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Using globular clusters to test gravity in the weak acceleration regime

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Abstract. We have carried out a study of the velocity dispersion of the stars in the outskirts of the globular cluster ω Cen, finding that the velocity dispersion remains constant at large radii rather than decrease monotonically. The dispersion starts to be constant for an acceleration of gravity of $a = 2.1^{+0.5}_{-0.4} \times 10^{-8}$ cm s^{-2}. A similar result is obtained reanalyzing existing data for the globular cluster M15 where the profile flattens out for $a = 1.7^{+0.7}_{-0.5} \times 10^{-8}$ cm s^{-2}. In both cases the acceleration is comparable to that at which the effect of dark matter becomes relevant in galaxies. Explanations for this result within Newtonian dynamics exist (e.g. cluster evaporation, tidal effects, presence of dark matter) but require ad hoc tuning of the relevant parameters in order to make in both clusters the dispersion profile flat starting exactly at the same acceleration. We suggest that this result, together with a similar one for Palomar 13 and the anomalous behavior of spacecrafts outside the solar system, may indicate a breakdown of Newton's law in the weak acceleration regime. Although not conclusive, these data prompt for the accurate determination of the internal dynamics of as many GCs as possible.

Key words. gravity – globular cluster – star dynamics

1. Introduction

Newton's law of gravity is routinely used to describe the physical properties of galaxies, even though its validity has been fully and directly verified only within the boundaries of the solar system. At the distance of Pluto, the sun produces an acceleration of $\sim 3 \times 10^{-4}$ cm s^{-2}. By contrast, the acceleration experienced by the sun in the gravitational field of the Milky Way is 2×10^{-8} cm s^{-2}. Thus, any time Newton's law is applied to galaxies (e.g., to infer the existence of dark matter, hereafter DM), its validity is extrapolated by several orders of magnitude. Although there are in principle no reasons to distrust Newton's law in the weak acceleration regime, testing it would be interesting on its own. That such a test may be important is also suggested by the strong observational evidence that all spacecraft in the outer solar system and beyond are experiencing an anomalous, unexplained additional acceleration toward the sun (Anderson et al. 1998).

In addition, a particular modification of Newtonian dynamics known as MOND (Milgrom 1983) claims to be able to describe many properties of galaxies without invoking DM (McGaugh & de Block 1998; Mortlock & Turner 2001; see Sanders & McGaugh 2002 for a recent review). MOND postulates a breakdown of Newton's law of gravity (or inertia) below few times $a_0 = 1.2 \times 10^{-8}$ cm s^{-2} (Begeman et al. 1991). If this is correct any physical system, not just galaxies, should deviate from Newton's law below this acceleration. Confirming such

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a breakdown would be of major importance regardless of the validity of MOND.

All these considerations prompted us to look for an experiment involving gravitational acceleration of the order of a_0. To reach such low accelerations in a laboratory is clearly difficult, so we focused our attention on a class of astrophysical objects useful for this purpose. Globular clusters (GC) are among the smallest virialized structures in the universe and it is currently believed that DM is not affecting their internal dynamics. This belief is based on solid observational results:

1) The existence of tidal tails (Leon et al. 2000) provides the strongest evidence against large amounts of DM, either baryonic or non-baryonic, in GCs. If present, the potential well would be so deep that no stars could escape the cluster. Numerical simulations (Moore 1996) show indeed that in order to form tidal tails the *maximum* mass-to-light ratio consistent with observations is $M/L < 2.5$ in solar units.

2) In GC studies good agreement is found between dynamical and luminous masses for an old stellar population (Mandushev et al. 1991).

3) Up to now micro-lensing studies have failed to detect the dense dark objects of GC dimension postulated by cold dark matter hierarchical model and predicted to exist in the Milky Way halo (Navarro et al. 1997; Ibata et al. 2002).

