final distribution of velocity dispersions for each binary fraction does not follow a Gaussian distribution but is rather asymmetric, the error bars show 68% of all renditions below the mean and 68% of all renditions above the mean.

We rejected stars, though, when their velocities were off the mean by more than 2.5 km s$^{-1}$, i.e., we only took into account stars within a velocity window of $\Delta v = 5$ km s$^{-1}$. This is similar
Figure 1. Mean velocity dispersions of the cluster renditions with 7000 $M_\odot$ and 14,000 $M_\odot$ as determined from all stars above 0.7 $M_\odot$ for 10 different binary fractions, $f_{\text{bin}}$. The error bars give the standard deviation from the mean. The velocity dispersion can increase by a factor of 5 for large binary fractions, compared to the binary free case. Above $f_{\text{bin}} = 0.5$ the binaries dominate the velocity dispersion such that the two cluster groups are indistinguishable. Also shown are the measured results from Jordi et al. (2009) with and without taking into account star 15 (see the text). Their velocity dispersion measurements allow a binary fraction of less than 0.1, or 0.2 taking into account star 15, respectively. (A color version of this figure is available in the online journal.)

Figure 2. Same as Figure 1 but additionally the velocity dispersions are shown which are derived from sub-sets of 17 stars above 0.7 $M_\odot$. For this measurement, all stars lying outside a velocity interval about the mean value of $\Delta v = 5$ km s$^{-1}$ were rejected. The data points show the mean of 3,000,000 renditions, and the error bars show the values in which 68% of all renditions lie. The results of Jordi et al. (2009) allow a binary fraction of less than about 0.1, or 0.3 taking into account star 15, respectively. (A color version of this figure is available in the online journal.)

Moreover, the scatter in our velocity dispersion measurement is huge. At $f_{\text{bin}} = 0.5$, we can measure values between 1 km s$^{-1}$ and 3 km s$^{-1}$, depending on which stars we take into our sample. At a binary fraction of 1.0 the mean measured velocity dispersion is about 7 times larger than the Newtonian velocity dispersion without binaries.

In Figure 3, we show the same experiment but with a velocity window of $\Delta v = 10$ km s$^{-1}$. The effect described above gets more significant. The mean value of the measured velocity dispersion increases and also the scatter grows. At $f_{\text{bin}} = 0.5$, we can get values between 1 km s$^{-1}$ and 4 km s$^{-1}$. At a binary fraction of 1.0, the measurements of a small sub-sample and the measurements of all stars barely agree within the error bars. More. Note that the mean value can be as large as 10 times the true Newtonian velocity dispersion without binaries. Moreover, by comparing Figure 2 to Figure 3 we see that the measured velocity dispersion strongly depends on the velocity window which we allow. We tend to increasingly overestimate the true velocity dispersion by increasing the size of the allowed velocity window.

In Figure 4, the velocity dispersion measurements are shown for the mass segregated clusters. The plot shows the velocity dispersion measurements for a cluster of 7000 $M_\odot$ without binaries, as shown in Figures 1–3 but for a mass segregation degree, $S$, varying from 0 to 0.95. From the figure, we see that mass segregation increases the velocity dispersion further. The segregated cluster ($S = 0.95$) has a 20% higher velocity dispersion than the unsegregated case ($S = 0$). This is due to the fact that through mass segregation the heaviest stars (which we observe for the velocity dispersion) move to the cluster center, and that stars on average move at higher velocities when they are in the cluster center. When a sample of observed stars was concentrated on the center of the cluster and was not well distributed over the cluster, we would get the same effect.
Figure 4. Mean velocity dispersions of the cluster renditions with 7000 $M_\odot$ as determined from all stars above 0.7 $M_\odot$ (as in Figure 1), as well as derived from sub-sets of 17 stars above 0.7 $M_\odot$ in a velocity interval of $\Delta v = 5$ km s$^{-1}$ (Figure 2) and $\Delta v = 10$ km s$^{-1}$ (Figure 3), respectively, but here for 10 different degrees of mass segregation, S, as defined by Subr et al. (2008). For increasing mass segregation, the velocity dispersion rises as heavy stars are preferentially located in the cluster center and hence move at a higher velocity on average, thus mass segregation cannot explain the low velocity dispersion measurement of Jordi et al. (2009).

(A color version of this figure is available in the online journal.)

3. DISCUSSION

Jordi et al. (2009) have determined the velocity dispersion of Pal 14 according to Pichon & Meylan (1993), i.e., they have made a maximum-likelihood estimation, which is, of course, necessary because unlike in our samples the measurement errors of their radial velocities are all different. From their sample of 17 stars they find one star (star 15) to lie 3σ off the mean value, and thus split their investigation into two parts: one with taking star 15 into account and the other without taking star 15 into account. For the sample with star 15, they find a velocity dispersion of (0.64 ± 0.15) km s$^{-1}$, and without star 15 they find (0.38 ± 0.12) km s$^{-1}$.

