BOUNDS ON THE MASS AND ABUNDANCE OF DARK COMPACT OBJECTS AND BLACK HOLES IN DWARF SPHEROIDAL GALAXY HALOS

F. J. Sánchez-Salcedo\textsuperscript{1} and V. Lora\textsuperscript{1}

Abstract

We establish new dynamical constraints on the mass and abundance of compact objects in the halo of dwarf spheroidal galaxies. In order to preserve kinematically cold the second peak of the Ursa Minor dwarf spheroidal (UMi dSph) against gravitational scattering, we place upper limits on the density of compact objects as a function of their assumed mass. The mass of the dark matter constituents cannot be larger than $10^4 \, M_\odot$ at a halo density in UMi’s core of $0.35 \, M_\odot \, pc^{-3}$. This constraint rules out a scenario in which dark halo cores are formed by two-body relaxation processes. Our bounds on the fraction of dark matter in compact objects with masses $\gtrsim 3 \times 10^3 \, M_\odot$ improve those based on dynamical arguments in the Galactic halo. In particular, objects with masses $\sim 10^5 \, M_\odot$ can comprise no more than a halo mass fraction $\sim 0.01$. Better determinations of the velocity dispersion of old overdense regions in dSphs may result in more stringent constraints on the mass of halo objects. For illustration, if the preliminary value of 0.5 km/s for the secondary peak of UMi is confirmed, compact objects with masses above $\sim 100 \, M_\odot$ could be excluded from comprising all its dark matter halo.

Subject headings: dark matter — galaxies: halos — galaxies: individual (Ursa Minor dwarf spheroidal) — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

The composition of dark halos around galaxies is a difficult problem. Many of the baryons in the universe are dark and at least some of these dark baryons could be in galactic halos in the form of very massive objects (VMOs), with masses above $10^4 \, M_\odot$. Astrophysically motivated candidates include massive compact halo objects (MACHOs) and black holes of intermediate mass (IMBHs; $10^1$-$10^3 \, M_\odot$) or massive ($\gtrsim 10^5 \, M_\odot$) IMBHs. IMBHs are an intriguing possibility as they could contribute, in principle, to all the baryonic dark matter and may be the engines behind ultraluminous X-ray sources recently discovered in nearby galaxies.

A successful model in which VMOs are the dominant component of dark matter halos could resolve some long-standing problems (Lacey & Ostriker 1985; Tremaine & Ostriker 1999; Jin et al. 2003). If the halos of dSphs are comprised by black holes of masses between $\sim 10^5$ and $10^6 \, M_\odot$, they evolve towards a shallower inner profile in less than a Hubble time, providing an explanation for the origin of dark matter cores in dwarf galaxies, and the orbits of globular clusters (GCs) do not shrink to the center by dynamical friction (Jin et al. 2002). Very few observational limits on VMOs in dSph halos have been derived so far. This Letter is aimed at constraining the mass and abundance of VMOs in the halos of dSphs by the disruptive effects they would have on GCs and cold long-lived substructures.

2. CONSTRAINTS FROM THE SURVIVAL OF FORNAX GCs

Fornax is a dark dominated dSph galaxy with an unusually high GC frequency for its dynamical mass. In order to place dynamical constraints on the mass of VMOs by requiring that not too many GCs are disrupted, the density of VMOs $\rho_h$ with mass $M_h$ along the orbits of the GCs should be known. Since the three-dimensional distances of the GCs to the center of Fornax are unknown, the density of VMOs at a mean distance of $\sim 1$ kpc will be adopted. By $f$ we will denote the halo mass fraction in VMOs, i.e. $f = \rho_h/\rho_m$, where $\rho_m$ is the halo density; $\rho_m = 0.02-0.05 \, M_\odot \, pc^{-3}$ at 1 kpc (Walker et al. 2006a).