It is a fortunate coincidence that stars located in the outskirts of GCs are subjected to a gravitational acceleration comparable to the one experienced by stars in the outskirts of
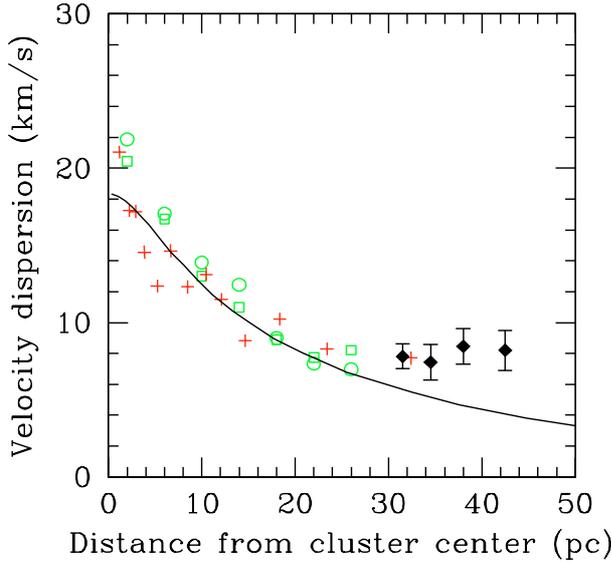
Fig. 1. The velocity dispersion profile of ω Cen. Proper motion data (**Circles** and **squares**) are from van Leeuwen et al. (2000). Radial velocities **Crosses** are from Meylan et al. (1995) up to 20 pc, while the last two points are from Meylan & Mayor (1986). The solid line is the best fit model of radial velocity data as derived by Meylan et al. (1995) (their Fig. 1). Note the good agreement between the last point of Meylan & Mayor (1986) and our radial velocities measurement (**diamonds**), which extend the profile to ~45 pc.

galaxies. Therefore, these stars are ideal test particles for probing Newton's law down to very weak acceleration regimes.

If as suggested by MOND, Newton's law really breaks down in the low acceleration limit and a different law controls the motion of stars, then the deviation from expectations must follow a systematic pattern. That is, GC dynamics must reproduce exactly the dynamics of galaxies (provided the regime of acceleration is the same). In particular, compact GCs should behave like high-surface-brightness galaxies, i.e., the velocity dispersion profile should be flat at large radii (Carollo et al 1995; Simie & Prugniel 2002). Loose GCs, on the other hand, should behave like low-surface-brightness galaxies and show large mass discrepancies at any radius (Mateo 1998).

In this Letter, we present the result of a pilot experiment reaching accelerations as low as 10^{-8} cm s^{-2}.

2. A pilot experiment on ω Centauri

We studied the dynamical properties of stars located in the outskirt of ω Cen, a nearby, well studied GC, chosen only for being one of the very few clusters for which internal proper motions are known, and because it is visible from the south.

Located at a distance of 6.4 kpc from the Galaxy center, ω Cen is the largest GC known, with mass estimates $>10^6\ M_\odot$, and tidal radius of ~70 pc (Meylan & Mayor 1986). In spite of the large dimension and relative proximity to the Galaxy center, the density of the Galactic halo (Bahcall & Soneira 1980) is so low that within its tidal radius ~$2\times10^4\ M_\odot$ of DM are expected, which is dynamically negligible. The cluster is therefore

suitable for testing Newton's law down to the smallest acceleration probed by the motion of its stars.

Available data allow the determination of the dynamical properties of the cluster central regions. In Fig. 1 the radial velocity dispersion profile, as derived using data for ~400 stars up to ~30 pc from the center (Meylan & Mayor 1986), is compared to the proper motion dispersion profile derived using data for many thousands stars up to 25 pc from the cluster center (van Leeuwen et al. 2000). The three components of the velocity dispersion agree well with each other, with no indication of anisotropy. This is very important for two reasons: i) it implies the cluster has reached dynamical equilibrium, making it irrelevant whether the cluster is the result of merging; ii) radial velocities, which are the easiest to determine and the simplest to interpret, are representative of the cluster's kinematics.

To extend the dispersion profile and reach the desired acceleration regime, we have selected from the list of van Leeuwen et al. 91 stars at distance >30 pc from the center and membership probability >90%. Selected stars are located only on the west side of the cluster, covering ~150 degrees in azimuth. This limitation is due to the technical details of val Leeuwen et al. observations and is in no way related to the physical properties of ω Cen. Thus this should not bias our result toward large velocity dispersions.

Stars were subsequently observed during August 2001 with the ESO Very Large Telescope (VLT), in order to measure their radial velocity. Spectra were obtained with UVES (UV-visual Echelle Spectrograph) with resolution $R = 40\,000$. The derived radial velocities have an average error of 1 km s^{-1}, as verified using telluric lines. With these new data, one can in principle study the velocity dispersion of all 3 components of the velocity. However, due to the low velocity of stars in the outskirt of the cluster, proper motion data have average errors comparable to the dispersion we are trying to measure (~8 km s^{-1}). Therefore, though useful for selecting probable cluster members, these data are not suitable for our purpose and we considered radial velocity data only. Having verified the isotropy of the velocity ellipsoid, this limitation does not affect the generality of the result.

3. Results for ω Centauri

The average radial velocity of ω Cen is 232 km s^{-1} (Meylan & Mayor 1986), allowing the discrimination of cluster members from foreground stars (Fig. 2). Of the initial candidates, 75 were found to be true cluster members (consistent with the assigned membership probability). The remaining have radial velocity of few km s^{-1} and are most likely part of the Galactic disk.

