What is a galaxy? How Cold is Cold Dark Matter?  
Recent progress in Near Field Cosmology

Gerard Gilmore¹, Dan Zucker¹, Mark Wilkinson², Rosemary F.G. Wyse³, Vasily Belokurov¹, Jan Kleyna⁴, Andreas Koch⁵, N. Wyn Evans¹, Eva K. Grebel⁶
¹) Institute of Astronomy, Cambridge, UK; ²) Leicester University, UK; ³) Johns Hopkins University, Baltimore, USA; ⁴) Institute for Astronomy, University of Hawaii, USA; ⁵) Dept of Physics and Astronomy, UCLA, USA; ⁶) Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Germany.

Abstract. There has been a vast recent improvement in photometric and kinematic data for star clusters, Ultra Compact dwarfs, galactic nuclei, and local dSph galaxies, with Subaru contributing substantially to the photometric studies in particular. These data show that there is a bimodal distribution in half-light radii, with stable star clusters always being smaller than 35pc, while stable galaxies are always larger than 120pc. We extend the previously known observational relationships and interpret them in terms of a more fundamental pair of intrinsic properties of dark matter itself: dark matter forms cored mass distributions, with a core scale length of greater than about 100pc, and always has a maximum central mass density with a narrow range. The dark matter in dSph galaxies appears to be clustered such that there is a mean volume mass density within the stellar distribution which has the very low value of about $0.1M_\odot\text{pc}^{-3}$. None of the dSphs displays kinematics which require the presence of an inner cusp, while in two dSphs there is evidence that the density profile is shallow (cored) in the inner regions. The maximum central dark matter density derived is model dependent, but is likely to have a mean value (averaged over a volume of radius 10pc) of about $0.1M_\odot\text{pc}^{-3}$, which is $5\text{GeV}/c^2\text{cm}^{-3}$). Galaxies are embedded in dark matter halos with these properties; smaller systems containing dark matter are not observed.

1. What is a galaxy

The existence of a clear observational distinction between massive star clusters and low-mass galaxies has been substantially strengthened recently, both through detailed studies of more luminous and massive star clusters in a wide range of environments, and through discovery of a large number of extremely low-luminosity satellite galaxies around the Milky Way (e.g. Willman et al. 2005; Belokurov et al. 2007) and around M31, mostly based on imaging from the SDSS, usually with supplementary - and crucial! – Subaru studies.

Fig. 1 shows the current sample in a plot of half-light radius against absolute magnitude in the V-band. Star clusters in all studied environments, with luminosities over the whole range from $M_V = -4$, $L \sim \ 10^3 \ L_\odot$, up to $M_V = -15$, $L \sim \ 10^9 \ L_\odot$, and a wide range of ages, invariably have characteristic scale sizes $r_h$ less than about 30pc. Thus the dynamical range over which both star clusters and galaxies exist, and over which there is a distinct size dichotomy, has now
been established to cover some six orders of magnitude in stellar luminosity. Figure 1 makes evident that there is a robust maximum radius to star clusters, at all luminosities. Figure 1 also illustrates that the dSph galaxies in both the Milky Way and in M31 have a minimum characteristic radius, and this minimum is a factor of > 4 larger than the largest star clusters. With the exception of the recently discovered object ComaBer (Belokurov et al. 2007) – the largest and brightest of the four systems indicated by open stars in Fig. 1 – there is no known object in the size-gap between $\sim 35\text{pc}$ and $\sim 120\text{pc}$. ComaBer manifestly merits further study, but is one of the new dSph which lie between the Sgr dwarf and the Magellanic Clouds, and which show significant indications of tidal disruption.

It is more correct to say that, modulo ComBer, there is no known stable object in the size gap. Fig 1 (lower panel) illustrates this further, showing that all possible transition objects are in a tidally-affected region, close to the Galactic centre. This intermediate size can be occupied transiently by a larger object.
Near-field cosmology

(a dwarf galaxy) in the very late stages of disruption by external (Galactic) tides, or by a small object (globular cluster) in the last stages of evaporation. In the first of these cases a low velocity dispersion compact core can be generated transiently, if outer, hotter, stars are removed by a suitable tide. In the second case the density profile changes systematically from the small scale typical of a compact star cluster to a very large scale, almost constant density, covering all possible radii during that (short-lived) process. Segue 1, Will 1 and Boo-II are also newly discovered and interesting tests of the conclusions of this section, with all showing photometric evidence for significant tidal disturbance. The two largest Galactic globular clusters are Pal 14, with size 28 pc, and Pal 5, 24 pc. Pal 5 is in an advanced stage of tidal disruption, with prominent streams of stripped stars (Odenkirchen et al. (2003)).

