Flattened Velocity Dispersion Profiles in Globular Clusters; Newtonian Tides or Modified Gravity ?

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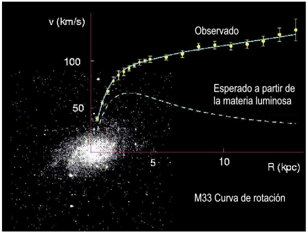
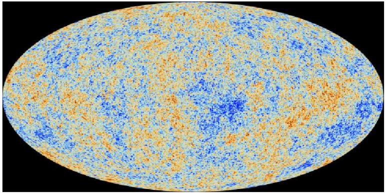
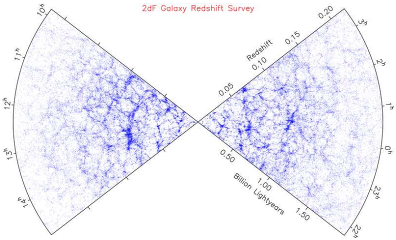
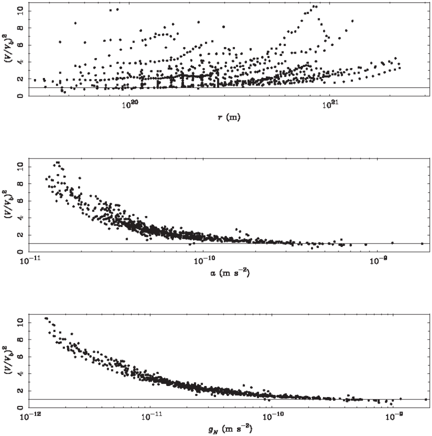
The dynamics of galactic and extragalactic systems, do not correspond to the observed mass-energy as they should if our understanding of gravity is complete.





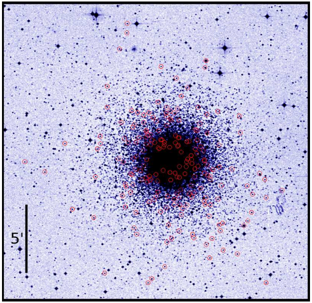


The mass discrepancy in spiral galaxies



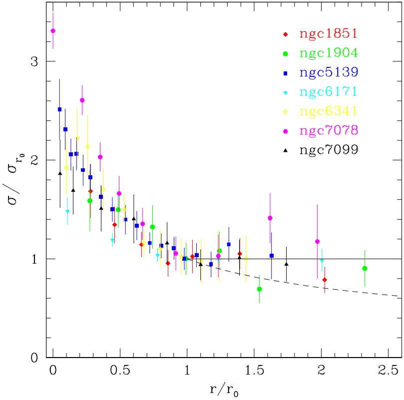
The mass discrepancy in spiral galaxies, $(V/V_b)^2$, where V is the observed velocity and V_b is the velocity attributable to visible baryonic matter. The ratio of squared velocities is equivalent to the ratio of total-to-baryonic enclosed mass for spherical systems. No dark matter is required when $V = V_b$, only when $V > V_b$.Many hundreds of individual resolved measurements along the rotation curves of nearly one hundred spiral galaxies are plotted. Famaey& MacGaugh (2012)

Messurements of the radial profiles of the projected velocity dispersion in GCs.



NGC1851

Observational studies show that the projected velocity dispersion along the line of sight for stars in a number of globular clusters in our Galaxy shows a profile that with increasing separation to the cluster center, first drop along Newtonian expectations and after a certain radius, settle to a constant value which varies from cluster to cluster. (Scarpa & Falomo 2010; Scarpa et al. 2007a,b, 2011; Lane et al. 2009, 2010a,b, 2011)



Scarpa et al. 2011

MOND (MOdified Newtonian Dynamics)/Modified Gravity (MG)

- MOND (Milgrom 1983 a,b y c)

$$ma\mu(\frac{a}{a_0}) = \mathbf{F}.$$

$$a_0 = 1.2x10^{-8} cms^{-2}$$
$$\mu(\frac{a}{a_0}) = \frac{a}{a_0} \text{ if } a \ll a_0$$
$$\mu(\frac{a}{a_0}) = 1 \text{ if } a \gg a_0$$

$$F = \frac{GMm}{r^2} = ma\mu(\frac{a}{a_0})$$

$$\Rightarrow \frac{GM}{r^2} = a\mu(\frac{a}{a_0})$$

$$\Rightarrow g_N = g\mu(g/a_0)$$

- Modified gravity law , Mendoza et al.(2011)

$$f(x) = a_0 x \frac{1 - x^n}{1 - x^{n-1}}. \quad (1)$$

Where $x := \frac{l_M}{r}$ y $l_M := \sqrt{(GM(r)/a_0)}$.

