What are we missing in elliptical galaxies ?

Jeremy Mould[1]

Centre for Astrophysics and Supercomputing, Swinburne University, Vic 3122, Australia

Matthew Colless

Research School of Astronomy & Astrophysics, Australian National University, ACT 2611, Australia

Lachlan Campbell

Western Kentucky University

Heath Jones

School of Physics, Monash University, Clayton, Vic 3800, Australia

John Lucey

Department of Physics, University of Durham, Durham DH1 3LE, UK

Christina Magoulas

School of Physics, University of Melbourne, Vic 3010, Australia

Robert Proctor

Universidad de Sao Paolo, IAG, Brazil

Christopher Springob[1]

ICRAR, University of Western Australia, WA 6009, and Australian Astronomical Observatory, NSW 2113, Australia

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ABSTRACT

The scaling relation for early type galaxies in the 6dF galaxy survey does not have the velocity dispersion dependence expected from standard stellar population models. As noted in recent work with SDSS, there seems to be an additional dependence of mass to light ratio with velocity dispersion, possibly due to a bottom heavy initial mass function. Here we offer a new understanding of the 6dF galaxy survey 3D gaussian Fundamental Plane in terms of a parameterized Jeans equation, but leave mass dependence of M/L and mass dependence of structure still degenerate with just the present constraints. Hybrid models have been proposed recently. Our new analysis brings into focus promising lines of enquiry, including stellar atmospheres computation, kinematic probes of ellipticals at large radius, and a large sample of one micron spectra, which must be pursued to lift this degeneracy.

Subject headings: galaxies: distances and redshifts – galaxies: elliptical and lenticular– galaxies: stellar content – stars: low-mass, brown dwarfs – stars: luminosity function, mass function

1. Introduction

Scaling relations for galaxies, like the Tully-Fisher relation for disks and the Faber-Jackson relation for ellipticals, are fundamental and powerful. They challenge theories of galaxy formation and they allow us to measure galaxy distances. Local galaxy distances provide us with maps of the mass distribution to compare with the light distribution.

Tully & Fisher (1977) and Faber & Jackson (1976) pioneered scaling relations, and the latter was soon replaced with the fundamental plane (Lynden-Bell et al. 1987), or FP. The virial theorem offered a partial explanation, e.g. Aaronson, Mould & Huchra (1979); Faber et al. (1987). Nearly two decades ago White (1996) opined that an understanding of scaling relations was within reach. But hydrodynamic models of galaxy formation and semi-analytic models have not led to a full understanding.

Nor has the comparison of mass maps and the galaxy distribution yet led to a satisfying resolution. On the one hand, the distribution of peculiar velocities in x-ray clusters of the 6dF galaxy survey (Magoulas 2012; PhD thesis[2]) and of Planck's kinetic Sunyaev Zeldovich peculiar velocities (Ade et al. 2013) is comparable; on the other, the bulk flow measured locally (Feldman et al. 2010; Magoulas et al. 2012) is on the high side of expectations from the ΛCDM model.

In this Letter we outline the scaling relation problem for early type galaxies from the perspective of the 6dF galaxy survey (Jones et al. 2005). Our findings parallel the SDSS result of Conroy et al. (2013). We consider what this means for the elliptical scaling relation. And we suggest what needs to be done to test the notion that a varying bottom-heavy initial mass function (IMF) is what we are missing in ellipticals.

