SCIENCE

First Evidence for an Extended Dark Halo in the Draco Dwarf Spheroidal

Jan T. Kleyna, Mark I. Wilkinson, Gerard Gilmore, N. Wyn Evans (IoA)

Over the past several years, we have been engaged in a project to obtain velocities at large radii in the Draco and Ursa Minor dwarf spheroidal (dSph) galaxies. Draco and UMi are low-luminosity ($L \approx 2\times10^5 L_\odot$) galaxies about 70 kpc from the Milky Way. Stellar velocity measurements in the centres of Draco and UMi suggest a central mass-to-light ratio $M/L \approx 10^2\ M_\odot/L_\odot$ (Aaronson, 1983; Armandroff, Olszewski, & Pryor, 1995; Hargreaves et al., 1996). If this excess mass takes the form of dark matter, then Draco, UMi, and other dSphs with large M/L should be excellent laboratories in which to study structure formation and dark matter haloes: low mass galaxies like the dSphs are probably the basic components from which all larger structures form, and an understanding of the low-mass end of the galaxy spectrum provides an important constraint for evaluating Cold Dark Matter (CDM) and other theoretical models of structure formation.

In the past, stellar velocity measurements have been concentrated in the cores of dSphs, and dynamical modelling has largely been limited to fitting the central velocity dispersion to an isotropic mass-follows-light King profile. However, the assumption that mass follows light is known to be incorrect for virtually all other galaxies, and the assumption of isotropy masks the crucial degeneracy between anisotropy and mass. Thus, a prime objective of this work is to obtain stellar velocities at large projected radii within Draco and other northern dSphs. Combined with modelling methods that relax the assumption that mass follows light and permit varying halo shapes, this new data set should allow us to map out the true masses and shapes of dSph matter distributions.

Draco

With the commissioning of the AUTOFIB2/WYFFOS instrument on the WHT, it became possible to obtain simultaneous spectra of about a hundred stars over a one degree field, overcoming the problem of Galactic contamination near the outer limits of the dSphs' stellar distribution. In four nights in June 2000, we were able to measure the velocities of 159 Draco member stars, extending nearly to the King tidal radius (Kleyna et al., 2001). From these data, it is apparent that Draco's velocity dispersion remains flat or even increases with radius, strongly suggesting the presence of an extended dark halo. An isotropic Jeans equation mass estimate of the mass contained within Draco's light distribution gives $M \sim 10^8\ M_\odot$, with a mean mass-to-light ratio $M/L \approx 500\ M_\odot/L_\odot$.

By performing a maximum likelihood fit of Draco to a family of dynamical models parameterised by the halo shape and anisotropy (Wilkinson et al., 2002), it was possible to lift the degeneracy between Draco's mass and orbital anisotropy. In these models, the overall velocity normalisation was fitted by the projected central dispersion, the halo shape parameter α could vary from from mass follows light ($\alpha=1$) to constant density ($\alpha=-2$), and the logarithmic anisotropy parameter ν could be radially anisotropic ($\nu>0$) or tangentially anisotropic ($\nu<0$). The likelihood contours of Figure 1 shows the result of our modelling: Draco is fit best with an isotropic orbital distribution in a halo that becomes approximately isothermal ($\alpha \approx 0$) at large radii. Both a mass-follows-light distribution and a completely flat halo density are ruled out at the ~2.5σ level. The best fit mass, $M \sim 8\times10^7 M_\odot$, is similar to the Jeans estimate.

Ursa Minor

Ursa Minor (UMi) resembles Draco in size, luminosity, and velocity dispersion. Unlike Draco, it is elongated and appears to have a second peak along the major axis. Often, this peak

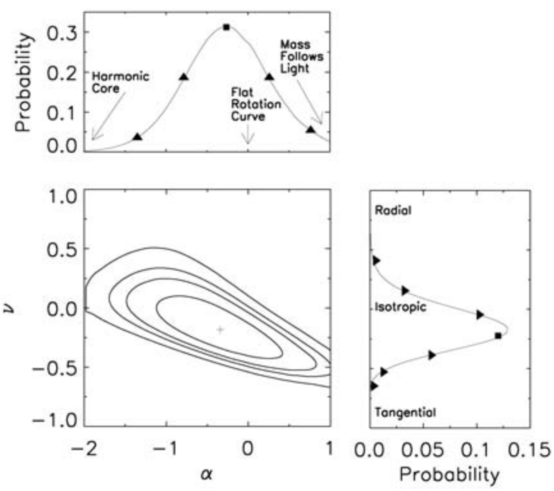

Figure 1. Likelihood contours of the fit of our Draco data to the two-parameter α,ν models of Wilkinson et al. (2002). The contours are at enclosed two-dimensional χ^2 probabilities of 0.68, 0.90, 0.95, and 0.997. The most likely value is indicated by a plus sign. The top and right panels of each plot represent the probability distributions of α and ν, respectively; the median of each distribution is represented by a square, and the triangles show the 1σ, 2σ and (for ν) 3σ limits.

is attributed to tidal disruption, though a plausible mechanism for this has not been proposed. In May 2002, we undertook a 4-night AF2/WYFFOS run to obtain large-radius stellar velocities in UMi, with the aim of fitting for the halo shape and orbital anisotropy using our α, ν models. However, 2.5 nights were clouded out, and poor seeing limited the quality of the data of the remaining 1.5 nights.