The radial velocity dispersion as a function of distance is given in Table 1. Columns 1 and 2 give the bin width in pc and the number of stars per bin. Column 3 gives the observed velocity dispersion in km s^{-1}. In order to trace the cluster potential, these values were combined in quadrature with the values for the cluster rotation given in Col. 4 (Meylan & Mayor 1986). This correction is marginal and is relevant only for comparing our data with published data. The final corrected values of the velocity dispersion σ are in Col. 5. These new data
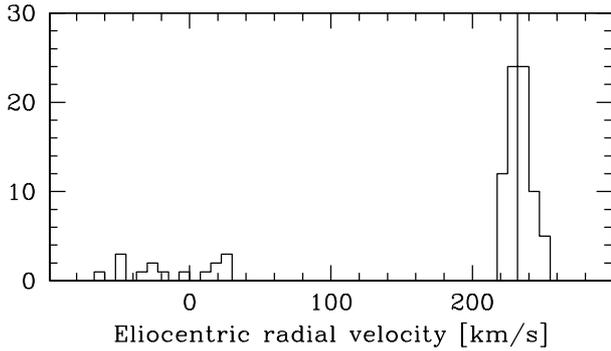
Fig. 2. Distribution of the heliocentric radial velocity for the 91 selected stars. Of all targets, 75 are clearly members having radial velocity comparable to the one of the cluster, marked by a vertical line. The remaining ones are most probably part of the Galactic disk.

Table 1. Radial velocity dispersion.

Bin	N stars	σ_{obs}	Rotation	σ
30–33	31	6.9	3.6	7.8 ± 0.8
33–36	18	6.6	3.4	7.4 ± 1.2
36–40	16	8.0	2.6	8.4 ± 1.2
40–45	10	7.9	1.9	8.2 ± 1.3

extend the study of the kinematics from 30 to 45 pc from the cluster center (projected distances, Fig. 1). We found the dispersion does not decrease monotonically with distance, as expected in Newtonian dynamics, remaining constant at large radii. Invoking a rapid increase of the velocity anisotropy outward of 25 pc from the center to make the profile falling as $1/\sqrt{r}$, implies that the other two components of the velocity dispersion have only ~70% of the energy of the radial component. Such a large and rapid increase of the velocity anisotropy seems very unlikely. Therefore, though limited to the west side of the cluster, the apparent constancy of the velocity dispersion is intriguing.

4. Discussion

This project was started as a pilot experiment to see if at least in one globular cluster interesting results, either in favor or against Newton's law of gravity, could be found. After the study of ω Cen was completed, we became aware of the existence of a similar set of data showing that also in M15 the velocity dispersion profile remains flat (within errors) at large radii (see Fig. 8 in Drukier et al. 1998).

The flattening of the velocity dispersion profile at large radii observed in both ω Cen and M15 can be due i) to tidal heating, as explicitly suggested for M15 (Drukier et al. 1998); ii) to a DM halo surrounding the clusters; iii) to a breakdown of Newton's law in the weak regime limit.

The first two scenarios are certainly possible. Despite the fact that they require ad hoc assumptions to maintain the profile flat, they can not be ruled out by the present data. Therefore, the purpose of this work is not to disprove these two scenarios, but to fully investigate the third one.

In an attempt to study Newton's law in a regime were its validity is not proved, the use of masses (required to compute accelerations) derived from dynamical models based on this law would lead to a circular argument. In particular masses derived from the virial theorem or King models may be overestimated (one should keep in mind that both man-made spacecrafts and MOND suggest gravity is pulling harder than expected). To estimate the mass of the clusters we therefore are better off converting the cluster luminosities into masses adopting a suitable mass-to-light ratio τ.

The total absolute V magnitude of ω Cen and M15 are −10.29 and −9.17 (Harris 1996), corresponding to a mass $M = 1.08\tau$ and 3.87τ millions of solar masses, respectively. The mass so estimated can be safely assumed to be all inside the radius at which the velocity dispersion profile becomes flat. In the case of ω Cen the profile flattens at 27 ± 3 pc from the center, where the acceleration is $2.1^{+0.5}_{-0.4} \times 10^{-8} \times \tau$ cm s^{-2}. In M15 the profile flattens at 18 ± 3 pc (that is 6 ± 1 arcmin from the center, see Fig. 8 of Drukier et al. 1998), corresponding to $1.7^{+0.7}_{-0.5} \times 10^{-8} \times \tau$ cm s^{-2}. Very interestingly, provided τ in the same in the two clusters, both profiles start to be flat for the same value (within errors) of the acceleration.

