A&A 462, L9–L12 (2007)
DOI: 10.1051/0004-6361:20066182


Astronomy & Astrophysics

LETTER TO THE EDITOR

# Using globular clusters to test gravity in the weak acceleration regime: NGC 7099⋆,⋆⋆

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Received 4 August 2006 / Accepted 23 October 2006

**ABSTRACT**

*Aims.* A test of Newton's law of gravity in the low acceleration regime using globular clusters is presented and new results for the core collapsed globular cluster NGC 7099 given.

*Methods.* The run of the gravitational potential as a function of distance is probed by studying the velocity dispersion profile of the cluster, as derived from a set of 125 radial velocities with accuracy better than 1 km s$^{-1}$. The velocity dispersion profile is traced up to ∼18 pc from the cluster center.

*Results.* The dispersion is found to be maximal at the center, then decrease until 10 ± 2 pc from the center, well inside the cluster tidal radius of 42 pc. After that the dispersion remains basically constant with an average value of 2.2 ± 0.3 km s$^{-1}$. Assuming a total $V$ mag of $M(V) = -7.43$ mag for NGC 7099, the acceleration at 10 ± 2 pc from the center is $1.1^{+0.4}_{-0.3}\tau \times 10^{-8}$ cm s$^{-2}$, where $\tau$ is the mass-to-light ratio. Thus, for $\tau \lesssim 2$ typical of globular clusters, the flattening of the velocity dispersion profile occurs for a value of the internal acceleration of gravity that is fully consistent with $a_0 = 1.2 \times 10^{-8}$ cm s$^{-2}$ observed in galaxies.

*Conclusions.* This new result for NGC 7099 brings to 4 the clusters with velocity dispersion profile probing acceleration below $a_0$. All four have been found to have a flat dispersion profile at large radii where the acceleration is below $a_0$, thereby mimicking elliptical galaxies qualitatively and quantitatively. Whether this indicates a failure of Newtonian dynamics in the low acceleration limit or some more conventional dynamical effect (e.g., tidal heating) is still unclear. However, the similarities emerging between very different globular clusters, as well as between globular clusters and elliptical galaxies, seem to favor the first of these two possibilities.

**Key words.** gravitation – globular clusters: general – globular clusters: individual: NGC 7099

## 1. Introduction

The gravitational accelerations governing the dynamics of cosmic structures are typically orders of magnitude smaller than the one probed in our laboratories or in the solar system. Thus, any time Newton's law is applied to galaxies (e.g., to infer the existence of dark matter), its validity is severely extrapolated. Although there should be no reason to distrust Newton's law in the weak acceleration regime, unanimous agreement has been reached (e.g., Binney 2004) on the fact that galaxies start deviating from Newtonian dynamics, and dark matter is needed to reconcile observations with predictions, *always* for the same value of the gravitational acceleration $a_0 \sim 1.2 \times 10^{-8}$ cm s$^{-2}$ (Begeman et al. 1991), as computed considering only baryons. This systematics, more than anything else, suggests that we may be facing a breakdown of Newton's law rather than the effects of dark matter.

If for a moment we assume that Newtonian dynamics breaks down in the low acceleration limit and non-baryonic dark matter does not exist, then the behavior of galaxies in the low acceleration limit should be typical of many other systems, as long as the acceleration is the same. According to this idea we looked at globular clusters, the largest virialized structure believed not to contain dark matter. Being free falling toward the Milky Way, globular clusters are only affected by tidal stress, which is in most cases well below $a_0$. Therefore the internal dynamic of globular clusters do probe the same range of accelerations probed by galaxies, making them ideal for testing gravity in the low acceleration regime without the complication of dark matter.

In previous papers we studied the dynamical properties of $\omega$ Centauri (Scarpa et al. 2003), M 15, and NGC 6171 (Scarpa et al. 2004a,b), where it was shown that the velocity dispersion remains constant at large radii as soon as the acceleration reaches $a_0$, as is the case for elliptical galaxies (e.g., Mehlert et al. 2000) – a puzzling and potentially important result. To further generalize it, we present here new results for NGC 7099, a compact cluster located at 8.0 kpc from the sun and 7.1 kpc from the Galactic center (Harris 1996).