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[1]ARC Centre of Excellence for All-sky Astrophysics

[2]http://dtl.unimelb.edu.au

2. Mass to light ratio

Magoulas et al. (2012) fitted a 3D Gaussian to the surface brightnesses, radii, and velocity dispersions of over 11000 early type galaxies in the 6dF survey. These variables are related to the dynamical mass by the virial theorem in appropriate units[3]

$$M_{total} = k\sigma^2 r_e \tag{1}$$

and

$$L = 2\pi I_e r_e^2 \tag{2}$$

The numerical constant k depends on the galactic structure, e.g. it is $(\sqrt{2}-1)^{-1}$ for a Hernquist profile (Hernquist 1990). Springob et al. (2012) and Proctor et al. (2008) measured Lick indices for the galaxies, giving estimates of metallicity, Z, and age, t, for their stellar populations. Maraston (2005) models[4] for the 2MASS J band (Skrutskie et al. 2006) adopted in the Magoulas dataset predict:

$$M_{model}/L = M/L(Z, t) \tag{3}$$

for some assumed IMF and horizontal branch distribution.

The foregoing equations allow us to plot Figure 1.

If $M_{total} = M_{model} = M$, we expect

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[3]Solar units and AU with velocities measured in 30 km s^{-1} units.

[4]http://www.icg.port.ac.uk/∼maraston/Claudia%27s_Stellar_Population_Model.html

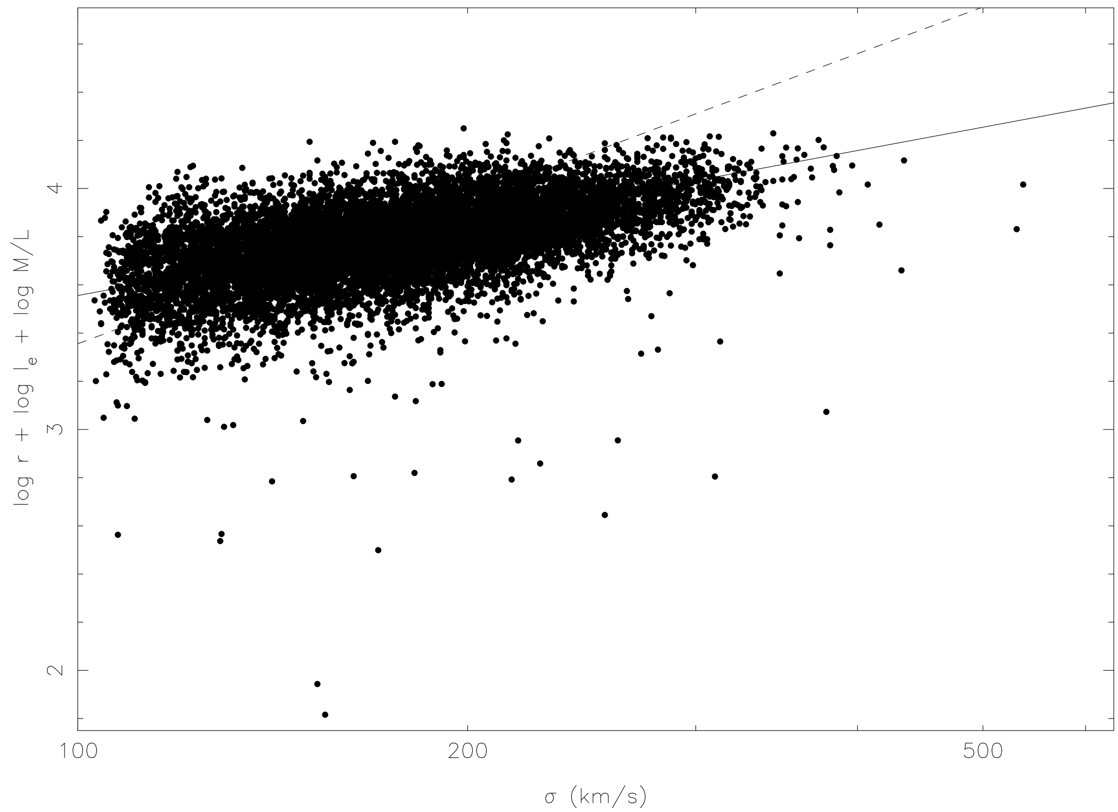

Fig. 1.— Model mass to light ratio combined with surface brightness and radius versus velocity dispersion. The dashed line is equation (4); the solid line is equation (5). Fits are weighted by the observational errors. The scatter in the ordinate is 0.13 dex.