These two clusters have very little in common: they have different masses, different positions and orbits in the galactic halo. Their dynamical evolution was also different. Moreover, it has been claimed that ω Cen could contain two stellar populations being the result of a merging of two cluster (Lee et al. 1999), or that it is the remnant of a dwarf galaxy (Hilker & Richtler 2000; Carraro & Lia 2000). Thus we find the fact that the two profiles are so similar a significant one.

To further investigate if this result is in agreement with the claim that deviations from Newtonian dynamics should appear at few times a_0 (Milgrom 1983), we need to explicitly adopt a value for τ. For a Salpeter's initial mass function with slope $x = 1.3$, updated theoretical evolutionary models (Cassisi et al. 1998) give $M/L = 1.4$ for simple stellar population. This value would apply to a GC that has retained all its initial mass. Real clusters do experience mass losses because of tidal interaction and evaporation (e.g. Aguilar et al. 1988; Smith & Burkert 2002). The dynamical evolution preferentially removes low mass stars that are the major contributors to the cluster mass, while contributing little to the luminosity. This effect has been verified in those GCs where the present day mass function has been determined, finding a slope $x = 0.7$ at low mass end (De Marchi 1999; Piotto et al. 1997; Andreuzzi et al. 2000). With this mass function the same models give $M/L = 0.6$. Considering that both values depend on the adopted low mass cutoff, we assume $M/L = 1$ as a fair estimate of the true value. For this τ the velocity dispersion profile of both clusters starts to be flat at ~$2a_0$, consistent with MOND prediction.

GCs are hundreds of times smaller and thousands of time lighter than galaxies, nonetheless the velocity dispersion profile of at least these two clusters precisely mimics, both in shape and absolute acceleration, the one of elliptical galaxies (explained invoking DM; Carollo et al 1995). There is no reason for the flattening in GCs and galaxies to occur for the same value of the acceleration. If tidal heating is responsible for the

observed profile, then we should conclude that the tidal action of the Milky Way not only conspires to make ω Cen and M15 very similar to each other, but also produces exactly the same effect as observed in galaxies. The same argument applies if a DM halo surrounding these two clusters is invoked to explain the effect. As we said, both scenarios are possible but require ad hoc assumptions to explain these coincidences, making them somewhat weak.

The parallel between GCs and galaxies can be pushed even further if we reanalyze a recent result for the GC Palomar 13. It has been reported that this GC has a velocity dispersion of 2 km s^{-1}, corresponding to $M/L \sim 40$ (Côté et al. 2002). This high dispersion can simply indicate that the cluster is out of dynamical equilibrium, in which case the virial theorem is not applicable and the derived M/L meaningless. Palomar 13, however, moves in an hardly disturbed orbit (Siegel et al. 2001) and its crossing time ($\sim$2 My for an internal dispersion of 2 km s^{-1}) is short enough to ensure stars reach dynamical equilibrium quickly. We therefore argue there are good reasons to believe Palomar 13 is in equilibrium. If this is the case, the data are either reflecting the effects of a massive DM halo or a break down of Newton's law. Palomar 13 is very loose, having central density of only $\sim$4 $M_\odot$ pc^{-3} (Harris 1996), corresponding to an internal acceleration of gravity $<10^{-9}$ cm s^{-2} all the way to the cluster center. It is therefore similar to low-surface-brightness galaxies which are characterized by very large M/L (Mateo 1998). If our interpretation of the result for ω Cen and M15 is correct, it is therefore not surprising that Palomar 13 shows a large mass discrepancy because this is expected in the case of a break down of Newton's law below $\sim a_0$. Indeed, it has been shown that both Palomar 13 Scarpa (2003) and low-surface-brightness galaxies McGaugh & de Block (1998) follows the predictions of MOND.

5. Conclusions

We have presented new measurements of the velocity dispersion of the GC ω Cen, which allow us to trace the gravitational potential down to an acceleration of 8×10^{-9} cm s^{-2}. We have found that the dispersion profile remains flat well inside the tidal radius as soon as the acceleration of gravity approaches a_0. A similar behavior is also observed in M15, though it was previously ascribed to tidal heating (Drukier et al. 1998).

This result is surprising and may suggest a failure of Newton's law at low accelerations. A conclusion also supported by data for Palomar 13.

Although present data can not rule out the standard dark-matter scenario, nor tidal heating effects, the coincidence we pointed out is remarkable. Combined with the anomalous acceleration experienced by spacecrafts in the periphery of the solar system (Anderson et al. 1998), this result prompts for accurate determination of the internal dynamics of as many GCs as possible. Beside the interest of testing a law of physics in a regime where its validity has never been verified, these observations have the potential of proving or disproving in a direct way the existence of non-baryonic DM.

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