## 2. Observation and data analysis

The initial selection of targets was based on color, as derived from the analysis of ESO Imaging Survey (EIS) frames. After

⋆ Based on observations collected at the European Southern Observatory, Chile (ESO Nos. 71.D-0311 and 075.D-0043).

⋆⋆ The radial velocities used in this work are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/462/L9

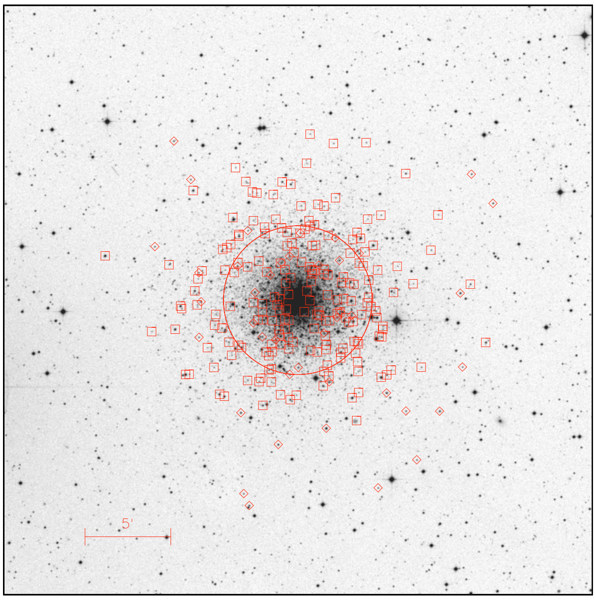


**Fig. 1.** The cluster NGC 7099 as seen in the digital sky survey with overplotted the location of the 234 stars for which a radial velocity with error smaller than 5 km s$^{-1}$ was derived. Squares mark cluster members, while diamonds are non-members. The cluster center was set to $21^{\rm h}40^{\rm m}22^{\rm s}$ $-23°10'45''$ (Harris 1996). North is up and east to the left. The circle has 10 pc radius.

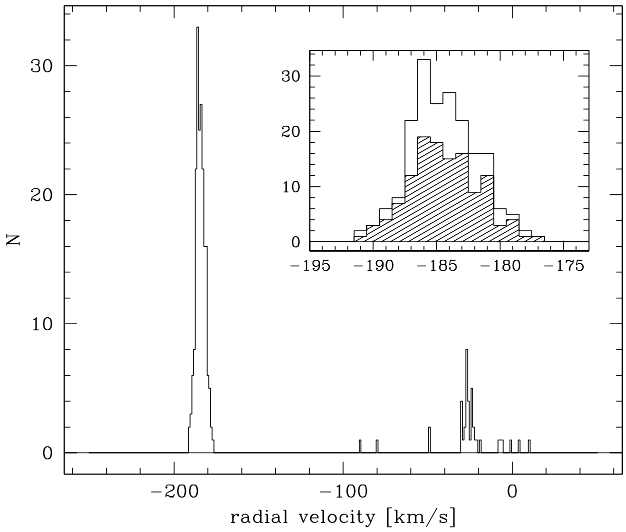


**Fig. 2.** Distribution of the 234 radial velocities with error smaller than 5 km s$^{-1}$. The position of the cluster members is evident at $v \sim -185$ km s$^{-1}$. The inset shows the distribution of the 194 cluster members. The shaded area corresponds to the 125 stars with errors on the radial velocity smaller than 1 km s$^{-1}$. These were used in Figs. 3 and 4 to derive the velocity dispersion.

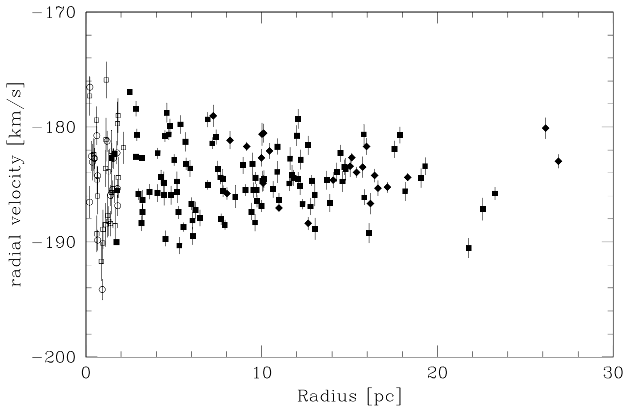


**Fig. 3.** The distribution of the 125 radial velocities with error smaller than 1 km s$^{-1}$. Objects observed during period 71 (solid diamonds) and period 75 (solid squares) are shown with different symbols. Data from Zaggia et al. (1992; open circle) and Gebhardt et al. (1995; open squares) covering the central region of the cluster are also shown.

