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Limits to Dark Matter in Globular Clusters

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Abstract

In this paper we discuss limits to the amounts of dark matter which might be present in globular star clusters. For well observed clusters we conclude that the total mass of dark matter is less than about 1.5 times the mass of luminous matter, i.e. $< 60\%$ of the entire cluster mass. In central regions and in some clusters the limits are even smaller; for example, in 47 Tuc at most $\sim 25\%$ of the total mass can be dark. Although dark matter can dominate the halo, the true tidal radius cannot exceed that of the 'observed' tidal radius, *i. e.* the one inferred through the standard fitting to a non-dark matter King model. Instead, and somewhat counter-intuitively, the 'observed' tidal limit turns out to be an overestimate of the true tidal limit, if globular clusters have dark haloes.

1. Introduction

Globular clusters are the largest laboratories in the Universe. Larger systems, such as galaxies and (super)clusters of galaxies, do not fit this description very well, for various reasons. For example, they can often not be considered as isolated systems, because of significant interactions of their luminous and/or dark matter content with their environment. And if they can be, there is always a lot of uncertainty both about their dark and luminous matter content, as well as about some of their driving physical principles, such as gas dynamics and star formation. In addition, they are dynamically young, in the sense that their two-body relaxation time generally far exceeds the age of the Universe.

In contrast, globular clusters are typically dynamically old and therefore well relaxed. Only their outskirts show appreciable effects of interaction with the outside world, in a very simple fashion: through the tidal effects of their parent galaxy. Globular clusters are caught inside a net which has the character of the stellar-dynamical equivalent of a Roche lobe in a binary star system. What simplifies life here is the extreme mass ratio, the matter of the galaxy enclosed by the cluster orbit being typically more massive than the cluster by a factor of order 10^4. Therefore, the tidal radius of a globular cluster is smaller than its distance to the galactic center by a factor of order $(10^4)^{(1/3)} \sim 20$.

In addition, the physics of the structure and evolution of the globular clusters is far simpler than that of galaxies or clusters of galaxies. At least the Galactic globulars are old, with the age of $> 10^{10}$yr of the stars implying a narrow mass range, with a main sequence cut-off mass of around $0.8M_{\odot}$. Also, our globulars have hardly any trace of gas and dust, which makes them an ideal laboratory for Newtonian (thermo)dynamics. A note on terminology: all this applies to the older globular clusters, a category which includes all the ~ 150 globulars circling our own Galaxy. Other galaxies, such as the Magellanic Clouds, show globular clusters which are (much) younger. Here, we will use the term 'globular cluster' in the more restrictive sense, limiting ourselves to the older variety, characteristic of our own Galaxy. For globular cluster systems around other galaxies, see Harris (1991) and references therein.

In recent years, globular clusters have attracted much attention through the discovery that they contained millisecond pulsars, several of them in binary stars, in addition to the X-ray sources found in the seventies. Also, the discovery of a significant number of more conventional binaries has strengthened the idea that a large fraction of globular cluster stars are members of primordial binary systems. Theoretically, great progress has been made in the dynamical studies of a rich variety of cluster evolution models. For a review of both the theoretical and observational developments in this area, see Hut *et al.* (1992).

In this paper, we will use the globular cluster laboratories in yet another way, by asking two questions. One is: "how can we hide dark matter in globular clusters in such a way that detection might be optimally difficult?". Another one is: "What will be the various observational consequences of the presence of possible forms of dark matter in globular clusters?". In §2 we address both questions mentioned in their generality.

In §3 we present a review of previous work in modelling the dark matter content of globular clusters. Nearly all of this modelling, with the notable exception of Peebles

(1984), has been concerned with setting limits of dark matter in the inner parts of the cluster, limits appropriate to degenerate stars. As far as we are aware, so far Peebles has been the only one to address the question of possible dark halo matter in globulars.

In §4 we present our own attempt to model the distribution of dark haloes around globular clusters. The limits on their total dark matter content, which follow from our modelling, are presented in §5. Our discussion and conclusions can be found in §6.

2. Questions of Hide and Seek

Before going into some of the details of model building, in the next two sections, we here give a brief overview of the main theoretical and observational questions.

2.1. A Theoretical Question: How Well Can We Hide?

There are five categories of dark matter, which can be hidden in globular clusters. We will list them in descending order of the mass of the constituents.

