Using Globular Clusters to Test Gravity in the Weak Acceleration Regime

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We report on the results from an ongoing programme aimed at testing Newton's law of gravity in the low acceleration regime using globular clusters. We find that all clusters studied so far behave like galaxies, that is, their velocity dispersion profiles flatten out at large radii where the acceleration of gravity goes below 10^{-8} cm s^{-2}, instead of following the expected Keplerian fall-off. In galaxies this behaviour is ascribed to the existence of a dark-matter halo. Globular clusters, however, are not supposed to contain dark matter, hence this result might indicate that our present understanding of gravity in the weak regime of accelerations is incomplete and possibly incorrect.

Newtonian dynamics and globular clusters

Stars within galaxies, and galaxies within clusters of galaxies, are very far apart from each other. As a consequence, the typical accelerations governing the dynamics of galaxies are orders of magnitude smaller than the ones probed in our earth-based 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 are in principle no reasons to distrust Newton's law in the weak acceleration regime, agreement has been reached (e.g., Binney 2004) that galaxies start to deviate from Newtonian dynamics, and that dark matter is needed to reconcile observations with predictions, always for the same value of the internal acceleration of gravity of $a_0 \sim 10^{-8}$ cm s^{-2}. This systematic property, more than anything else, raises the possibility that we may be facing a breakdown of Newton's law, rather than the effects of dark matter.

Since globular clusters are free falling toward the Milky Way, their internal dynamics are only affected by tidal stress, which is in most cases well below a_0. Therefore the internal dynamics of globular clusters can be used to probe the same range of accelerations typical of galaxies, without the complication of dark matter. Following this idea, we have studied the dynamics of the external regions of ω Centauri (Scarpa, Marconi and Gilmozzi 2003). This massive cluster was selected because proper motions for several thousand stars were available in the literature. Combining proper motions with radial velocity information allows all three components of the velocity vector to be obtained, thus fully addressing the possible effects of anisotropy. The result is clearly shown by Figure 1. The velocity dispersion profiles, as derived for the three components of motion, are very similar, showing that the cluster is isotropic (as is also indicated, by the way, from its very nearly circular shape). Moreover, the dispersion is found to be constant at large radii.

Following this initial result, that could be due to some other effect like tidal heating, we collected data for three more globular clusters: NGC 7078 (M15) and NGC 6171 (Scarpa, Marconi, and Gilmozzi 2004A,B), and NGC 7099 (Scarpa et al. 2006). Data for a fourth cluster, NGC 6341 (M92), appeared recently in the literature (Drukier et al. 2006) and this cluster is also presented here. In all cases (see Figure 2) the velocity dispersion profile mimics what is observed in high surface brightness elliptical galaxies. That is, the dispersion is maximal at the centre, then decreases toward a constant value at large radii, where the acceleration goes below a_0. With data for five globular clusters, one can start comparing results and, interestingly, we found that in all cases the flattening of the dispersion profile occurs for very similar values of the internal acceleration of gravity. Values are collected in Table 1, where we present, for each cluster, its absolute V magnitude, the radius where the flattening occurs, and the corresponding acceleration derived assuming a mass-to-light ratio of one. Within errors all profiles flatten out at a_0. It is worth pointing out that these five clusters are different in size, mass, position in the halo of the Milky Way and dynamical history. Therefore there is no obvious reason why they should conspire to have a similar velocity dispersion profile at large radii.

Galaxies provide us with another powerful tool to further disentangle non-Newtonian effects from other more classical phenomena like tidal heating, or a combination of effects like the distribution of dark remnants plus tidal heating plus cluster evaporation and so on, that might be responsible for increasing the velocity dispersion in the outskirts. High surface brightness galaxies (HSB) and low surface brightness galaxies (LSB) are known to behave differently. The latter have a remarkably flat velocity dispersion profile (e.g., Mateo 1997; Wilkinson 2006), allegedly due to LSB galaxies being dark matter dominated all the way to their centre, while HSB galax-