identifying the giant branch and main sequence of the cluster in the H-R diagram, we prepared a catalog of about 300 targets, mostly in the sub-giant branch and turn off, and apparent $V$ magnitude $16 < V < 19$. Observations were then obtained with FLAMES (Pasquini et al. 2002) at the ESO VLT telescope. FLAMES is a fiber multi-objects spectrograph, allowing the simultaneous observation of up to 130 objects. We selected the HR9B setup that includes the magnesium triplet covering the wavelength range $5143 < \lambda < 5346$ Å at resolution $R = 25\,900$. Stellar astrometry was derived by cross correlating the stellar positions on the EIS frame with coordinates from the US Naval Observatory (USNO) catalog, which proved to have the required accuracy (0.3 arcsec) for FLAMES observations. Three different fiber configurations were used in order to cover the external region of the cluster as much as possible (Fig. 1). For each configuration, three 2700 s exposures were obtained under good atmospheric conditions (clear sky and seeing ~1 arcsec). The first set of images was obtained during period 71 on December 5, 2003, and the other two during period 75 on August 29 and 30, 2005.

Data reduction was performed within IRAF, using standard reduction procedures. After extraction and wavelength calibration, all spectra were cross correlated with respect to the target with the best spectrum. The three configurations shared a small number of stars, to evaluate and eliminate possible offsets in the velocity zero point. A posteriori, we verified that no correction was necessary down to a level of accuracy of 300 m s$^{-1}$, well below the accuracy required for our study. Finally, keeping in mind that we are only interested in the velocity dispersion, the global velocity zero point was simply derived by identifying a few lines in the spectrum of the template. In total, 234 radial velocities (all velocities presented here are heliocentric) with accuracy better than 5 km s$^{-1}$ were obtained.

Final membership was assigned according to the observed radial velocity. In total 194 members were identified without ambiguity in the velocity space (Fig. 2) at a radial velocity of ~−185 km s$^{-1}$, that is fully consistent with the quoted velocity for this cluster of $-185.9 \pm 0.6$ km s$^{-1}$ (Gebhardt et al. 1995). All cluster members have error on the radial velocity smaller than 2.5 km s$^{-1}$, with 125 members having error smaller than 1 km s$^{-1}$. The larger errors, up to 5 km s$^{-1}$, refer to field stars that have a significantly different spectral energy distribution from the one of the template, degrading the accuracy of the cross correlation.

Finally, in NGC 7099 we found no evidence of ordered rotation to the level of 0.75 km s$^{-1}$.

## 3. Velocity dispersion profile of NGC 7099

Our cluster member velocity measurements have uncertainties between 0.5 and 2.5 km s$^{-1}$. Thus, to avoid artificially inflating the dispersion we are trying to measure, we computed the dispersion profile for subsets of our data, each one with increasing maximum error. Statistically indistinguishable dispersion