A central black hole. During and after core collapse, central densities in globular clusters are high enough to cause frequent traffic accidents to occur, in which stars physically run into each other. This will often give rise to the merging of the two stars, probably leading to the formation of blue stragglers, stars which are observed to lie beyond the main sequence turn-off (*cf.* Leonard & Duncan 1988, 1990). Although stellar evolution proceeds more rapidly for these more massive stars, a high enough stellar density may lead to repeated merging, before stellar evolution can catch up with burning the freshly provided fuel. Therefore, there is the possibility of a run-away merger to occur, which can lead to the formation of a central black hole (*cf.* the review by Shapiro 1985).

Neutron stars or black holes as end products of stellar evolution. This form of dark matter is guaranteed to be present in modest quantities, for two reasons. First there is the *a priori* plausibility of the early presence of at least some massive stars, resulting in the formation of these heavy remnants. More directly, there is observational evidence in the form of X-ray sources in globular clusters, interpreted as containing neutron stars (*cf.* van den Heuvel & Rappaport 1992). The total mass in these remnants must be a rather small fraction of that of the whole cluster, for any reasonable initial mass function. However, they could make a significant contribution to the mass of the core of a cluster: since they are heavier than the average stellar mass by at least a factor two, mass segregation will tend to precipitate them towards the central regions (Larson 1984).

White dwarfs as end products of stellar evolution. While there are likely to have been many more white dwarfs formed than neutron stars and black holes, many of them will not be much heavier than the average stellar mass. As a result, they will be distributed throughout the whole cluster. Since again their total mass is unlikely to be more than a modest fraction of the total luminous mass, they are not expected to play an important dynamical role. The only exception may be the class of heavy white dwarfs, around $1M_\odot$ or more, which will sink to the center. For all purposes, they behave like the stars in the previous category (*cf.* Murphy *et al.* 1990, Grabhorn *et al.* 1992).

Brown dwarfs or Jupiters, stars with a mass much lower than that of the average globular cluster star, and with a resulting luminosity low enough to have escaped detection. This is the first category which has at least the potential to dominate the total mass of the cluster. Since most globular clusters have a half-mass relaxation time well below the age of the cluster, these light stars are likely to have been dispelled towards the halo of the globular cluster, the region beyond the half-mass radius.

Non-baryonic matter, in the form of elementary particles which may make up the bulk of the mass of the universe. These particles cannot be too light (e. g. few-eV neutrinos are excluded), since otherwise they could not have collected in the cramped quarters of globular clusters (Tremaine & Gunn 1979). But apart from these limits, there is a very broad range of masses allowed, ranging up towards that of Jupiters if we include the possible presence of, say, primordial black holes (ex-baryonic matter?). In each case, these forms of matter will behave dynamically like an extreme form of low-mass star, as in the previous category.

2.2. An Observational Question: How Well Can We Seek?

How good are the prospects of detecting any or all of the five types of dark matter, discussed above? In most cases, we will have to use circumstantial evidence, based on the perturbation of the distribution of luminous matter, caused by the gravitational effects of the presence of the dark matter. However, there are a few tantalizing possibilities of direct detections, as we will discuss at the end of this subsection.

A central black hole. During the first few years after the discovery of globular cluster X-ray sources, one of the interpretations put forward was that they were generated in a massive central black hole (Bahcall & Ostriker 1975, Silk & Arons 1975). However, subsequent observations showed the X-ray sources to possess many of the characteristics of X-ray binaries present in the bulge of our galaxy, ruling out the massive black hole interpretation. Of course, this does not exclude the possible presence of an X-ray quiet central black hole. The total mass of such an object is unlikely to exceed the mass of a typical cluster by more than a few percent, and in some clusters the upper limits are significantly tighter (*cf.* Lauer *et al.* 1991, Shapiro 1985).

Neutron stars or black holes. As mentioned above, the presence of X-ray sources can be effectively regarded as a direct detection of the presence of neutron stars in globular clusters. More recently, and even more directly, the discovery of a large number of millisecond pulsars has added to the number of discovered neutron stars. More indirectly, it seems clear that a modest population of collapsed objects such as neutron stars and heavy white dwarfs is needed to reconcile kinematic data with the observed surface density profile (e.g. Illingworth & King 1977, Gunn & Griffin 1979, Pryor *et al.* 1989, Meylan & Mayor 1991, Grabhorn *et al.* 1992).