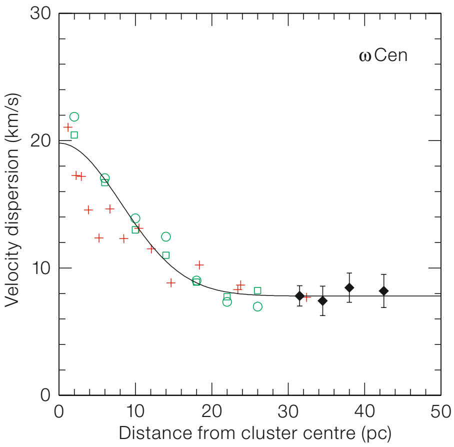

Figure 1: The velocity dispersion profile of ω Centauri. Circles and squares represent the dispersion as derived from proper motion data. Crosses are radial velocity dispersions from the literature, to which we added data for 75 stars (the four last points with error bars). The solid line is not a fit to the data. It is a Gaussian plus a constant drawn to emphasise the flattening of the dispersion at large radii.

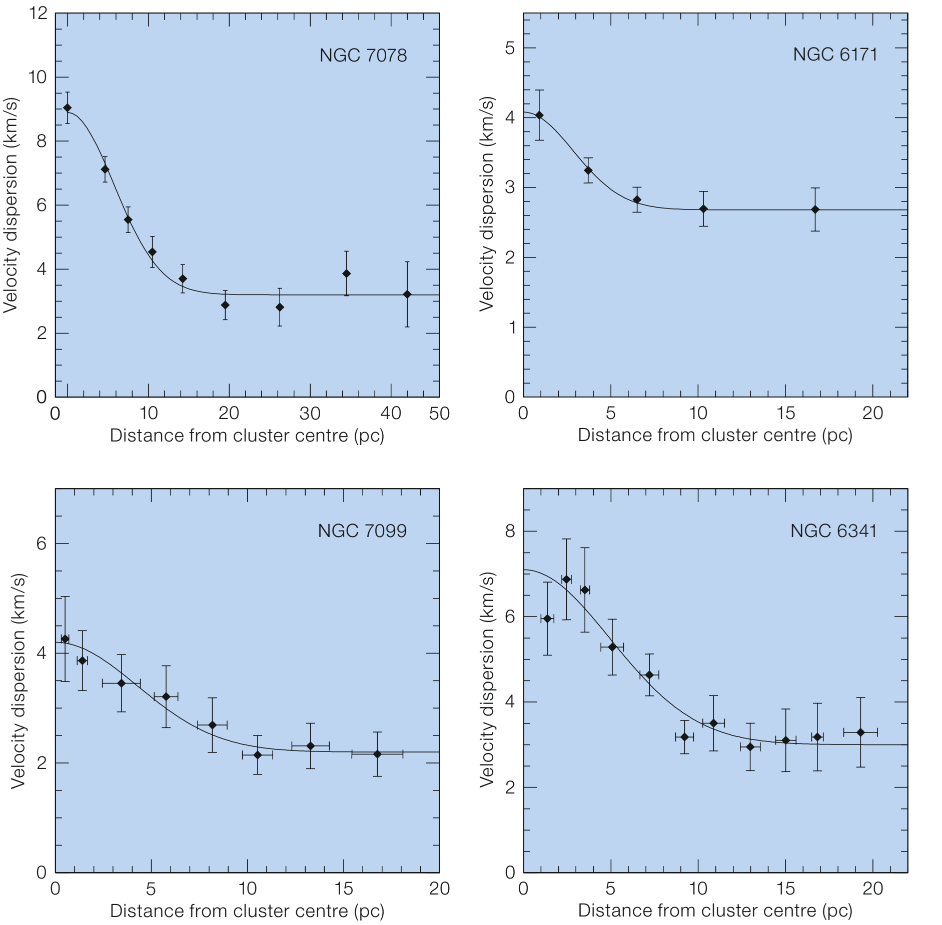

Figure 2: Velocity dispersion profiles of the other four clusters studied so far. In all cases the velocity dispersion is maximal at the centre, then decreases to converge toward a constant value at large radii. This is similar to the case of high surface brightness elliptical galaxies. Note that the profiles of NGC 6171 and NGC 7099 were derived from our own data, while the profiles of NGC 7078 and NGC 6341 were derived from data in the literature (Drukier et al. 2006 and references therein). The solid line has the same meaning as in Figure 1.

ies are baryon-dominated at the centre. In view of what we have found for dense globular clusters that probe the same accelerations as HSB galaxies, it is natural to wonder whether low-concentration globular clusters behave like LSB galaxies. That is, do low-concentration globular clusters have constant velocity dispersion?