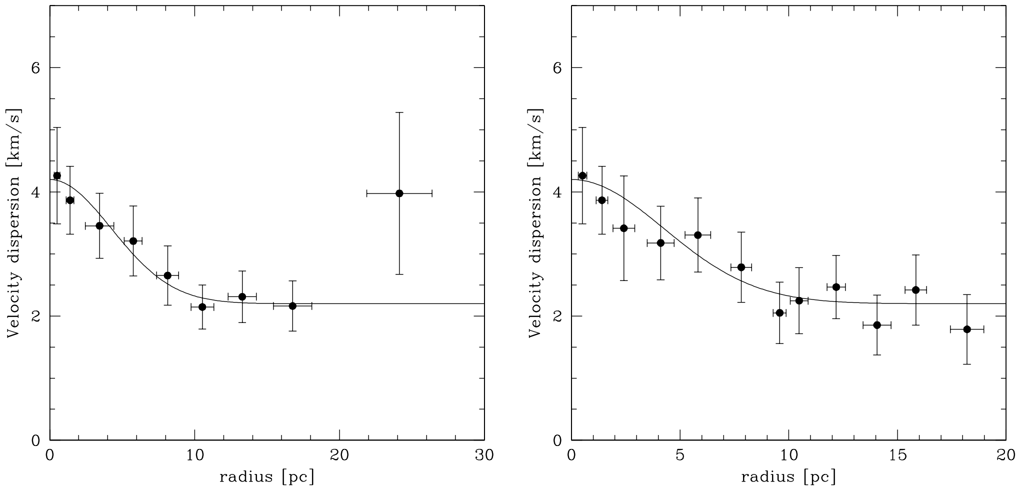


**Fig. 4.** *Left*: the radial velocity dispersion profile as derived from the 125 radial velocities with error smaller than 1 km s$^{-1}$, plus 16 velocities from Zaggia et al. (1992) and 27 from Gebhardt et al. (1995). Data from the literature contributes only to the two innermost points. The abscissa of each point is the average of the points in the bin. Error bars in the $x$ direction show the $1\sigma$ dispersion of the data in the bin, while error bars in the $y$ direction represent the $1\sigma$ uncertainty on the dispersion. The solid line (a Gaussian plus a constant) is not a fit to the data but is meant only as a guide for the eye. *Right*: enlargement of the previous figure showing the profile with different binning.

**Table 1.** Radial velocity dispersion of NGC 7099.

| Bin limits (pc) | Stars/bin | Bin center (pc) | $\sigma$ (km s$^{-1}$) |
|---|---|---|---|
| 0–0.9 | 16 | 0.51 | 4.26 ± 0.78 |
| 0.9–1.8 | 27 | 1.45 | 3.87 ± 0.55 |
| 1.8–4.8 | 24 | 3.44 | 3.45 ± 0.52 |
| 4.8–7.0 | 18 | 5.76 | 3.21 ± 0.56 |
| 7.0–9.5 | 18 | 8.14 | 2.65 ± 0.48 |
| 9.5–12 | 23 | 10.53 | 2.15 ± 0.35 |
| 12–15 | 19 | 13.29 | 2.31 ± 0.41 |
| 15–20 | 18 | 16.76 | 2.16 ± 0.40 |
| >20 | 5 | 24.13 | 3.97 ± 1.30 |

profiles were found, with the higher accuracy on the velocity balanced by the smaller size of the sample. Here we present the dispersion profile as derived from the 125 members with accuracy on the radial velocity better than 1 km s$^{-1}$. These stars are distributed over $2 < r < 27$ pc from the cluster center. To cover the very central region of the cluster we included two data sets from the literature. The first refers to 16 stars within 50 arcsec from the center (Zaggia et al. 1992). These velocities, which have average error of about 0.9 km s$^{-1}$, have been shifted by 2.5 km s$^{-1}$ to match our average radial velocity. The second data set is from a sample of 132 velocities (Gebhardt et al. 1995), from which we selected the 27 velocities with errors smaller than 2 km s$^{-1}$. The data cover the central 1 arcmin and have been shifted by 1.5 km s$^{-1}$ to match our data. The larger error associated with these data is not a problem because, at the center, the dispersion is significantly larger than this. As a whole the data from the literature smoothly match our data in the region of overlap (Fig. 3), allowing us to build a well-sampled velocity dispersion profile from the center to almost 20 pc (Table 1). Beyond that we found only 5 cluster members, providing little or no information at all on the velocity dispersion at these distances (Fig. 4).

Looking at Figs. 3 and 4, we see no indication of the expected Keplerian fall off of the velocity dispersion at large radii, but rather, the dispersion seems to remain noticeably constant if not increasing toward the very end of the probed region. Excluding the very last point in Fig. 4, that due to the huge associated uncertainty is consistent with any conceivable model, we conclude that the dispersion converges beyond $r = 10 \pm 2$ pc toward the asymptotic values of $2.2 \pm 0.3$ km s$^{-1}$. Note that the flattening occurs well inside the cluster tidal radius of 42 pc (Harris 1996).