White dwarfs Apart from the heaviest white dwarfs, discussed in the previous paragraph, it is difficult to get any strong handle on the distribution of the typical white dwarfs, since they are so ordinary in stellar mass, while sub-dominant in total mass. To mention one example, in table 1 of Murphy *et al.* (1990), white dwarfs are thrown in with the giants and turn-off stars in their group 2, as well as with their main-sequence groups 3

and 4. Uncertainties in mass function will make it rather difficult to perform a reliable subtraction of modelled mass and observed light, which is needed to determine the dark mass fraction of each mass group.

Brown dwarfs or Jupiters. These are the types of dark-matter candidate which we will investigate below. Specifically, we are asking how tight the limits are which can be placed on unseen matter at greater radii (between, say, the projected half-mass radius and the tidal radius). Here the kinematic data is sparser, the density profile is less well known, and the possibilities for concealing matter are less constrained than in the inner parts.

Non-baryonic matter. Although very different in many other aspects, from a stellar dynamical point of view, more (or less) exotic types of elementary particles behave in a way which is practically indistinguishable from that of brown dwarfs or Jupiters. We will therefore treat the last two categories, particles and low-mass stars, together without worrying about their detailed make-up.

2.3 Motivations for Placing Limits on the Dark Matter Content

There are several reasons to be interested in the amount of dark matter in globular clusters. Dark matter is known to be the primary constituent of many galaxies and clusters of galaxies, dominating over the luminous matter by a large factor (*cf.* Trimble 1987; Kolb & Turner 1990). This alone leads to the natural question whether globular clusters can contain significant amounts of whatever the galactic dark matter consists of, in the form of a dark halo (Peebles 1984), or in a more centrally concentrated form (Silk & Stebbins 1992). As the latter authors, among others, suggest, globular clusters may even be useful in detecting dark matter, if they contain a large enough amount.

For example, if the dark matter consists of some new elementary particle δ and large numbers of δ's were concentrated in and around globulars, then reactions such as $\delta\bar{\delta} \rightarrow \gamma\gamma$ might occur, giving rise to observable gamma ray lines (Silk & Srednicki 1984; Ipser & Sikivie 1987; Giudice & Griest 1989). Such an observation would allow measurement of the mass of the particle. Non-observation of such gamma rays can place constraints on the properties of dark matter particles. Since the annihilation rate is proportional to the square of the particle number density, the detectability of such a signal depends crucially upon the allowed density of dark matter.

Large concentrations of particle dark matter in globular clusters may also change stellar evolution, since large numbers of particles can be accreted into stars. Measurable effects on the age and luminosity function of globular clusters can result (Faulkner & Swenson 1991; Dearborn *et al.* 1992). Since the accretion rate is proportional to the particle number density, again the allowed range of particle densities is important. In this case, the density is needed at the positions where stars are observed.

Finally, if the dark matter is not made up of some new type of elementary particles, it could consist of massive compact halo objects (machos) such as jupiter-like planets, brown dwarfs, or black holes. In this case, gravitational microlensing of background stars by the dark objects might be observable. (For stars in the LMC and a macho galactic halo this is certainly feasible (Alcock *et al.* 1992, Moscoso & Spiro 1991, Paczynski 1992, Andrzej *et al.* 1992)). If globular clusters have large extended dark haloes, one might try monitoring

the cluster stars for microlensing by the globular halo objects, although the rates will be small. The rate of microlensing is proportional to the halo density, so one is interested in how extended and massive a dark halo could exist without coming into conflict with surface brightness and kinematic observations.

Other examples are possible, but the three examples given above serve to illustrate that one would like to know from observation how much dark matter is allowed in globular clusters.

3. Previous Modelling of Globular Clusters with Dark Matter

Before embarking on our own modelling exercise, in the next section, we briefly review earlier forms of globular cluster modelling. A note on our terminology: we will present *background-loaded* models, defined as models in which the dark matter is distributed with a constant density throughout the cluster, to first-order approximation. This assumption gives the dark matter a passive bystander role in the dynamics of the cluster. The distribution of luminous matter is thus influenced by that of the dark matter, but we neglect *its* effect on the dark matter.