$$2\pi I_e r_e M/L = k\sigma^2 \tag{4}$$

However, what we observe is

$$I_e r_e M/L \propto \sigma \tag{5}$$

This implies that the hypothesis is not correct, and that rather

$$M_{total}/M_{model} \propto \sigma \tag{6}$$

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Conroy et al. (2013) see something similar in SDSS. This prompts the question which is the title of this Letter. In ATLAS^{3D} Cappellari et al. (2013a) find M/L $\sim$ $\sigma_e^{0.72}$ where σ_e is the velocity dispersion within the effective radius, and this is consistent with equation (5). By making dynamical models, they affirm that the effective radius in equation (1) is the same as the effective radius in equation (2). Our radii are calculated from the galaxy redshifts neglecting peculiar velocities. If the *rms* peculiar velocity is ∼200–500 km s^{-1} (Peebles 1976, 1987), the corresponding error in the ordinate of Figure 1 is 2–5% for a galaxy at 10^4 km s^{-1} and is not a significant contributor to the scatter. The majority of the sample is at higher redshift, i.e. in the Hubble flow for present purposes. Allanson et al. (2009) saw a similar dependence of M/L on σ, fitting stellar population models to galaxies in the Coma cluster.

A possible concern is selection effects in the 6dF Galaxy Survey. Could we be missing a cloud of low I_e, low r_e galaxies at $\sigma \approx 100$ km s^{-1} ? Magoulas et al. (2012) have calculated selection probabilities for the sample and these are implemented in a V/V$_{max}$ manner. When this correction is turned on, the fitted logarithmic slope in Figure 1 rises from 0.79 to 1.00. Sample selection is therefore not the source of the discrepancy between equations 5 & 6.

Much discussion has centered around representations of the variables involved as a tilted plane in a data cube. Since we have five variables and three equations in the present analysis, the FP approach may have most merit as a diagnostic tool for checking the three equations against the data. While the FP in 3-space is preferable to a volume in the full 5 variable hypercube, the approach we take here still allows us the open up in the next two sections the important physical questions. These relate more to parameters which have not yet been measured than to those five that have.

3. The initial mass function

Missing mass is usually interpreted as dark matter. But it would be naive to immediately assume this is the basis for equation (6) for two reasons. Our measurements are made inside the half-light radii of early type galaxies. We believe these are baryon dominated. Dark matter only dominates well beyond 10 kpc in large galaxies. Second, it is the very smallest dwarf elliptical galaxies where mass to light ratios reach 100 and dark matter is the primary constituent. Figure 1 is for galaxies with $\sigma > 100$ km s^{-1}, the cutoff of the 6dF spectrograph.

And so, like Conroy et al. (2013), we are led to a bottom-heavy IMF hypothesis to explain equation (6). This hypothesis is an old one. Spinrad & Taylor (1971) conjectured that the strong lined M31, M32 and M81 nuclei might have power law IMFs $n(m) \propto m^{-s}$ with $s >> 2.35$, the Salpeter value. The 0.8–2 micron spectra of these galaxies would be dominated by M dwarfs, rather than the conventional giant branch.

One micron spectra of nearby ellipticals, however, have not led to clear confirmation. One the one hand, Conroy & van Dokkum (2012), Spiniello et al. (2012), Ferreras et al. (2013), and Smith et al. (2013) favor a Salpeter IMF. On the other, there is no clear trend in their fitted IMF with velocity dispersion. Cappellari et al. (2013b) find a transition of the mean IMF from Kroupa to Salpeter in the interval $\sigma_e \simeq 90$–290 km s^{-1}, with a smooth variation in between. Dutton et al. (2013) find from mass models, not stellar population models, a mass-dependent IMF which is *lighter* than Salpeter at low masses and *heavier* than Salpeter at high masses.