Based on a Kolmogorov–Smirnov test, Jordi et al. (2009) argue that star 15 is most likely not a regular member of Pal 14, i.e., a foreground contamination or part of a long-period binary system. Thus, at the bottom line they favor the lower value of 0.38 km s$^{-1}$.

From Figure 1, we see that such a low velocity dispersion would imply that the binary fraction of Pal 14 was less than 0.1. Taking star 15 into account the velocity dispersion of Pal 14 would imply a binary fraction of less than 0.2.

In Figure 2, the velocity dispersion derived from a sub-sample of 17 stars within a velocity interval of $\Delta v = 5$ km s$^{-1}$ shows that the lower value of 0.38 km s$^{-1}$ would be consistent within the error bars with values less than $f_{bin} = 0.2$, while the higher value of 0.64 km s$^{-1}$ would be consistent with values less than $f_{bin} = 0.4$. Allowing for $\Delta v = 10$ km s$^{-1}$ reduces the latter to $f_{bin}$ less than 0.3 (Figure 3).

From Figure 4, we see that mass segregation does not help in understanding the low observational value of Pal 14’s velocity dispersion, since mass segregation tends to increase the observed velocity dispersion of a cluster by up to 20% compared to the unsegregated case. In contrast, since Pal 14 is supposed to be mass segregated (Jordi et al. 2009), its velocity dispersion may be even inflated. Our previous estimates on Pal 14’s binary fraction therefore have to be taken as upper limits.

4. CONCLUSIONS

From our test of the observed velocity dispersion of the Milky Way globular cluster Pal 14, we have seen that the binary fraction within Pal 14 has to be less than 0.2 in the case of star 15 not being considered a member, in order to be consistent with a velocity dispersion as low as (0.38 ± 0.12) km s$^{-1}$. Taking star 15 into account the maximum binary fraction consistent with the observational uncertainties is about 0.4. This poses a number of questions on the nature of Pal 14.

As a first explanation of these findings we may assume that the binary fraction within Pal 14 is indeed as low as found. But, as stated above, the density within Pal 14 is as low as 0.1–0.2 stars pc$^{-3}$. The effect of disruption of binaries due to dynamical stellar evolution within its age of about 11.5 Gyr is therefore negligible, and we even may see here the primordial binary population of a globular cluster (Hasani Zonoozi et al. 2010). Thus, the formation of Pal 14 must have been significantly different from what is observed in all other star-forming sites today, or Pal 14 must have undergone a very dense and violent phase in which most of the binaries were burned. But as we can see in the Orion Nebula Cluster today, this is very unlikely to happen for a sufficiently long time span that the binary fraction drops below 0.5. Furthermore, such a scenario would give rise to the question how Pal 14 could have expanded that much, as with a half-light radius of about 34 pc it is one of the most expanded globular clusters of the Milky Way today. Recent numerical studies moreover show that this expansion is very unlikely to be of pure dynamical origin, since expansion takes place on a relaxation timescale, and the relaxation time of Pal 14 is of the order of a Hubble time (Hasani Zonoozi et al. 2010).

A second option would be that the binary population is normal, i.e., above 0.5, and thus the observed velocity dispersion has to be corrected for the effect of binaries. As we have seen, this can be as much as a factor of 10 in the case of 17 stars drawn from a cluster with a binary fraction of 1.0. Since the lower mass limit of Pal 14 is determined to be about 7000 $M_\odot$ (Jordi et al. 2009) this would imply that the true velocity dispersion of Pal 14 is much lower than the Newtonian prediction, i.e., Pal 14 is “kinematically frigid.” This would be inconsistent with our understanding of Newtonian gravity and could neither be explained by considering MOND to be valid in Pal 14.

Moreover, we found that mass segregation increases the observed velocity dispersion of a cluster even further, and thus cannot explain the low velocity dispersion of Pal 14. The observed, flattened mass function of Pal 14 on the other hand suggests that Pal 14 is significantly mass segregated (Jordi et al. 2009). Thus, its unsegregated, i.e., for the effect of mass segregation corrected, velocity dispersion may be even lower than the values reported by Jordi et al. (2009), which would worsen the problem.

Thus, the present state of knowledge on Pal 14 is that either its binary fraction is highly abnormal, given its low density, or that it is significantly sub-virial. The former possibility would imply a non-standard star formation event which formed Pal 14, while the latter indicates a problem understanding the dynamics of Pal 14.

In any case, this investigation has shown that one has to be cautious with low velocity dispersions derived from small samples of cluster stars. The observed value from such a
sub-sample tends to be significantly larger than the true velocity dispersion. This effect gets larger with increasing size of the allowed velocity window about the mean radial velocity. This could be especially important in the outer parts of star clusters (e.g., Scarpa et al. 2007), as was also recently shown by Küpper et al. (2010).

More LOS velocity measurements, e.g., as a second epoch spectroscopic snapshot, may help to reduce the statistical uncertainties and improve the significance of findings on whether or not Newtonian dynamics is valid in Pal 14 (see also Gentile et al. 2010).

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