PROCEEDINGS OF SCIENCE

# Using globular clusters to test gravity in the weak acceleration regime: NGC 6171

PoS(BDMH2004)

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As part of an ongoing program to test Newton's law of gravity in the low acceleration regime using globular clusters, we present here new results obtained for NGC 6171. Combining VLT spectra for 107 stars with data from the literature, we were able to trace the velocity dispersion profile up to $\sim$ 16 pc from the cluster center, probing accelerations of gravity down to $3.5 \times 10^{-9}$ cm s$^{-2}$. The velocity dispersion is found to remain constant at large radii (with an asymptotic values of 2.7 km s$^{-1}$) rather than follow the Keplerian falloff. Similar results were previously found for the globular clusters $\omega$ Centauri and M15. We have now studied three clusters and all three have been found to have a flat dispersion profile beyond the radius where their internal acceleration of gravity is $\sim a_0 = 1.2 \times 10^{-8}$ cm s$^{-2}$. Whether this indicates a failure of Newtonian dynamics or some more conventional dynamical effect (e.g., tidal heating) is still unclear. However, the similarities emerging between globular clusters and elliptical galaxies seem to favor the first of the two possibilities.

*Baryons in Dark Matter Halos*
*5-9 October 2004*
*Novigrad, Croatia*

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## 1. Introduction

We present here results of an ongoing experiment designed to test the validity of Newton's law of gravity in the low acceleration regime. The idea sparked from the consideration that the typical acceleration governing the dynamics of stellar structures is much smaller than the smallest acceleration probed in our laboratories or in the solar system. Thus, any time Newton's law is applied to galaxies, for instance to infer the existence of non-baryonic dark matter (hereafter DM), its validity is extrapolated by several orders of magnitude. Interestingly, unanimous agreement has been reached (e.g., [1]) on the fact that deviations from Newtonian dynamic are *always* observed when and only when the gravitational acceleration falls below a certain value ($\sim 10^{-8}$ cm s$^{-2}$, as computed considering only baryons). This systematic behavior suggests we may be facing a breakdown of Newton's law rather than the effects of a still undetected medium. This fact is at the foundation of a particular modification of Newtonian dynamics known as MOND ([2]), which postulates a breakdown of Newton's law of gravity (or inertia) below $a_0 = 1.2 \times 10^{-8}$ cm s$^{-2}$ ([5]). MOND successfully describes the properties of an increasingly large number of stellar structures without invoking DM ([3]; [4]). Unfortunately, in the realm of galaxies MOND and DM provides alternative though indistinguishable descriptions of the data, making it difficult to decide in favor of one of the two options.

Irrespectively of the validity of MOND, to discriminate between a failure of Newton's law and DM one as to perform an experiment known *a priori* to be free from the effects of DM. For instance, if deviations from Newtonian dynamic were to be observed in the laboratory these will have to be ascribed to a breakdown of Newtonian dynamics rather than to the effects of DM. Interestingly, there is general agreement that, if any, the effects of DM on globular clusters are dynamically negligible, making them perfect for testing Newtonian dynamics down to arbitrarily small accelerations. In two previous papers [6] [7] we presented a study of the dynamical properties of the globular clusters $\omega$ Centauri and M15, in which accelerations below $a_0$ are probed. It was shown that as soon as the acceleration reaches this value the velocity dispersion remains constant instead of following the Keplerian falloff (Fig. 2). This result is similar to what is observed in galaxies and explained invoking DM, something we can not do in the present case. In an attempt to generalize this result, we report here new results for NGC 6171, a compact globular cluster located 6.4 kpc from the sun and 3.3 kpc from the galactic center ([8]).