3.1. King Models, without Background Loading

Naturally, most previous modelling of globular clusters has not assumed the presence of any background of dark matter, since there never was any observational reason to do so. Traditionally, *i. e.* for the last quarter century, globular clusters have been modelled by King models (King 1966). The motivation for these models is as follows. The Fokker-Planck equation describes the effect of encounters on the distribution of stellar velocities, but this is complicated by the shape of the potential well across the cluster. If, as a first approximation, this is taken to be a square well, then a lowered Maxwellian distribution is found to be a good approximation, after initial transients have died away (Spitzer 1987, Fig. 3.1). King's models arose from assuming that the distribution remains of this form even in a self-consistent potential well.

Empirically, the models work well. It has been known for a long time that they provide a good fit to the surface density profiles of most clusters, perhaps surprisingly (Da Costa 1979). Improved surface brightness photometry, and the addition of valuable kinematic data, have stimulated the modification of these models to include a number of important dynamical phenomena, mainly anisotropy of the stellar velocity distribution and equipartition of velocities in multi-mass systems. The former in particular has a significant effect on the surface brightness at large radii, and for certain clusters is required for satisfactory agreement with observations (e.g. Meylan & Mayor 1991).

3.2. A Background-Loaded Isothermal Sphere

Peebles (1984) pioneered the study of background-loaded globular cluster models. He took the simplest and sensible approach of positing the simplest dark halo (a homogeneous density distribution) together with the simplest distribution of luminous matter (an

isothermal sphere). Loading the isothermal sphere with the dark background matter resulted in the appearance of an effective cut-off in the light distribution, not unlike that of the observed truncation of star light, traditionally interpreted as a tidal cut-off.

This intriguing observation led Peebles to suggest that globular clusters could well contain many times more mass in their dark halo than in their luminous material. As a corollary, the true tidal radius was thought to potentially extend well beyond the observed cut-off radius of the star counts. As we will illustrate in the next section, these features change dramatically when we take the next step in the improvement of modelling accuracy, from a loaded isothermal sphere to a loaded King model.

3.3. More Detailed Models, without Background Loading

Limits on the amount of dark matter present in some globular clusters can already be found in the literature. The work of Richer & Fahlman (1988) suggests that between 50% and 90% of the mass of the cluster M71 may consist of stars less massive than $0.33M_{\odot}$. Leonard *et al.* (1992), using three-dimensional velocity data, conclude that as much as 50% of the total mass of M13 may consist of objects less massive than about $0.1M_{\odot}$. Though none of the dark matter in these cases need be exotic, within the assumptions of the modelling it suggests an upper limit on such matter.

Gunn & Griffin (1979), Meylan (1988, 1989), Pryor *et al.* (1989), Grabhorn *et al.* (1992) and Meylan & Mayor (1991) all find satisfactory fits to the structure and velocity data for several other clusters, using stars down to a limit which varies from one investigation to another, but always in the range 0.11 and $0.16M_{\odot}$. Whether this finding leaves room for non-stellar dark matter near the centers of these clusters depends on how plausible the chosen stellar mass distributions are. Though Pryor *et al.* and Grabhorn *et al.* point out that there is some conflict here with a suspected correlation between metallicity and the slope of the mass-function, the status of this correlation is unclear, and the other authors find no contradiction with actual faint star counts in clusters.

Even though these estimates leave room for considerable amounts of dark matter in the form of low-mass stars or even less massive objects, they are global estimates. Limits on the central density of these objects are much more stringent, because mass segregation expels low mass objects. If a cluster can be reasonably well modelled as a multi-component King cluster, an example given by Gunn & Griffin (1979) illustrates the point. They considered a three-component model ("model A") dominated globally by low-mass stars. Their total mass was almost five times that of the heavier components, but at the centre their projected mass density fell 0.2 dex below that of stars of intermediate mass, and their relative space density would be even lower. Only in a very unevolved, virtually unrelaxed cluster can the central proportion of low-mass objects reflect the global proportion. The Fokker-Planck models of Chernoff & Weinberg (1990) imply advanced mass segregation on a time scale of order 10^9 years or less for almost all galactic globular clusters.