Klessen & Burkert (1996) give the “survival diagram” of GCs, considering different encounter histories for $\rho_h = 0.026 \, M_\odot \, pc^3$ and a velocity dispersion of halo particles $\sigma_h = 120$ km s$^{-1}$. The survival diagram establishes the range of mass and concentration such that GCs with central densities between $10^3 \, M_\odot \, pc^{-3}$ and $10^5 \, M_\odot \, pc^{-3}$ (or, equivalently, core radii between 0.5 and 2 pc) have a probability of less than 1% to survive after 10 Gyr. Since the dissolution timescale for a certain GC (and a given $M_h$) scales as $\propto \rho_h^{-1} \sigma_h^3$, and $\sigma_h \approx 20$ km/s in Fornax, it will be a factor of (5–12) $f$ less in Fornax as compared to the Galactic case considered by Klessen & Burkert (1996). Therefore, the survival diagram for Fornax’s GCs can be derived at once (see Fig. 1). GCs in the region above the thick line have a probability of less than 1% to survive in a dark halo with $\rho_h M_h = 10^3 \, M_\odot \, pc^{-3}$. For such a $\rho_h M_h$ value and if the present parameters of the GCs are representative of their parameters at the time they formed, we would be observing the lucky survivors of an initial population of $\gtrsim 500$ GCs of $\sim 2 \times 10^5 \, M_\odot$, which turns out to be very unrealistic for a galaxy with a V-band luminosity of $1.5 \times 10^7 \, L_\odot$.

It is possible to estimate the probability that we are observing only the survivors of a larger original population that are in the process of quick disruption (Tremaine & Ostriker 1999). The distribution of the dissolution age of GCs is expected to follow a scale-free power law $F = C(t_{dis} + t_H)^{-q}$, where $t_{dis}$ is the characteristic dissolution timescale and $t_H$ is the age of the cluster population (Gnedin & Ostriker 1997). Fig. 1 shows that at

\textsuperscript{1} Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad Universitaria, Apto. 70 264, C.P. 04510, Mexico City, Mexico (jsanchez@astroscu.unam.mx, vlora@astroscu.unam.mx)
least 4 GCs are above the thick line: this indicates that their present disruption timescales are < 0.22\(t_H\). If the exponent of distribution of lifetimes is \(q \approx 2\), as derived for Galactic GCs (Gnedin & Ostriker 1997), the probability to have 4 out of 5 GCs with lifetimes less than 0.22\(t_H\) is \(< 1\%\), whereas the probability that the lifetimes of all the GCs are less than 0.5\(t_H\) is 0.4\%. Hence the probability that the whole dark halo is comprised of objects with masses \(> 5 \times 10^4 (\rho_0/0.02 M_\odot \text{pc}^{-3})^{-1} M_\odot\) is less than 1\%. If only a fraction \(f\) of the dark mass is in compact objects of mass \(M_h\), then \(f < 5 \times 10^4 M_\odot/M_h\).

3. Persistence of Dynamically-Cold Subpopulations

Localized regions with enhanced stellar density and, where data permit, extremely cold kinematics have been detected in some dSphs (e.g., Olszewski & Aronson 1985; Kleyna et al. 2003; hereafter K03; Coleman et al. 2004; Walker et al. 2006b). In particular, UMi dSph has received the most attention. Collecting the velocity of stars (e.g., Binney & Tremaine 1987; Gieles et al. 2006). Doing so, and for a distribution of clumps and VMOs with a relative one-dimensional velocity dispersion \(\sigma_{\text{rel}}\), we obtain:

\[
\Delta v^2 = \frac{16 \sqrt{\pi} g G^2 \rho_h M_h r^2 \Delta t}{9 \sigma_{\text{rel}} r_{1/2}^2}.
\]

For UMi, the persistence of the clump for a large fraction of a Hubble time indicates a core of the dark halo of at least 2-3 times the size of the orbit of the clump, which is \(\gtrsim 150\) pc. In terms of the stellar core radius (\(\sim 200\) pc), this makes a halo core 1.5–2 times the stellar core and, consequently, the velocity dispersion of the halo particles in the core is, at least \(\sim 1.5\)–2 times the stellar velocity dispersion, corresponding to \(\sigma_h \sim 15–20\) km/s. The impulsive approximation is valid for \(b \omega \ll V\), where \(\omega = \sigma_s/r_{1/2}\) and \(\sigma_s\) is the internal one-dimensional velocity dispersion of the subpopulation. For the encounters with \(b \lesssim 5 r_{1/2}\), responsible for most of the velocity impulse, this condition is well satisfied for \(\sigma_h \gtrsim 5 \sigma_s\). Therefore, for \(\sigma_s \sim 1\) km/s, this requirement is fulfilled within the isothermal dark core of UMi.