The case of NGC 288

In an attempt to answer this question we studied NGC 288, a low-concentration cluster located at 8.3 kpc from the Sun and 11.6 kpc from the Galactic Centre, that has internal acceleration of gravity everywhere below a_0, as is the case for LSB galaxies. The initial selection of targets around NGC 288 was based on colour, as derived from the analysis of ESO Imaging Survey frames. A catalogue of targets was prepared including mostly stars from the sub-giant branch down to the turn off, between 15 and 18 apparent V mag. Observations were then obtained with FLAMES at the ESO VLT telescope. FLAMES is a fibre multi-object spectrograph, allowing the simultaneous observation of up to 130 objects. We selected the HR9B set-up that includes the magnesium triplet covering the wavelength range $5143 < \lambda < 5346$ Å at resolution R = 25900. Stellar astrometry was derived cross correlating the stellar positions on the EIS frames with coordinates from the US Naval Observatory (USNO) catalogue, which proved to have the required accuracy (0.3 arcsec) for FLAMES observations. Two different fibre configurations were necessary to observe all the selected stars (Figure 3). For each configuration three 2700 s exposures were obtained under good atmospheric condition (clear sky and seeing ~ 1 arcsec) on 29 and 30 August 2005.

Radial velocities were derived by cross-correlating the spectra of each target with a template (the target with the best spectrum). The two 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 250 m s^{-1}, well below the accuracy required for our study. Finally, keeping in mind that we are interested only in the velocity dispersion, the global velocity zero point was derived by identifying a few lines in the spectrum of the template. Altogether 126 radial velocities with accuracy better than 1 km s^{-1} were derived. Of these, all but two were found to be cluster members, consistent with the very low contamination expected at the high Galactic latitude (b = −89 degrees) of this cluster.

To better constrain the velocity dispersion close to the cluster centre, we combined our data with data for 24 additional stars, mostly within 6 pc from the cluster centre, and radial velocity accuracy better that 1 km/s (from Pryor et al. 1991). After applying an offset of 2.9 km/s to match our radial velocity zero point, these

Cluster Name	M_V	R (pc)	a (cm s^{-2})
NGC 5139 (ω Centauri)	−10.29	27 ± 3	2.1 ± 0.5 × 10^{-8}
NGC 6171 (M107)	−7.13	8 ± 2	1.3 ± 0.6 × 10^{-8}
NGC 6341 (M92)	−8.20	12 ± 2	1.5 ± 0.6 × 10^{-8}
NGC 7078 (M15)	−9.17	20 ± 2	1.4 ± 0.4 × 10^{-8}
NGC 7099 (M30)	−7.43	10 ± 2	1.1 ± 0.4 × 10^{-8}

Table 1: For each globular cluster studied, the absolute magnitude, radius at which the velocity dispersion flattens and the corresponding acceleration due to gravity for a mass-to-light ratio of 1, are listed.

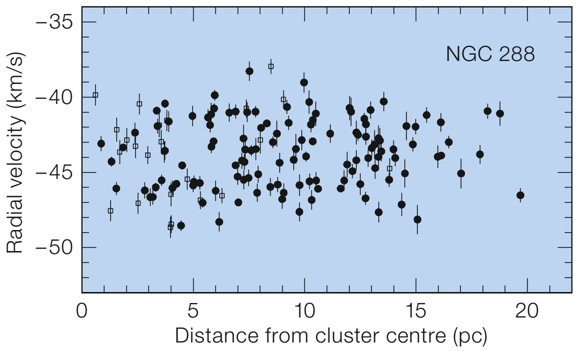

Figure 3: Radial velocity distribution for the low-concentration cluster NGC 288. The 124 stars studied as part of this work are shown as solid circles, while 24 velocities from Pryor et al. 1991 are shown as open squares. The data distributes uniformly from the centre to 20 pc, showing no indication of a decrease of the dispersion.