It is not implausible that dark objects, substantially *heavier* than the brightest main-sequence stars, are present in the cores of some clusters, and are not properly accounted for in existing multi-mass models. The evidence for this is the existence in a few clusters of one or two high-speed stars, when the models predict that there should be none (Gunn

& Griffin 1979, Meylan *et al.* 1991, and possibly Pryor *et al.* 1991). Larson (1984) was able to account for those found by Gunn & Griffin by assuming the presence of a cusp of heavy remnants (perhaps black holes of a few $M_\odot$ each). The continued discovery of high-speed stars suggests that this may be a deficiency in the orthodox models.

4. Background-Loaded King Models

In this paper we explore the effect of a modification of King models: inclusion of a background distribution of dark matter. We shall not specify (nor do we need to, from a dynamical point of view) what form this matter may take. We shall, however, assume that its spatial extent is no greater than that of the luminous stars, for the following reason. Even if the primordial stellar distribution had been less extended than that of the dark matter, two mechanisms would have acted to spread the stellar distribution out to the tidal radius of the cluster, and beyond. One is mass loss through evolution of massive stars in the early evolution of the cluster (Applegate 1986), and the other is two-body relaxation (cf. Chernoff & Weinberg 1990, Oh & Lin 1992).

The problem, then, reduces to repeating the construction of King's models with an additional matter density ρ_d, and so the differential equation to be solved for the scaled potential becomes

$$\frac{d^2W}{dz^2} + \frac{2}{z}\frac{dW}{dz} + 9\frac{\rho_*(W) + \rho_d}{\rho_*(W_0)} = 0,$$

where W and z are the scaled potential and radius, respectively, and ρ_* is the space density given by the usual King formula (eq.(11) in King 1966); the central value of the scaled potential is W_0, and W vanishes at the tidal radius. Once the variation of W with radius is known, the space density of the luminous matter can be computed, along with the mass contained within a given radius. Note that these models can be thought of either as an elaboration of King's models, by the addition of dark matter, or as a generalization of Peebles' model (Peebles 1984), in which dark matter was added to the isothermal model.

Fig.1 illustrates some models constructed in this way. One is a standard King model ($\rho_d = 0$) with $W_0 = 8.6$, which leads to a tidal radius (r_t) of approximately $100r_c$, where r_c (corresponding to $z = 1$) is the dynamical core radius. The others are obtained (a) by taking neighboring values for W_0 (dashes), but still $\rho_d = 0$, and (b) by taking various values for ρ_d, and adjusting W_0 to maintain nearly the same value of r_t as the standard King model with $W_0 = 8.6$ (see Table 1). It can be seen that the introduction of increasing amounts of dark matter raises the surface density profile at large radii until the total mass of dark matter rises to a value about 6 times the total mass of the stars (between the first two models of Table 1). Thereafter, a further increase in the amount of dark matter progressively lowers the surface density profile and makes the drop-off to the tidal cutoff start at smaller radii.

5. Limits on the Dark Matter Content

We now consider the extent to which dark matter might be detectable in observations of real systems, and take as examples the clusters listed in Table 2. They have concentration

parameters comparable with those of our models, though in the case of M28, which lies in a rich field, this is relatively poorly determined. Its photometry extends to radii where the surface brightness is fainter than the central value by only about 2.5 dex, but for the other two clusters the ratios are nearer 4 dex (NGC 6397) and 6 dex (47 Tuc). These latter values are more typical of well observed clusters, and near the tidal radii the typical errors in the surface brightness amount to around 0.2 dex (*cf.* , in particular, Meylan & Mayor 1991).

It can be seen from Fig.1 that large amounts of dark matter cause an easily detectable change in the surface brightness profile. Consider, for example, the curves corresponding to the first two models in Table 1. These differ by as much as 0.7 dex from the fiducial King model with $W_0 = 8.6$, at radii where the surface brightness falls 3 dex below its central value.