Since stars in the clump are unbound, the self-gravity of the clump in a first approximation can be ignored considering only orbit diffusion in the large-scale harmonic potential of the parent galaxy. In a one-dimensional harmonic potential, a velocity impulse \(\Delta v_{\perp}\) produces a change in the velocity dispersion \(\Delta \sigma_{\perp}^2 = \Delta \langle v_{\perp}^2 \rangle = \Delta v_{\perp}^2/2\), where the brackets \(\langle \ldots \rangle\) refer to the mean value after averaging over one orbit. Combining this relation with Eq. (2), we find the change of \(\sigma_s\) in a time \(\Delta t\):

\[
\Delta \sigma_{\perp}^2 = \frac{8 \sqrt{\pi} g G^2 \rho_h M_h r_{1/2}^2 \Delta t}{27 \sigma_{\text{rel}} r_{1/2}^4},
\]

where \(\sigma_{\text{rel}} \approx \sigma_h\) is assumed, since the population of clumps is expected to have a velocity dispersion similar to the stellar background, \(\sim 9\) km/s in UMi. The ratio \(\eta = \tau_{1/2}/r_{1/2}\) depends on the model: for a Plummer cluster \(\eta = 4\), whereas \(\eta = 1.5\) for both a King profile with a dimensionless potential depth of \(W_0 = 9\) (e.g., Gieles et al. 2006) and a Gaussian density distribution. In order to take a conservative value and to facilitate comparison with photometric and theoretical analysis that assume Gaussian models, we will adopt \(\eta = 1.5\) constant in time.

By \(t_{2.5}\) we will indicate the time required for a very cold group of unbound stars \(\sigma_s \sim 0\), to acquire a velocity dispersion of 2.5 km/s. From Eq. (3) with \(g = 3\) we then
obtain:

\[ t_{2.5} = 5 \text{ Gyr} \left( \frac{\rho_h}{0.1 \text{ M}_\odot/\text{pc}^3} \right)^{-1} \left( \frac{M_h}{5 \times 10^3 \text{ M}_\odot} \right)^{-1} \left( \frac{\sigma_h}{20 \text{ km/s}} \right) \]  

(4)

Since many of the recent dynamical models suggest mean dark matter densities within the stellar core radius of UMi \( \gtrsim 0.1 \text{ M}_\odot \text{ pc}^{-3} \), corresponding to a central mass-to-light ratio of \( \gtrsim 15 \text{ M}_\odot/\text{L}_\odot \) (Lake 1999; Prvor & Kormendy 1994; Irwin & Hatzidimitriou 1995; Mateo 1998; Wilkinson et al. 2006), \( \rho_{dm} = 0.1 \text{ M}_\odot \text{ pc}^{-3} \) will be accepted as a conservative reference value.

The mean-square radius of the subpopulation increases in time with \( \sigma_s \), according to the relation \( r^2 \simeq \sigma_s^2/\Omega^2 \), where \( \Omega \) is the orbital frequency in the constant-density core. If the core is dominated by the dark matter component \( \rho_{dm}/\Omega^2 = (4\pi G/3)^{-1} \), then

\[ r^2 = r_0^2 + \frac{f}{\sqrt{\pi}} GM_h t . \]  

(5)

If \( \sigma_s = 2.5 \text{ km/s} \), the mean radius \( \sqrt{\pi} r \simeq \sigma_s/\Omega \approx 60 \text{ pc} \). This corresponds to a 1 \( \sigma \) radius of 25.5 pc for a Gaussian density profile, implying an angular size of almost 2' at the distance of UMi (\( \sim 66 \text{ kpc} \)). This value is comparable to but slightly larger than the observed 1 \( \sigma \) radius of the secondary peak \( \sim 1.6' \). As a consequence, \( \sigma_s \lesssim 2.5 \text{ km/s} \); otherwise, the stellar subpopulation would appear more extended and diffuse than is observed. This upper value is in agreement with the observations of K03.