Though our data was insufficient for detailed modelling, we were nevertheless able to obtain a number of velocities in the vicinity of UMi's second density peak. After combining our data set with previously published UMi velocities, we noted that the velocity histogram of the clump appeared narrower than the dispersion of UMi as a whole (Kleyna et al., 2003). Accordingly, we modelled UMi's velocity distribution as the sum of two Gaussians: a Gaussian subpopulation with adjustable normalisation, width and mean, and an 8.8 km s^{-1} Gaussian representing the bulk of UMi's stars. We then scanned the face of UMi to determine where there was a signature of a kinematical subpopulation. As suggested by the histograms, only the region near the second clump contained statistically significant (p=99.45%) evidence of a second kinematical population (Figure 2).

We note that a dynamically coherent population can survive inside a cored halo, because sinusoidal orbits in the (nearly) harmonic potential of a core do not diverge over time. However, kinematical substructure would be quickly smeared out if UMi's halo had a density cusp, as predicted by CDM. Detailed dynamical simulations demonstrate that a cold clump could survive for a Hubble time in a 5×10^7 $M_\odot$ UMi-like dSph if the halo has a core larger than ~500 pc. If the halo has a cusp, however, all evidence of substructure is erased within several hundred million years.

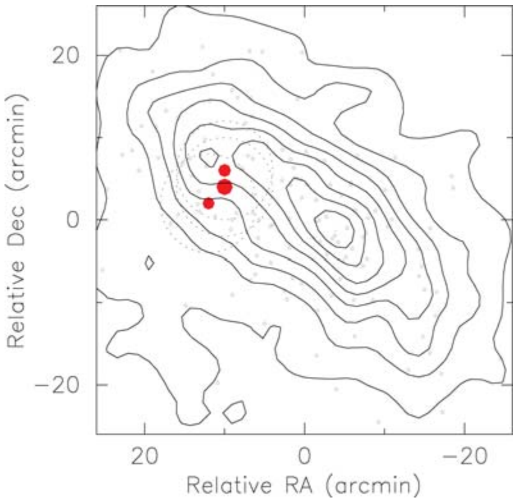

Figure 2. Result of search for kinematic sub-populations in UMi. Coutours are linearly spaced stellar isopleths; the second peak of UMi's stellar population is visible above and to the left of the centre. Gray stars are UMi red giant branch member stars with measured velocities. The filled circles represent points where a model with a kinematically cold sub-population is at least 1000 times more likely than a model composed of a single 8.8 km s^{-1} Gaussian. The size of each dot is proportional to the logarithm of the relative likelihood.

Summary

Using large-radius velocity data obtained using AF2/WYFFOS, we show that the Draco dSph possesses an anisotropic velocity distribution and a dark halo that is isothermal in the limit of large radii. In Ursa Minor, we show that the second peak in the stellar density has a cold kinematical signature. This signature strongly suggests that the feature is a persistent clump sloshing back and forth within a dark matter core, and is inconsistent with the cusped halos that are predicted by Cold Dark Matter theory.¤

Jan Kleyna (kleyna@ast.cam.ac.uk)

References:

Aaronson, M., 1983, *ApJ*, **266**, L11.

Armandroff, T. E., Olszewski, E. W., Pryor, C., 1995, *AJ*, **110**, 2131.

Hargreaves, J. C., Gilmore, G., Irwin, M. J., Carter, D., 1996, *MNRAS*, **282**, 305.

Kleyna, J. T., Wilkinson, M. I., Evans, N. W., Gilmore G., 2001, *ApJ*, **563**, L115.

Kleyna, J. T., Wilkinson, M. I., Gilmore G., Evans, N. W., 2003, *ApJ*, **588**, L21.

Wilkinson M. I., Kleyna, J. T., Evans, N. W., Gilmore G., 2002, *MNRAS*, **330**, 778.

The SAURON Deep Field: Investigating the Diffuse Lyman-α Halo of "Blob1" in SSA 22

R. G. Bower[1], S. L. Morris[1], R. Bacon[2], R. Wilman[1], M. Sullivan[1], S. Chapman[3], R. L. Davies[4], P. T. de Zeeuw[5]

1: Physics Department, University of Durham. 2: CRAL-Observatoire, Lyon. 3: California Institute of Technology. 4: Dept. of Astrophysics, University of Oxford. 5: Sterrewacht Leiden.

Recent studies of star-forming objects in the early universe, measuring their clustering properties and determining their luminosity functions, have shown that these galaxies are key to understanding the star formation and metal enrichment history of the universe and the role of galactic "super-winds" in regulating the conversion of baryons into stars.

In this article, we describe how, using the SAURON integral field spectrograph, we study the formation of the most massive galaxies in the Universe. The primary target is the bright Ly-α emission line halo in the conspicuous SSA 22 super-cluster at z=3.07–3.11 (Steidel et al., 2000). The highly-obscured very luminous submillimeter galaxy found by SCUBA near the centre of this halo probably is an example of a forming massive elliptical galaxy (Chapman et al., 2001).