**Table 1:** Radial velocity dispersion for NGC 6171

| Bin limits | Stars/bin | bin center | $\sigma$ (km s$^{-1}$) | Stars/bin | bin center | $\sigma$ (km s$^{-1}$) |
|---|---|---|---|---|---|---|
| | VLT data | | | VLT plus Piatek data | | |
| $0-2$ | | | | 28 | 0.9 | $4.03 \pm 0.36$ |
| $2-5$ | 30 | 3.8 | $3.25 \pm 0.28$ | 54 | 3.7 | $3.24 \pm 0.18$ |
| $5-8$ | 35 | 6.5 | $2.53 \pm 0.19$ | 46 | 6.5 | $2.82 \pm 0.18$ |
| $8-13$ | 23 | 10.4 | $2.40 \pm 0.25$ | 27 | 10.3 | $2.69 \pm 0.25$ |
| $13-23$ | 20 | 16.7 | $2.68 \pm 0.31$ | 20 | 16.7 | $2.68 \pm 0.31$ |

Distances in parsecs.

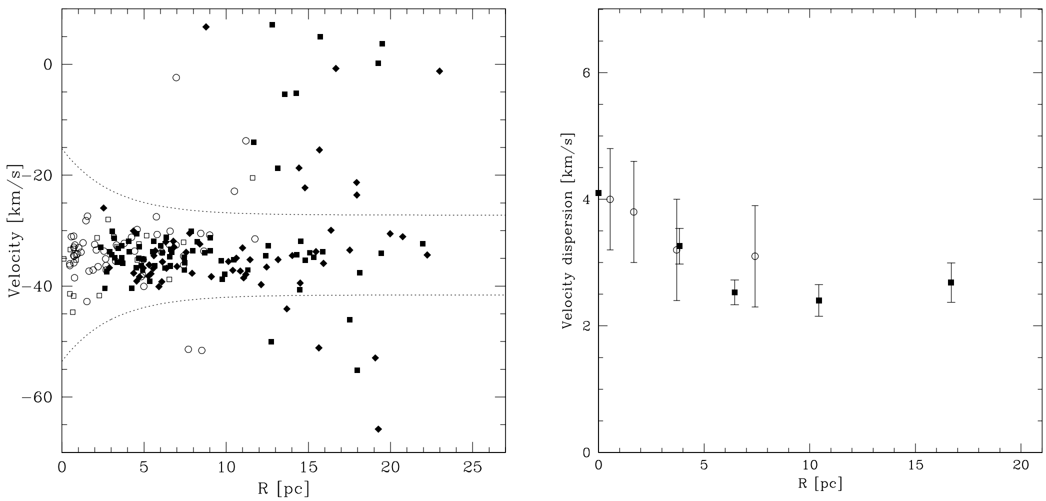


**Figure 1:** **Left:** Radial velocities as a function of distance from the cluster center. Squares and diamonds refer to stars from the bright and faint dataset, respectively. Only data with accuracy better than 1.25 km $s^{-1}$ are shown. Data from [9] are plotted as open symbols. Circles and squares refer to values with uncertainty smaller and greater than 1.25 km $s^{-1}$, respectively. The two dotted lines define the region used to select cluster members. **Right:** Comparison of the velocity dispersion as derived using our data (Squares) and data published by [9] (Circles). Within uncertainties (error-bars represent 1$\sigma$ uncertainties) there is good agreement between the two datasets. The central velocity dispersion of 4.1 km $s^{-1}$ is from [8].

## 2. Observation and results for NGC 6171

Data for NGC 6171 were obtained at the ESO VLT telescope using FLAMES, a fiber multi-objects spectrograph. Two sets of stars, selected based on color, were prepared. One containing red-giant branch stars, an the other fainter stars down to the turn off of the main sequence. In total spectra for $\sim$ 170 were obtained in the wavelength range 5143-5356 Å at resolution $\sim$ 25900. Data reduction was performed with the FLAMES pipeline and radial velocities derived using Fourier cross correlation techniques. In most cases, an accuracy better that 0.75 km $s^{-1}$ was achieved in the radial velocity. Due to the small dispersion we are trying to measure ($\sim 2-3$ km $s^{-1}$), we decided to consider only those stars for which a final accuracy better that 1.25 km $s^{-1}$ was achieved. This left us with 118 stars.