$a \gg a_0$ and $x \gg 1$,

We recovered the Newtonian gravity law.

$$f(x) \longrightarrow a_o x^2 = \frac{GM(r)}{r^2}$$

$a \ll a_0$ and $x \ll 1$

Is equivalent to MOND.

$$f(x) \longrightarrow a_o x = \frac{(Ga_0 M(r))^{1/2}}{r}$$

In the regime $a < a_0$ for a test particle orbiting a mass M.

$$g_N = g\mu(g/a_0)$$

$$g_N = \frac{g^2}{a_0} \Rightarrow \frac{\sqrt{GMa_0}}{r} = g$$

$$\frac{v^2}{r} = \frac{\sqrt{GMa_0}}{r} = g$$

$$v = (GMa_0)^{1/4} (Tully - Fisher) \quad (2)$$

Gravitational equilibrium models for globular clusters

Hernández X., & Jiménez M.A., 2012, ApJ, 750, 9

We have performed models of GCs as populations of self gravitating stars in spherically symmetric equilibrium configurations, under a modified Newtonian gravitational force law.

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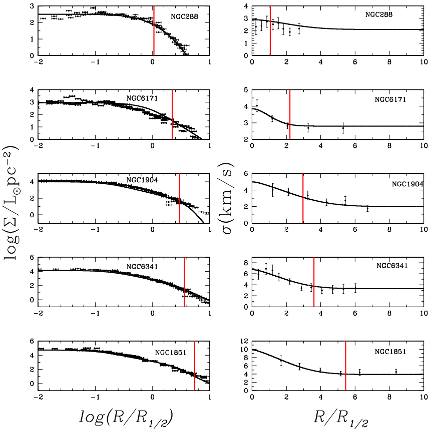
The equation of hydrostatic equilibrium for a polytropic equation of state $P = K\rho^{\gamma}$ is

$$\frac{dK\rho^{\gamma}}{dr} = -\rho \bigtriangledown \phi, \tag{3}$$

Since $\rho = (4\pi r^2)^{-1} dM(r)/dr$, going to locally Maxwellian conditions $\gamma = 1$ and $K = \sigma^2(r)$, the preceding equation can be written as:

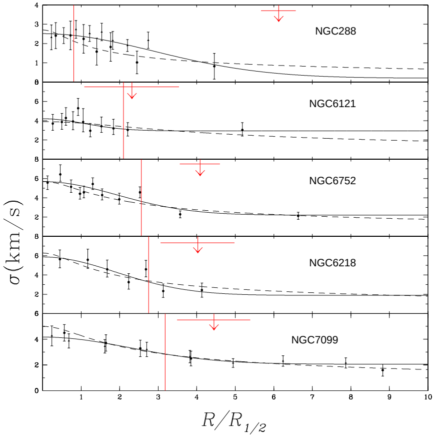
$$2\sigma(r)\frac{d\sigma(r)}{dr} + \sigma(r)^2 \left[\left(\frac{dM(r)}{dr} \right)^{-1} \frac{d^2M(r)}{dr^2} - \frac{2}{r} \right]$$
$$= -a_0 x \left(\frac{1 - x^n}{1 - x^{n-1}} \right) \tag{4}$$

where $\sigma(r)$ is the isotropic Maxwellian velocity dispersion for the population of stars.



Flattened velocity dispersion profiles in globular clusters: Newtonian tides or MG?

Hernandez X., Jimenez M.A., Allen C., 2013, MNRAS, 428, 3196



- We begin by modelling $\sigma_{obs}(R)$, in the GCs in our sample, which can be achieved through the function $\sigma(R) = \sigma_1 \exp\left(-\frac{R^2}{R_\sigma^2}\right) + \sigma_\infty$.
- We now take the observed data points $\sigma_{obs}(R)$, along with the errors associated with each data point, to determine objectively through a maximum likelihood method the best-fitting values for each of the three parameters in equation.
  .
- Then we compare our fit with the Lane's function $\sigma(R)^2 = \sigma_0^2 / \sqrt{1 + \frac{R^2}{r_s^2}}$.

Data are from Drukier et al. (1998), Scarpa, Marconi & Gilmozzi (2004), Scarpa et al. (2007a,b, 2010, 2011), Lane et al. (2009, 2010a,b, 2011)

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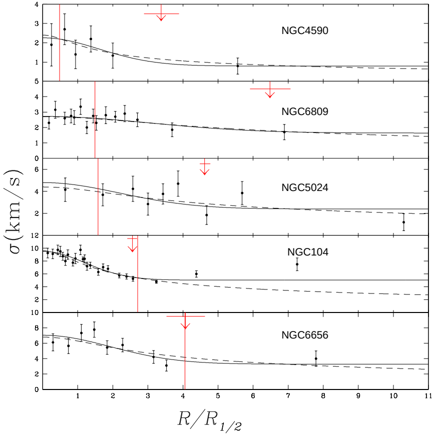
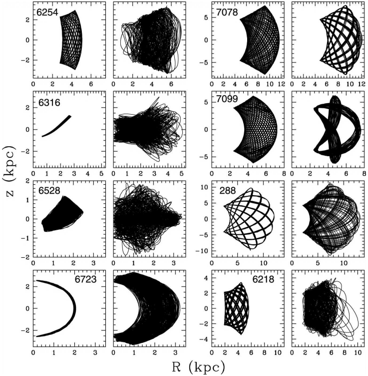