Assuming power law IMFs persist to Jupiter masses, M/L is very sensitive to s, as shown in Figure 2. In this case, the difference between equations 5 & 6 can be accommodated by a modest dependence of s on σ.

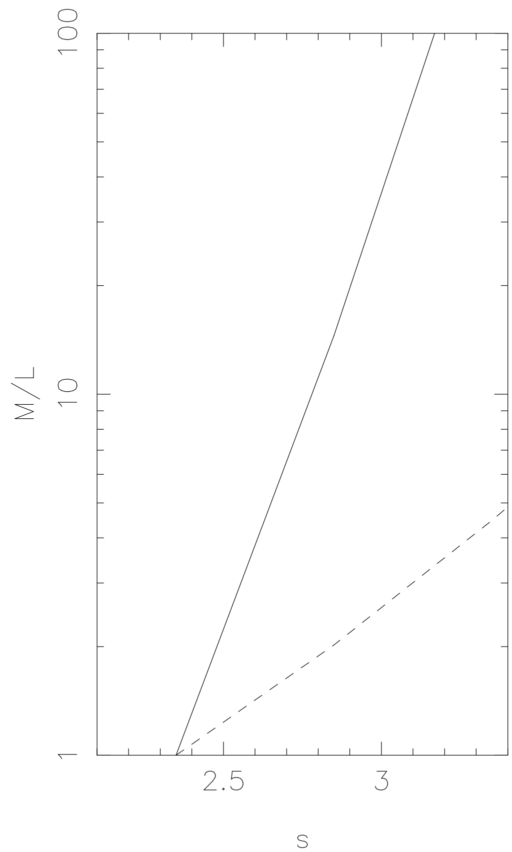

Fig. 2.— The mass to light ratio relative to that from a Salpeter IMF, assuming that a power law IMF persists to Jupiter masses. White dwarfs of $0.6M_\odot$ are assumed to be the progeny of stars of initial mass 0.8–$8M_\odot$. In this s-regime the effect of higher mass remnants is negligible. The dependence is less steep if the lower mass cutoff is 10 Jupiters (dashed line).

4. Galaxy structure

Notwithstanding the similarity of dynamical and luminous radii found by Cappellari et al. (2013a), one can imagine a large elliptical with a tidal radius of 10 kpc surrounded by a 100 kpc spherical shell of dark matter of equal mass. Its mass half radius (equation 1) would be much larger than its luminosity half radius (equation 2) and it could lie on the dashed line of Figure 1. Is the baryonic fraction of high σ ellipticals smaller than that of low σ ellipticals due to structural differences related to the fraction of the dark halo that is occupied by baryons? At first blush this idea does not sit well with the observation that it is ellipticals like the Draco dwarf galaxy that have very low baryonic fractions (Mateo 1998), rather than giants like M49 in the Virgo cluster. However, there may be not one, but two, factors at work. Almost all theories of dwarf elliptical galaxies' low metallicity, e.g. Larson (1974); Kirby et al (2011); Mould (1984),involve loss of a major part of the primordial gas due to feedback, probably simply the action of the first supernovae to explode in these shallow gravitational potentials. One class of solutions to the missing satellite problem involves this or similar baryonic processes (Nickerson et al. 2012). The mass metallicity relation is clearly delineated in our 6dF data (Springob et al. 2012).

So, two separate phenomena may be required to account for the baryonic fraction in ellipticals, (1) an initial underfilling of the largest halos with baryons, and (2) feedback evacuating the smallest halos of baryons. The kinematics of ellipticals' globular cluster systems have been extended beyond $6r_e$ (Norris et al. 2012; Forbes et al. 2011; Mould et al. 1990), so these ideas can be tested.