## 4. Discussion

Within errors the velocity dispersion profile of NGC 7099 is flat for $r > 10 \pm 2$ pc. Assuming a total absolute magnitude of $M_V = -7.43$ (Harris 1996), the mass of NGC 7099 is $7.8\tau \times 10^4\ M_\odot$, where $\tau$ is the mass-to-light ratio. A simple look at Fig. 1 shows that virtually all the mass of the cluster is contained well within 10 pc. Thus, whatever the mass distribution in NGC 7099 might be, the internal acceleration of gravity at this radius is $a = GM/r^2 = 1.1^{+0.4}_{-0.3}\tau \times 10^{-8}$ cm s$^{-2}$. Theoretical considerations and direct estimates of the mass to light ratio in globular clusters indicate $\tau \lesssim 2$ (e.g., McLaughlin & van der Marel 2005). The flattening therefore occurs at an acceleration that is in reasonable agreement with what is observed in galaxies. It is indeed remarkable that given a bit of information from galaxies rotation curves, $a_0$, one can predict within a factor 2 the flattening of the dispersion profile in a globular cluster, a structure 3 order of magnitude smaller and 6 order of magnitude less massive than a typical galaxy.

As a whole, the new data for NGC 7099 brings to four the number of globular clusters for which the dispersion profile is seen to flatten out below $a_0$. Specifically, in all four cases the velocity dispersion is maximal at the center, then rapidly declines to converge toward a constant value at large radii where $a < a_0$, instead of decreasing according to a Keplerian falloff. These four clusters have different physical properties (mass and size), as well as different dynamical and evolutionary histories, nevertheless they behave exactly in the same way, also quantitatively and qualitatively mimicking the behavior of high surface brightness elliptical galaxies e.g., Mehlert et al. 2000).

It might be argued that these 4 clusters are all at comparable galactocentric distances and therefore are at present experiencing similar tidal stresses and external fields. This might be why they behave similarly. However, the dynamical history is different, and comparable tidal stresses are deemed to produce very different effects on clusters of different size and mass, thus a non negligible amount of fine tuning is necessary to explain our observations.

The alternative, which is what we are trying to test, is that the flattening might be due to a breakdown of Newtonian dynamics. It is well known that the flattening of the dispersion profile and/or the rotation curve occurs at $a_0$ in galaxies. This is at the base of a particular modification of Newtonian Dynamics known as MOND (Milgrom 1983), capable of successfully fitting the properties of a large number of stellar systems without invoking the existence of non-baryonic dark matter (McGaugh & de Block 1998; Sanders & McGaugh 2002; Milgrom & Sanders 2003; Scarpa 2006). According to MOND, however, the velocity dispersion in NGC 7099 should remain constant as soon as the total, i.e. internal plus external, acceleration of gravity is $a \lesssim a_0$. At the distance of NGC 7099, the acceleration of gravity due to the Milky Way is $v^2/r \sim 2 \times 10^{-8}$ cm s$^{-2}$, assuming a rotational velocity of 220 km s$^{-1}$ for the Galaxy. Thus, the total acceleration is somewhat above $a_0$, and according to MOND as originally stated (Milgrom 1983), only minor deviation from the Newtonian prediction should occur. Nevertheless – and whatever MOND might predict – in NGC 7099 and the other clusters we have studied so far, something happens to the velocity dispersion at $a_0$, and this cannot be due to dark matter as it allegedly is in galaxies. Whether this indicates something as fundamental as a breakdown of Newtonian dynamics is unclear. In this respect, it is worth noting that the four globular clusters studied so far probe the typical accelerations observed in high surface brightness galaxies (and they behave like them). By contrast, the velocity dispersion profile of low surface brightness elliptical galaxies is remarkably flat (e.g., Mateo 1997; Wilkinson et al. 2006). These galaxies, believed to be dark matter dominated all the way to their center, do have internal acceleration everywhere below $a_0$. Thus, if the parallel with galaxies holds, then also low-concentration globular clusters with acceleration everywhere below $a_0$ should have constant velocity dispersion. This firm prediction will be the subject of the next paper of this series; but in the meanwhile, we conclude by saying that both alternatives remain viable, although the evidence of a breakdown of Newtonian dynamics in the low acceleration limit is growing.

*Acknowledgements.* We thank R. Falomo, T. Richtler, and R. Capuzzo Dolcetta for useful discussions and suggestions, and the referee D. Mc Laughin for his useful report that helped in improving the manuscript.

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