Our estimates for the size and velocity dispersion of the subpopulation are independent of the eccentricity of the orbit because there is little variation of the macroscopic properties of the halo, \( \rho_h, \sigma_h \), and \( \Omega \), within the core where the clump is orbiting. Nevertheless, the dark halo could have suffered significant evolution due to two-body processes and tidal stirring. For \( M_h \lesssim 10^5 \text{ M}_\odot \), relaxation processes induce an insignificant change in the internal properties of the halo (e.g., Lim et al. 2005). Tidal heating can lead to a reduction of both the density of dark matter particles and its velocity dispersion (e.g., Mayer et al. 2001B; Read et al. 2006). Since the phase-space density, \( \rho_h/\sigma_h^3 \), for collisionless systems is nearly constant or decreases with time, the rate of energy gained by the clump due to encounters with VMOs should have been more intense in the past. The inclusion of evolution of halo properties by tidal effects would lead to a stringent upper mass limit.

If the stellar progenitor cluster became unbound immediately after formation when supernovae expel the gas content (Goodwin 1997; K03), \( t_{2.5} \) should be greater than the age of the cluster \( t_H \sim 10 \text{ Gyr} \). This requirement combined with Eq. (4) implies:

\[ M_h \lesssim 2.5 \times 10^3 \text{ M}_\odot \left( \frac{\rho_h}{0.1 \text{ M}_\odot/\text{pc}^3} \right)^{-1} \left( \frac{\sigma_h}{20 \text{ km/s}} \right) . \]  

(6)

If initially the stellar cluster is gravitationally bound, the increase in the internal energy gained by encounters with VMOs will eventually exceed its binding energy after a time \( t_{be} \). Let us estimate \( t_{be} \), the time at which the cluster becomes unbound. K03 infer a total mass of the cluster, \( M_h \), of \( 3 \times 10^4 \text{ M}_\odot \). If this cluster followed the recently observed relation between radius and mass of Larsen (2004), \( r_{1/2} \approx 4 \text{ pc} \). Adopting the reference values of the dark matter halo (\( \rho_{dm} = 0.1 \text{ M}_\odot \text{ pc}^{-3} \) and \( \sigma_h = 20 \text{ km/s} \)) and rescaling the survival diagram of Klessen & Burkert (1996) (their figure 11) for the parameters of UMi, we infer that more than 95% of the clusters with mass \( 3 \times 10^4 \text{ M}_\odot \) will become unbound after \( t_{be} \approx 3 \text{ Gyr} \) if \( M_h \gtrsim 3.5 \times 10^5 f^{-1} \text{ M}_\odot \). Therefore, in order to have a dynamically cold subpopulation with \( \sigma_s < 2.5 \text{ km/s} \), as that observed in UMi at the present time \( t_H \sim 10 \text{ Gyr} \), we need \( t_{2.5} \gtrsim t_H - t_{be} \), which implies the following upper limit for \( M_h \):

\[ M_h \lesssim 3.5 \times 10^3 \text{ M}_\odot \left( \frac{\rho_h}{0.1 \text{ M}_\odot/\text{pc}^3} \right)^{-1} \left( \frac{\sigma_h}{20 \text{ km/s}} \right) . \]  

(7)

Other corrosive effects such as mass loss by stellar evolution or tidal heating may also accelerate the dissolution of the cluster. Therefore, our estimates for \( t_{be} \) and, hence, for \( M_h \), are upper limits.

The survival probability after collisions with VMOs increases for progenitors that are more compact. For instance, if the progenitor were a supercluster with a core radius \( r_c \approx 0.5 \text{ pc} \) and central density \( \sim 3 \times 10^4 \text{ M}_\odot \text{ pc}^{-3} \), the probability of its remaining gravitationally bound after 6 Gyr is \( \sim 25\% \), for \( M_h = 6.5 \times 10^3 f^{-1} \text{ M}_\odot \). Hence, there may be a non-negligible probability that such a supercluster has survived bound for 6 Gyr and that during the subsequent 4 Gyr it is dynamically heated by \( 6.5 \times 10^3 f^{-1} \text{ M}_\odot \) VMOs to reach \( \sigma_s = 2.5 \text{ km/s} \) at the present time. Unfortunately, the evaporation time for this supercluster, setting the scale for dynamical dissolution by internal processes, is very short. In fact, for such a stellar cluster, the evaporation time is \( \sim 20 t_{be} \), with \( t_{be} \) the half-mass relaxation time (Gnedin & Ostriker 1997). The resulting evaporation time is \( \lesssim 1 \text{ Gyr} \) for an average stellar mass \( \sim 1 \text{ M}_\odot \) and, hence, internal processes would have produced a fast desintegration of such a cluster. We conclude that the upper limit given in Eq. (7) is realistic and robust.