We now have to consider whether the deviation in the profile could instead be interpreted by modifying the King model without introducing dark matter. Fig.1 shows several other King profiles (corresponding to different values of the scaled central potential W_0). Choice of a suitable "best-fitting" King model (in which we allow for a rescaling of the central density and core radius, as well as W_0) reduces the difference to about 0.5 dex, but this is still detectable. Note that the best-fitting model actually extends to larger radii than the model with dark matter. This conclusion differs from that of Peebles, who found that the addition of dark matter reduces the radial extent of a cluster. Peebles' conclusion is true if dark matter is added to a cluster with a given central density and velocity dispersion. By contrast our models with dark matter have been constructed in such a way as to preserve the ratio of tidal to core radius. The presence of *two* independent length scales in King models is essential in this regard.

Varying W_0 is not the only way in which the King model can be modified to improve the fit with the profile, but use of a two-component model does not improve the fit, in the following sense. We have constructed such models (not illustrated here) in which the individual stellar masses are taken to be in the ratio of 0.8 to 0.13 (which is about the extreme range of main-sequence masses, in solar units, used in published dynamical models). We have attempted to fit the *heavier* component to the surface brightness profiles, since this component should dominate the light. But the heavy component falls off more steeply than in a single-component model, by mass segregation, and so the fit is expected to be poorer. Indeed this is what we found. Another modification of the one-component King models which we have *not* considered is the introduction of an anisotropic velocity distribution. In fact this would tend to flatten out the rapid downturn of the density near the tidal radius (King 1975), which again makes the fit with the loaded model harder.

The conclusion of these investigations is that even the first model of Table 1 would produce deviations in the surface brightness profile which exceed, by a factor of about 2.5, typical errors in the observations. Since this model has a mass of dark matter equal to 3.6 times that of the luminous stars, if we assume that the effect of dark matter is roughly proportional to its mass if this is not too large, then it follows that the observations should be able to rule out a mass of dark matter exceeding that in the luminous stars by a factor of about 1.5 or more (i.e. dark matter whose mass exceeds about 60% of the whole). This conclusion is based on the assumption that surface densities can be measured with an

error of about 0.2 dex down to values 6 dex smaller than the central value, and that we are considering clusters with a concentration parameter of order 2.

Kinematic data is available for a substantial fraction of the Galactic globular clusters (*cf.* Mandushev *et al.* 1991). For many clusters this is a measure of the central velocity dispersion, which imposes limits on dark matter mainly in the region of the core. But for a growing number of clusters estimates of the velocity dispersion extend to several projected core radii. For the three clusters in Table 2, for instance, measures have been made to about 30 r_c. Within this radius the mass of dark matter in the last model of Table 1 is already approximately twice that of the luminous stars, and thus may be expected to have a substantial effect on their kinematics. This is confirmed by Fig.2, which shows, for the same models as in Fig.1, the variation with projected radius r of the root-mean-square projected velocity. Evidently, kinematic data discriminates at least as well as the surface density profiles; the effect on the profile is more distinctive, and the typical errors in observational estimates are smaller – typically 0.1 dex or less. For example, in the first model of Table 1 the velocity dispersion at $30r_c$ exceeds that of the King model with $W_0 = 8.6$ by about 0.2 dex, which exceeds the errors of the observed value at this radius in NGC 6397 by a factor of order 3.

6. Discussion and Conclusions

The effect of dark matter on the surface density profile of a globular cluster is somewhat counterintuitive. If the scaled central potential is held fixed, then the surface brightness is depressed at all radii, and the cluster is truncated at a smaller radius than in the absence of dark matter. Even an isothermal model, though still infinitely extended, has a steeply decreasing profile resembling that of a tidally truncated model (Peebles 1984). What we have done with the background-loaded King models, however, is to adjust W_0 to keep the tidal radius at a given value, which is comparable with values found in some well observed clusters. Now the effect of adding dark matter is to *raise* the surface density profile in large parts of the halo.

Even more remarkable is the observation that, if one were to try to fit this profile with a normal (unloaded) King model, much as an observer might do, the tidal radius of the best-fitting model actually somewhat *exceeds* the true tidal radius of the system. Therefore, even if globular clusters do contain large amounts of dark matter at large radii, it does not seem probable that this dark matter extends to greater radii than the cutoff radius inferred from the surface brightness profile.

Quantitatively, we find the following result. It follows both from the surface density profiles and kinematic data that the amount of mass in dark matter, in typical well observed galactic globular clusters, cannot exceed the luminous mass by a factor of more than about 1.5. The resulting limits on the space density of dark matter (in absolute units) therefore vary from one cluster to another.