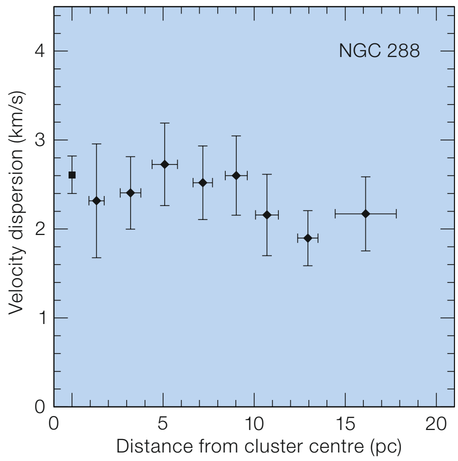

Figure 4: The velocity dispersion profile of the low-concentration cluster NGC 288. From the point of view of the internal acceleration of gravity, this cluster is the equivalent of a low surface brightness galaxy and, similarly to what is found in these galaxies, the dispersion profile is remarkably flat.

Bin limits (pc)	Stars/bin	bin centre (pc)	σ (km s^{-1})
0–2	8	1.34	2.32 ± 0.64
2–4	21	3.21	2.41 ± 0.41
4–6	20	5.09	2.73 ± 0.46
6–8	22	7.18	2.52 ± 0.41
8–10	20	9.02	2.60 ± 0.45
10–12	14	10.71	2.16 ± 0.46
12–14	25	12.95	1.90 ± 0.31
14–20	17	16.12	2.17 ± 0.42

Table 2: Data on the binned radial velocity dispersion for NGC 288.

data smoothly merge with ours in the region of overlap, showing basically the same velocity dispersion (Figure 3). This combined sample was used to search for ordered rotation in NGC 288 that might contribute to sustain the cluster, finding no evidence for rotation down to the level of 0.5 km/s.

Velocities from this combined data set allowed us to build a well-sampled velocity dispersion profile from the centre to almost 18 pc (Figure 4). In Table 2 we report the velocity dispersion in km/s with 1σ uncertainties, together with the limits of the bins, the number of stars in each bin, and the bin centre, defined as the mean of the radii of the stars in the bin.

Looking at both Figures 3 and 4, we see no indications of a vanishing velocity dispersion at large radii, rather, the dispersion remains constant with an average value of 2.3 ± 0.15 km/s over the full range of radii covered by the data.

The five clusters ω cen, NGC 7078, NGC 6171, NGC 7099, and NGC 6341, while having different sizes, different masses, and different dynamical histories, have the common property of being highly concentrated, thus the acceleration of gravity in their central regions is above a_0. Only in the outskirts is the acceleration below this value. All these clusters are found to behave like HSB elliptical galaxies, i.e. to have a constant velocity dispersion at large radii. By contrast, NGC 288 has the peculiar property of being rather diffuse, with a central surface brightness of ~ 20 mag arcsec^{-2} in the V band. This has the important consequence that the internal acceleration of gravity is extremely small. Indeed it can be shown to be everywhere below a_0 for any of the typical mass-to-light ratios assumed for globular clusters.

It is well known that LSB galaxies have velocity dispersion profiles which are remarkably flat, with no central maximum (Mateo 1997; Wilkinson et al. 2006). If this property is due to a breakdown of Newtonian dynamics below a_0 (and not because of dark matter), then the velocity dispersion of NGC 288 should mimic what is observed in these galaxies. Within the errors, this is certainly the case (Figure 4). The similarity between NGC 288 and LSB galaxies is striking. The canonical explanation for the constant velocity dispersion in LSB galaxies is that these objects are dark matter dominated all the way to their centres. In the case of a globular cluster, this explanation is quite unpalatable. Thus, in view of these results for globular clusters and also of the amazing ability of a particular modification of the Newtonian Dynamics known as MOND (Milgrom 1983) to describe successfully the properties of a large number of stellar systems without invoking the existence of non-baryonic dark matter, we see here evidence for a failure of Newtonian Dynamics for accelerations below a_0. Given the potential impact of this claim, we urge the astronomical community to disprove or generalise our results.

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