Our approximations break down when the halo only contains a few VMOs; at least 5 objects within a radius of 600 pc are required, implying that our analysis is restricted to masses \( M_h < 2 \times 10^6 f \text{ M}_\odot \). In Fig. 2 the observational limits on VMOs over a wide range of masses and dark matter fractions are shown.

### 4. Discussion and conclusions

The analysis of the survival of Fornax’s GCs rules out the mass range that would be interesting for explaining the origin of dark matter cores in dwarf galaxies (K03; Goerd et al. 2006; Sánchez-Salcedo et al. 2004), because the relaxation timescale for VMOs of mass \( 5 \times 10^4 \text{ M}_\odot \) exceeds the Hubble time. Moreover, it was found that the integrity of cold small-scale clustering seen in some dSphs imposes more stringent constraints on the mass of VMOs. A source of uncertainty is the mean density of dark matter within the core of dSphs. In the particular case of UMi and according to the scaling relations compiled in Kormendy & Freeman (2004), the corresponding central dark matter density is \( 0.35 \text{ M}_\odot \text{ pc}^{-3} \). A slightly larger value has been derived from its internal dynamics (Wilkinson et al. 2006). At a density \( \rho_{dm} = 0.35 \text{ M}_\odot \text{ pc}^{-3} \), Eq. (7) implies that \( M_h \lesssim 1000 f^{-1} \text{ M}_\odot \). We strongly encourage better determinations of the velocity dispersion of cold density aggregates (bound or unbound) in dSphs. For instance, if the preliminary quoted value of 0.5 km/s for the secondary peak of UMi were confirmed,
our upper limit for \( M_h \) would be immediately reduced by a factor of 25, implying a very tight bound \( M_h \lesssim (40-120) f^{-1} M_\odot \), depending on the adopted dark matter density (0.3 \( M_\odot \) pc\(^{-3}\) to 0.1 \( M_\odot \) pc\(^{-3}\)).

In a unified scheme such as the ‘stirring scenario’ by Mayer et al. (2001), the composition of the dark halos of low-surface brightness and dSph galaxies should be the same. Rix &Lake (1993) found an upper limit of \( 10^4 M_\odot \) by examining the dynamical heating of the stellar disk of GR 8 (Tremaine & Ostriker 1999) warn about the weakness of the argument of Rix & Lake (1993) because the rotation curve of GR 8 decays in a Keplerian fashion as expected if the dark halo has evaporated by two-body collisions. However, there exist dwarf galaxies with flat rotation curves. From the sample of Hidalgo-Gáméz (2004), we have selected dwarf galaxies with high inclination and estimated the maximum permitted value of \( M_h \) consistent with the thickness of the old stellar disk. Perhaps one of the most pristine cases is the edge-on galaxy UGCA 442. This galaxy shows the typical flat rotation curve, implying the existence of a halo of dark matter with a central density of \( 0.\)\( h \) pc\(^{-3}\) to \( 0.1 \) \( M_\odot \) pc\(^{-3}\).

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The value has been updated according to the discussion in Sánchez-Salcedo (1999), §1.
Fig. 1.— Survival diagram for GCs in Fornax’s halo for $\rho_h M_h = 10^3 M_\odot^2 \text{pc}^{-3}$. If GCs had core radii in the range from 0.5 to 2 pc, their probability of survival after 10 Gyr would be less than 1% in the region left and above the thick line. The core radii of Fornax 3, 4 and 5 lie within the mentioned range, but Fornax 1 and 2 present core radii of 10 and 5.6 pc, respectively (Mackey & Gilmore 2003). Therefore, the probability of survival for the latter GCs will be much less than 1%. 

![Graph showing survival diagram for GCs in Fornax's halo](image-url)
Fig. 2.— Observational constraints on VMOs from MACHO microlensing experiments, the distribution of wide binaries in the thoroughly validated Bassel mass model of the Milky Way (Bissantz, Englmaier & Gerhard (2003)), the heating of the Galactic disk, the heating of the stellar disk of UGCA 442, and the survival of UMi’s dynamical fossil in UMi with $\rho_{dm} = 0.35 \, M_\odot \, pc^{-3}$. 