A crucial aspect of this study is the membership determination. This is important in the present case because of the low galactic latitude of NGC 6171 and its radial velocity of only -33.6 km $s^{-1}$ ([8]). In Fig. 1 the locus of cluster members is immediately identified as an over-density in the parameter space, in particular for stars closer than 10 pc from the center. To identify the members outward of 10 pc, we used data in the region between 6 and 9 pc from the center, which have velocity dispersion $\sigma = 2.4$ km $s^{-1}$. We then define as members all stars with velocity falling within $\pm 3\sigma$ from the average. This procedure left us with 107 stars that, notably, are all well within the cluster tidal radius (32.5 pc, [8]). The corresponding velocity dispersion is given in Tab. 1 and compared to data from the literature in Fig. 1.

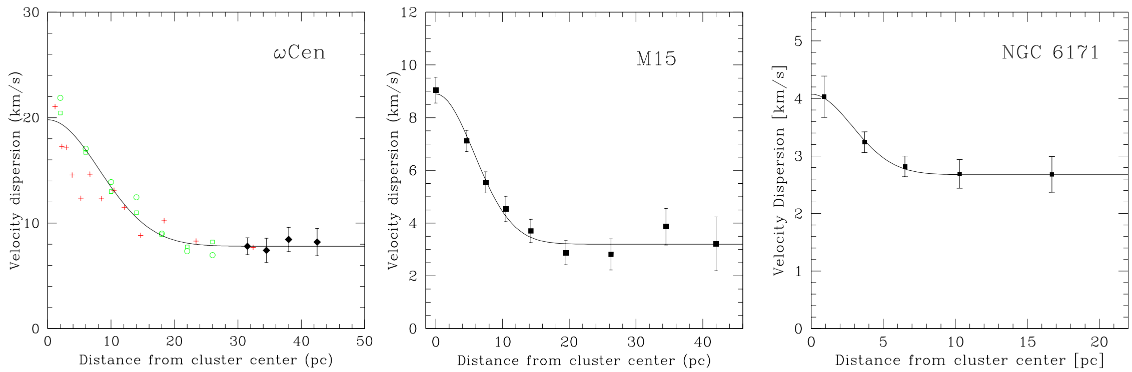


**Figure 2: Left:** The velocity dispersion profile of ω Centauri (as presented in [6]) flattens out at R= $27 \pm 3$ pc, where $a = 2.1 \pm 0.5 \times 10^{-8}$ cm s$^{-2}$. **Center:** Dispersion profile for M15 as derived from data by [10]. The flattening occurs at R= $18 \pm 3$ pc, equivalent to $a = 1.7 \pm 0.6 \times 10^{-8}$ cm s$^{-2}$. **Right:** Velocity dispersion profile for NGC 6171 as derived combining our VLT data with data from [9]. The profile remains flat within uncertainties outward of $8 \pm 1.5$ pc, where $a = 1.4^{+0.7}_{-0.4} \times 10^{-8}$ cm s$^{-2}$. In all panels, the solid line is a fit obtained using a Gaussian plus a constant, ment to better evintiate the flattening of the profile.

## 3. Discussion

We have presented new data for NGC 6171, bringing to three the number of globular clusters for which accelerations below $a_0$ have been probed. In spite of having different physical properties as well as different dynamical and evolutionary histories, all three clusters behave exactly in the same way, both quantitatively and qualitatively (Fig. 2). Assuming a mass-to-light ratio of one in solar units, the flattening of the dispersion profile occurs for very similar values of the internal acceleration of gravity, with an average value of $a = 1.78 \pm 0.4 \times 10^{-8}$, very close to the MOND prediction $a_0$.

While a striking similarity with elliptical galaxies is emerging, it is still possible to find explanations for this behavior within the boundaries of Newtonian dynamics (tidal heating would be a possible one), though more and more fine tuning is necessary to explain all these “coincidences”.

## References

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