The largest Ultra Compact Dwarf galaxies (UCDs), also with size 25pc, are associated with the centre of the Virgo cluster, and the galaxy M87, and were for a long time suspected of being small galaxies severely affected by tides. Our interpretation of their status, based on their position in Figure 1, is that they are simply very massive star clusters, with no associated dark matter, perhaps embedded in a lower surface brightness galaxy which has an associated dark matter halo. There are two recent detailed dynamical analyses of the masses of ultra compact dwarf galaxies, by Hilker et al. (2007) and by Evstigneeva, Gregg, Drinkwater, & Hilker (2007). They show that all these systems are similar, in structure and dynamics, and that the dynamical mass-to-light ratios for the UCDs are (almost) consistent with simple stellar models: there is no evidence for any dark matter associated with these objects. They are the (very) high-mass/high-luminosity extreme of more typical globular cluster populations. We note a recent study by Dabringhausen et al. (2008) which has 2 UCD and one compact elliptical in or close to the size gap. The compact elliptical is M32, which is in tidal interaction with M31. The 2 UCDs are in fact systems in which there is a small UCD (radius 10pc) embedded in an extended (200pc) halo. The plotted size is the mean of these two, and is not the UCD. The size gap remains empty of stable objects. We have apparently really identified a minimum size for a galaxy.

2. Mass profiles in dSph galaxies

We can know more than just the sizes of the dSph galaxies. Extensive kinematic studies provide the information to determine dark mass profiles in these galaxies. Gilmore et al. (2007) describe in detail the current status of a uniform Jeans’-equation based study. Fig 2 here summarises that information. We conclude that the Jeans analysis demonstrates that the observed velocity dispersion profiles and cored light distributions of dSphs are consistent with their inhabiting dark matter haloes with central cores. Where sufficient data exist, more sophisticated distribution function modelling also, in every case studied, produces a small preference for cored dark matter mass distributions at small scales. We find no evidence in any case to support the cusped profile predicted by standard CDM models. The implications of this are discussed further by Gilmore et al. (2007), and summarised in our abstract.
Figure 2. Derived inner mass distributions from isotropic Jeans’ equation analyses for six dSph galaxies. The modelling is reliable in each case out to radii of log \( r \) kpc \( \sim 0.5 \). The general similarity of the inner mass profiles is striking, as is their shallow profile, and their similar central mass densities. Also shown is an \( r^{-1} \) density profile, predicted by many CDM numerical simulations. The dynamical analyses are described in more detail in [Gilmore et al.] (2007).

Briefly, it seems that all dSph galaxies have cored mass distributions, with surprisingly low central mass densities. This mass distribution is associated with an even more surprising large spatial scale length. The central mass densities seen are of order \( 10 \text{GeV}/c^2 \text{cm}^{-3} \), while we note that the mass scale of the Higgs, and its heavier partners, is above \( 100 \text{ GeV}/c^2 \) per particle. The corresponding length scales are of order \( 10^{18} \text{m} \), significantly longer than expected for extremely low velocity dispersion ‘cold’ particles.

References

Belokurov, V. et al 2007 ApJ, 654, 897
Dabringhausen, J., Hilker, M., & Kroupa, P., 2008 arXiv:0802.0703
Efstigneeva, E.A., Gregg, M.D., Drinkwater, M.J., & Hilker, M., 2007 AJ 133 1722
Gilmore, G., Wilkinson, M., Wyse, R.F.G., Kleyna, J., Koch, A., Evans, N. Wyn, & Grebel, Eva T., 2007 ApJ 663 948
Hilker, M., Baumgardt, H., Infante, L., et al. 2007 A& A 463 119
Odenkirchen, M., etal 2003 AJ 126 2385
Willman, B., et al. 2005, AJ, 129, 2692