A more quantitative model can be constructed from the Jeans equation,

$$GM(r) = -r\sigma_{rr}^2 [\, \frac{\mathrm{d}\ \ln\ \nu}{\mathrm{d}\ \ln\ r} + \frac{\mathrm{d}\ \ln\ \sigma_{\mathrm{rr}}^2}{\mathrm{d}\ \ln\ r} + \beta(r)] \tag{7}$$

In a potential with a flat circular velocity and isotropic orbits with radial velocity dispersion σ_{rr}, only the first of the three terms in the brackets is nonzero. For a power law density distribution this is the index of the power law. If we manipulate this term so that the index is –4 for galaxies at the left of Figure 1 and flatter for larger velocity dispersions, we can set the first term to 400(km s^{-1})/σ_{rr} and obtain in the units of equation (1),

$$M_{total} = 13.3\ r\ \sigma_{rr} \tag{8}$$

If this replaces equation (1), we obtain the same σ dependence in Figure 1 as equation (5). If dlnν/dlnr = –4 with σ = 100 km s^{-1}, the density distribution is the black curve in Figure 3. And if dlnν/dlnr = –2 with σ = 200 km s^{-1}, the density distribution is the green curve in Figure 3. The ratio of mass half radii between the red and black curves is between 3 and 4, depending on the precise treatment of the core. The red curve is closest to the expectation from CDM simulations (Navarro et al. 1996). This is a a rather extreme model compared with the modest mass dependence of halo structure seen in CDM simulations by Ludlow et al. (2013).

5. Hybrid Models

Although the structural model of equation (8) may be extreme and other other two terms in the brackets of equation (7) are also likely to be closer to zero than one, we can parameterize departures from equations (1) & (8) as

$$M \propto r\sigma^{1+\delta} \tag{9}$$

with 0 $< \delta$ < 1.

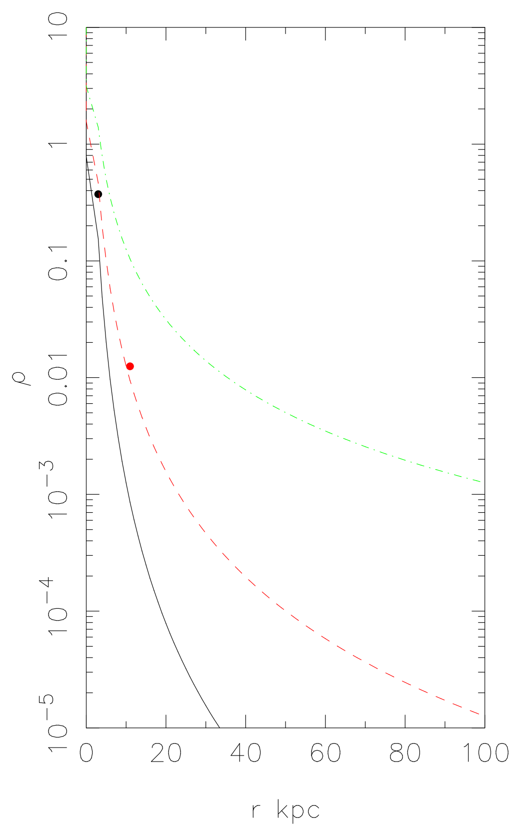

Fig. 3.— Power law spherical density distributions with a core inside 1 kpc. The power law index is –2,–3,–4 in the green (dotted), red (dashed), and black (solid) curves respectively. Half mass radii in the latter two cases are marked. The NFW (Navarro et al. 1996) profile resembles the red curve at large radii and the isothermal sphere resembles the green curve.

Our fit to the FP (Magoulas et al. 2012) can be written, together with equation (2) as

$$L \propto r_e^{0.9} \sigma^{1.65} \tag{10}$$

Dividing the two at r_e gives

$$M/L \propto r_e^{0.1} \sigma^{1+\delta-1.65} \tag{11}$$

To the extent that equation (11) is almost independent of r_e, the pure structural approach to the elliptical galaxy scaling ratio requires $\delta = 0.65$.