In some cases stronger statements can be made. For example in the case of 47 Tuc (Meylan 1989) models can be constructed in which much of the inferred mass can be accounted for by observed stars, and all that is required is a modest extrapolation of the observed mass function from the faintest stars that can be counted (corresponding to

$\simeq 0.3M_\odot$) down to the least massive stars used in the models ($0.13M_\odot$). In this case the total mass of dark matter (which may simply be stars too faint to be counted) is less than 0.3 times the total mass of visible stars. This is a global limit; the central density ratio must be much smaller.

Our conclusion holds independent of whether the mass has a distribution like that of the low-mass stars (in which case our conclusion is implied by existing models in the literature) or whether the dark matter extends more-or-less uniformly to the tidal radius. On the other hand, our conclusion does depend on the assumptions of the models, and could in principle be challenged if there were sound reasons for supposing that approximately relaxed, isotropic distribution functions could differ widely from the truth.

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Table 1. Details of models with dark matter

Central Ratio ρ_d/ρ_*	Ratio of Dark to Luminous Mass	W_0
0.0001	3.6	11.3
0.0002	7.1	13
0.0005	21.8	17
0.001	61.4	24

Table 2. Some Well Observed Clusters

Designation	Source	$\log(r_t/r_c)$
NGC 6397	Meylan & Mayor 1991	2.5
47 Tuc	Meylan 1988, 1989	2.1
M28	Pryor *et al.* 1989	~ 2.4

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FIGURE CAPTIONS

Figure 1. Surface density profiles (as a function of projected radius d, in units of r_c) for five King models and four models with varying amounts of dark matter. The heaviest line is a King model with scaled central potential $W_0 = 8.6$, and the dashed lines show King models for $W_0 = 7.6,\ 8.1,\ 9.1$ and 9.6 (in order of increasing tidal radius r_t). The thin continuous curves give models in which the ratio of the density of dark matter to the central density of luminous stars is 0.0001, 0.0002, 0.0005 and 0.001, respectively. The first two of these almost coincide, and the last two are progressively more truncated.

Figure 2. Root mean square projected velocity as a function of projected radius d, for the same models as Fig.1.

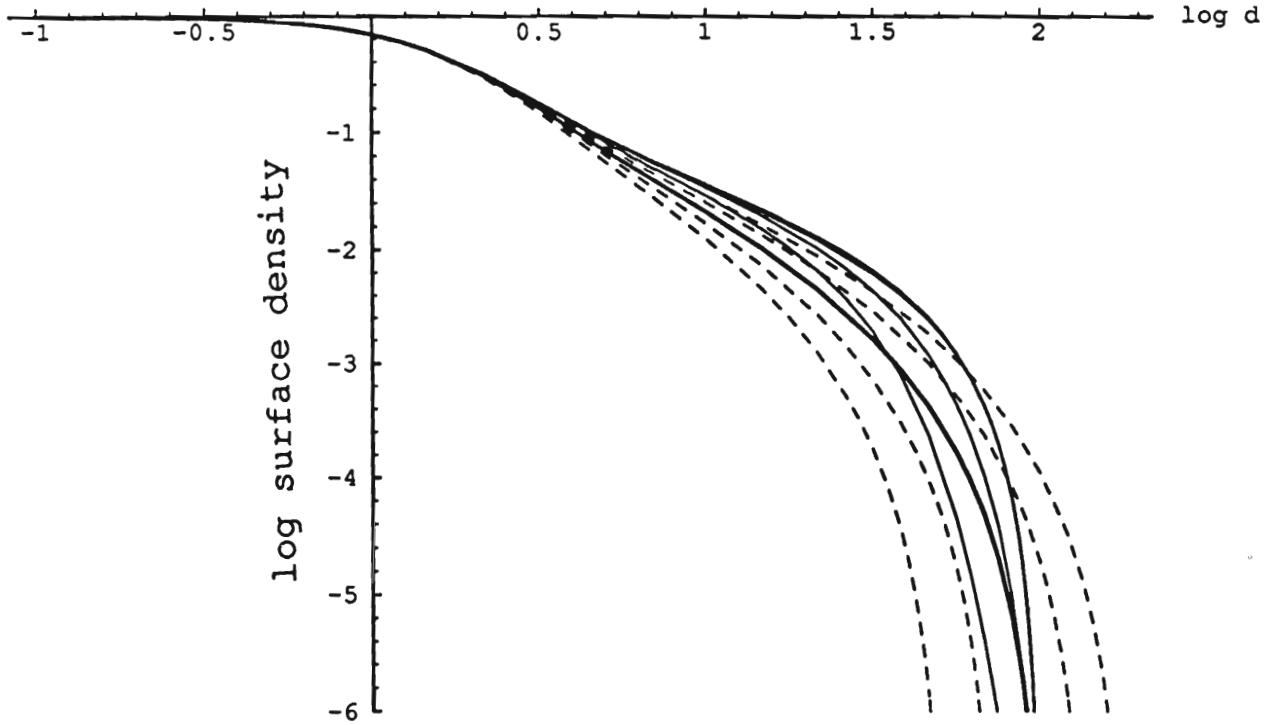
log d
-1
-0.5
0.5
1
1.5
2
log surface density
-1
-2
-3
-4
-5
-6