- R_f, is an adequate empirical estimate of the radius beyond which the dispersion velocity profile becomes essentially flat
  $R_f = 1.5 R_\sigma$, in terms of equation for $\sigma(R)$, which can be seen to be highly consistent with the observed velocity dispersion profiles, R_f is the radius such that $\sigma(R_f) = 0.1\sigma_1 + \sigma_\infty$.
- R_a, is an empirical definition of the radius where the typical acceleration felt by stars drops below a_0, where $3\frac{\sigma(R_a)^2}{R_a} = a_0$.
- R_T, is the Newtonian tidal radius obtained from *Allen et al. (2006) and Allen et al. (2008)*

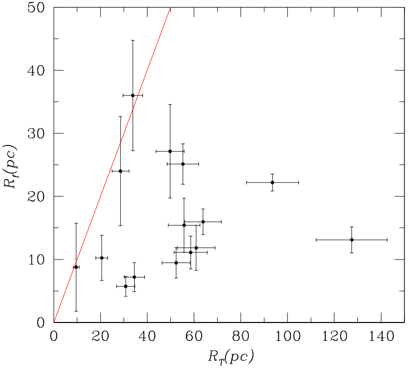
Testing the Newtonian explanation

In Allen, Moreno & Pichardo (2006, 2008) performed detailed orbital studies for 54 GCs for which absolute proper motions and line-of-sight velocities exist. In that study, both a full *3D* axisymmetric Newtonian mass model for the Milky Way and a model incorporating a Galactic bar were used to compute precise orbits for a large sample of GCs, which includes the 16 of our current study.



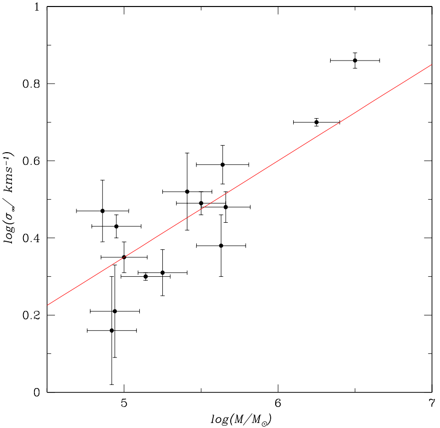
Meridional Galactic orbits of some clusters. In each pair of frames, the orbits with the axisymmetric and nonaxisymmetric potentials are shown on the left and right, respectively. The axisymmetric potential assembles three components: a bulge and a flattened disk and a massive spherical halo extending to a radius of 100 kpc.

Testing the Newtonian explanation R_f vs R_T



- The flat velocity dispersion regime occurs at radii substantially smaller than the tidal radii, for all of the GCs in our sample.
- Only three of the clusters studied are consistent with $R_T \approx R_f$ at 1σ.
- Actually, the average values are closer to $R_T = 4R_f$, with values higher than 8 appearing.
- Given the R^3 scaling of Newtonian tidal phenomena, even a small factor of less than 2 inwards of the tidal radii, tides can be safely ignored.
- It therefore appears highly unlikely under a Newtonian scheme that Galactic tides could be responsible for any appreciable dynamical heating of the velocity dispersion of the studied clusters.

Tully-Fisher relation in globular clusters



The relation between the observed asymptotic dispersion velocity measurements and the total mass of each cluster. The line indicates the best-fitting $\sigma \propto M^{1/4}$ scaling for the data, and is consistent with the galactic scale Tully–Fisher relation.

Summary & Conclusion

- We have shown that for a sample of sixteen GCs, spherically symmetric equilibrium models can be constructed using a modified Newtonian force law.
- We have tested the Newtonian explanation of Galactic tides as responsible for the observed $\sigma(R)$ phenomenology, and found it to be in tension with the observations, given the tidal radii (at perigalacticon) which the GCs in our sample present are generally larger than the points where $\sigma(R)$ flattens, on average, by factors of 4, with values higher than 8 also appearing, making the explanation under the Newtonian hypothesis suspect.
- Through a careful modelling of the observed velocity dispersion profiles, we corroborate an average correlation between the appearance of a flat region in $\sigma(R)$ and the crossing of the a_0 threshold, as expected under modified gravity schemes.
- By including results from careful stellar population modelling of the GCs studied to derive total mass estimates, we show that the asymptotic values of the measured velocity dispersion profiles, σ_∞, and total masses for these systems, M, are consistent with the generic modified gravity prediction for a scaling $\sigma_\infty^4 \propto M$.
- An explanation under a MONDian gravity scheme appears probable, given the correlations we found for the clusters in our sample, all in the expected sense.

Thanks!