But if we also parameterize M/L as σ^ϵ, we have

$$\epsilon = \delta - 0.65 \tag{12}$$

This gives rise to the notion of hybrid models (Onofrio et al. 2013). In other words, the scaling relation problem is currently underconstrained. One can either propose a nonzero ϵ or a nonzero value of (δ – 0.65), or both in the hybrid case.

The Jeans equation tells us that, if ellipticals are formed from dry mergers, and their potentials in the outer parts are always close to NFW potentials, then δ can differ from unity only in as much as dlnσ/dlnr or β are negative and a function of σ (i.e. galaxy mass). If ellipticals form in wet mergers, or if AGN feedback or adiabatic contraction are important, the the baryons may force exceptions to NFW profiles, and δ is more free (until future hydrodynamic models constrain it).

A number of questions arise from this.

(1) Since there is a rising metallicity trend with velocity dispersion in ellipticals, e.g. Springob et al. (2012); Graves & Faber (2010), is the IMF governed by metallicity ?

(2) Are the spectroscopic indicators of M dwarf enrichment metallicity sensitive ? Hydride bands are strong in metal poor halo M dwarfs (Mould 1976; Burgasser et al. 2003). FeH is a hydride band with similar properties to CaH in molecular equilibria (Mould & Wyckoff 1978).

(3) Is M dwarf enrichment independent of metallicity or age but directly coupled to velocity dispersion through, possibly, a Jeans mass dependence on the density of the

collapsed and star-forming protogalaxy ? Two stages of star formation are considered by Weidner et al. (2013).

(4) Are brown dwarfs enriched in high-σ ellipticals, long faded from their L and T dwarf origins ? The IMF does not end at the hydrogen burning limit (Chabrier 2003; Kroupa et al. 2012). Only lensing will find such objects (Barnabé et al. 2013; Alcock et al. 1993). A heavyweight IMF is strongly disfavored for the closest lensed early type galaxy (Smith & Lucey 2013).

These questions in turn suggest further work to isolate what we are missing in ellipticals.

(1) The one micron spectra of stars and galaxies are eminently able to be modeled and metallicity dependences predicted. The FeH band may offer some challenges, but lines such as K I are straightforward, and the continuum is well defined at high resolution, e.g. McLean et al. (2007).

(2) Early type galaxy redshift surveys (e.g. TAIPAN[5]) could be extended to one micron to permit a principal components analysis separation of Z, t, and s.

(3) Hydrodynamic simulations of the formation of ellipticals are needed right down to the star formation scale, so that theory can make a statement about the $0.5M_{\odot}/0.1M_{\odot}$ stellar mass ratio expectations for massive and intermediate mass ellipticals. Analytic approaches look promising, e.g. Hopkins (2013).

(4) The dynamics of ellipticals must be probed to larger halo radii.

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[5]http://physics.mq.edu.au/astronomy/workshop_2012/

6. Conclusions

The ratio of dynamical mass to standard stellar population mass in the 6dF galaxy sample of early type galaxies is approximately proportional to velocity dispersion in the range $100 < \sigma < 300$ km s^{-1}.

A bottom heavy IMF is a simpler explanation of this trend than the notion, for example, that the baryonic fraction of these galaxies has a peak at ~ 200 km s^{-1} velocity dispersion. However, a greater dark matter mass fraction in large halo potentials is an alternative hypothesis that cannot at present be ruled out. Hybrid models are very possible (Onofrio et al. 2013). Stellar atmospheres (Allard et al. 1997, 2013), stellar populations, globular cluster dynamics, and galaxy formation theory can all play valuable roles in tying down what we are missing in elliptical galaxies.

The question posed in the title of this Letter deserves a simple answer. Our answer is that we are missing δ and ϵ. Unambiguous determination of the level of late M dwarf light in ellipticals will measure ϵ. Kinematic probes of the outer gravitational potentials of ellipticals will measure δ, as neutral hydrogen did for disk galaxies back when scaling relations were first proposed.

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[6]www.caastro.org

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