fig. 1

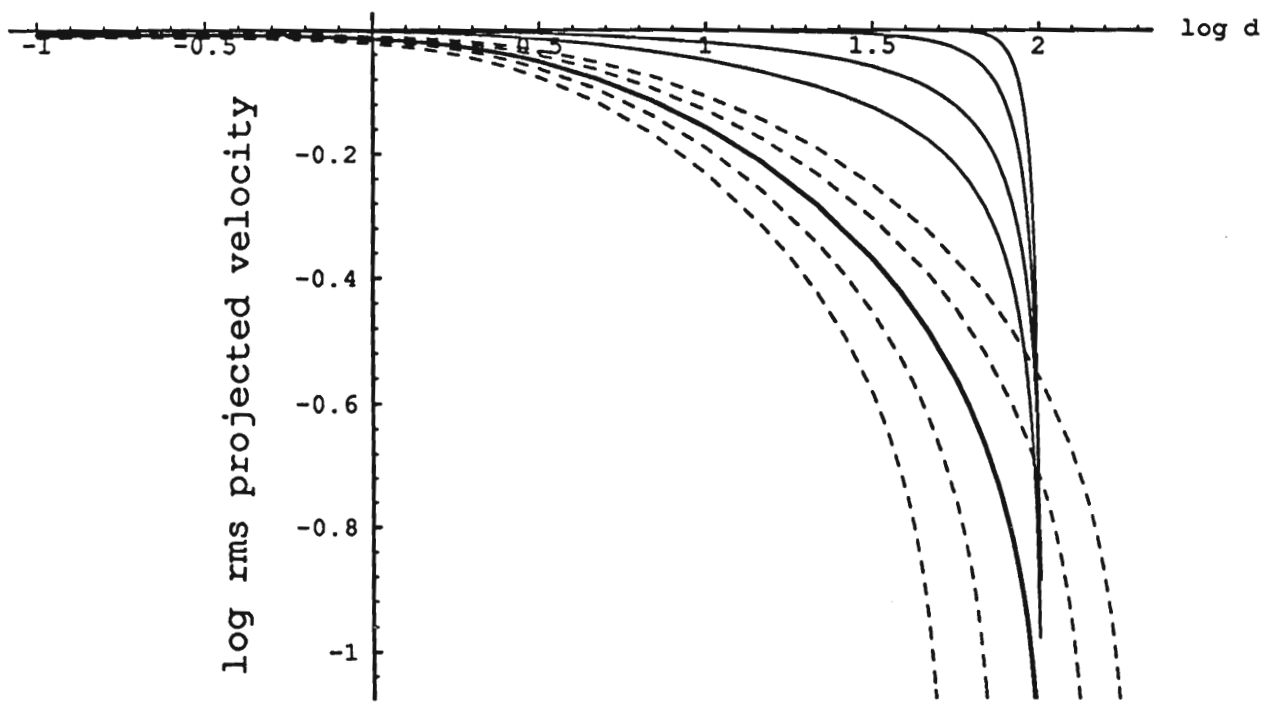
log d
-1
-0.5
0.5
1
1.5
2
log rms projected velocity
-0.2
-0.4
-0.6
-0.8
-1

fig. 2