Probing the Dark Matter Content of Local Group Dwarf Spheroidal Galaxies with FLAMES

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We present preliminary kinematic results from our VLT programme of spectroscopic observations in the Carina dwarf spheroidal galaxy using the FLAMES multi-object spectrograph. These new data suggest that the dark matter halo of this galaxy has a uniform density core. The implications for our understanding of the nature of the dark matter are discussed.

Dark matter in dSphs

According to the current cosmological paradigm, non-luminous, non-baryonic matter contributes approximately 20 % of the overall mass-energy budget of the Universe. Locally, on the scale of galaxies like the Milky Way, it constitutes about 90 % of the gravitating mass. Determining the nature of this dark matter is a key goal of contemporary astronomy. The dwarf spheroidal galaxies (dSphs) of the Local Group provide a particularly valuable window on the properties of dark matter on small (~ 1 kpc) scales. Several of these low-luminosity galaxies have been found to have extremely large mass-to-light (M/L) ratios (up to 1000 in solar units) which suggests that these are the most dark-matter-dominated stellar systems known in the Universe (e.g. Kleyna et al. 2001, Wilkinson et al. 2004, Mateo et al. 1998). Given the apparent absence of dark matter in globular star clusters, they are also the smallest stellar systems (in terms of stellar mass and radial length scale) which are inferred to contain dynamically significant quantities of dark matter.

The proximity of the Milky Way dSph satellites makes it feasible to obtain spectra for large numbers of individual stars in them, facilitating more detailed studies of their properties than are possible for galaxies beyond the Local Group. These spectra provide radial velocities and chemical abundance determinations which, respectively, enable us to to probe the stellar velocity distribution function and halo potential within a dSph and provide detailed information about the star-formation history of these systems.
Two recent Messenger articles have discussed in detail the insights into the chemical evolution of the stellar populations in dSphs which have been gained by recent observations with the FLAMES spectrograph on the VLT (Koch et al. 2006a; Tolstoy et al. 2006). In this article we will focus on the implications of the kinematic data in the Carina dSph for our understanding of the dark matter.

The dSphs are the lowest-luminosity satellites of the Milky Way and M31, characterised both by their low stellar luminosities (up to 2×10^7 solar luminosities, with the majority in the range 10^5–10^6 solar luminosities) and the apparent absence of gas and on-going star formation. The recent discovery of the Ursa Major dSph (Willman et al. 2005) and the Canes Venatici (Zucker et al. 2006) and Bootes (Belokurov et al. 2006) dSph candidates brings to twelve the number of dSphs around the Milky Way. A similar number have been identified orbiting M31. At least one dSph is clearly being disrupted by the tidal field of the Milky Way – the Sagittarius dSph has extensive debris trails which have been observed over much of the sky. The stellar distributions of most dSphs exhibit some level of disturbance in their outer regions, although whether this is due to their proximity to their parent galaxies remains controversial. Although the dSphs were once thought to be the primordial building blocks whose disruption contributed to the hierarchical build-up of the stellar halo of the Milky Way, recent studies have found that the chemical composition of the stars in the present-day dSphs differs substantially from that of field stars (Shetrone et al. 2001; Tolstoy et al. 2006). Thus, the Galactic halo was not predominantly formed by disrupting galaxies like the present-day dSphs. Nevertheless, the chemical properties of dSphs provide valuable insights into the processes of galaxy formation and evolution on the smallest scales.

It is the large apparent mass-to-light ratios of dSph galaxies, and the conclusion that they contain significant amounts of dark matter, that has caused them to attract much attention in recent years. The first evidence of this emerged in 1983, when Aaronson published velocity measurements of three carbon stars in the Draco dSph. These data implied a velocity dispersion for Draco of 6.5 km/s, from which Aaronson cautiously inferred a mass-to-slight ratio of 30 solar units. As this was significantly higher than the values typical of globular star clusters, this provided the first hint that the dSphs were a class of stellar system distinct from the globular clusters, despite the fact that in many cases their stellar mass was similar. Subsequent observations have borne out these early estimates and all dSphs observed to date have velocity dispersions in excess of 6.5 km/s.

By 1998, due to the dedicated efforts of several teams, velocity dispersions had been measured for eight dSphs (Mateo 1998). However, dSph velocity distributions were still represented solely by the central velocity dispersion, which contains only limited information about the nature of the system. The situation changed in 1997, with the publication of the first velocity dispersion *profile* for a dSph (Mateo 1997). Using 215 individual stellar velocities in Fornax, Mateo showed that the velocity dispersion remains approximately flat almost to the edge of the light distribution. This profile is inconsistent with the simplest model of Fornax in which the mass is distributed in the same way as the light and the stars have an isotropic velocity distribution.

The past decade has seen a rapid increase in the size of dSph kinematic data sets, driven by the availability of multi-object spectrographs on 4-m to 10-m-class telescopes which allow the simultaneous acquisition of spectra for large numbers of stars. The first dSph disper-

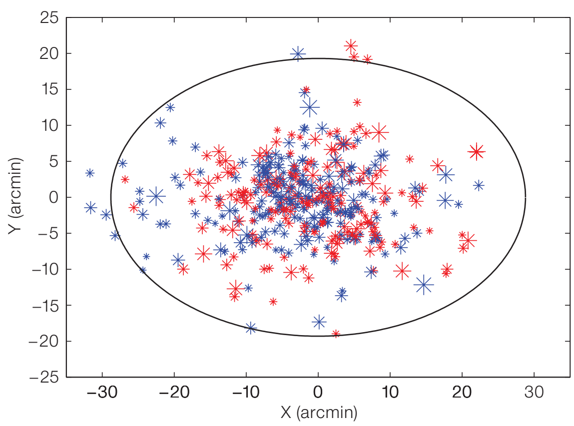

Figure 1: Spatial distribution of Carina members observed in our survey. Stars approaching and receding (relative to Carina) are shown as blue and red symbols, respectively. The size of the symbol is proportional to the magnitude of the radial velocity. The ellipse indicates the nominal tidal limit of Carina with semi-major axis of 28.8 arcmin.

sion profile based on multi-fibre observations was that of Draco, based on velocities for 159 stars obtained using the WYFFOS spectrograph on the William Herschel Telescope (Kleyna et al. 2001). Since that time, dispersion profiles have been measured for all the Milky Way dSphs. For most Milky Way dSphs, the large (25 arcmin diameter) field of view of the FLAMES spectrograph on the VLT is ideally matched to their angular size facilitating the efficient coverage of the full area of each object.

The properties of dSph haloes are largely determined by the physical properties of the dark matter. For example, the number of low-mass dark-matter haloes in the vicinity of a Milky Way-type galaxy is a strong function of the nature of the dark matter – cold dark matter (CDM) simulations typically predict hundreds of low-mass haloes around the Milky Way while warm dark-matter models contain significantly fewer. However, it is currently not clear which objects in the simulations correspond to the observed dSphs. A number of authors have claimed that the properties of dSphs are consistent with their residing in haloes of mass > 10^9 solar masses. In this case, the numbers of dSphs might be consistent with CDM simulations. One of the key goals of our observations in Carina is to test in detail whether its properties are consistent with those of an object with a massive, extended dark halo.

The shapes of the dark-matter density profiles of dSphs are also sensitive to the type of dark matter. Galaxy haloes composed of cold dark matter are predicted to be cusped, with the density in the inner regions rising as $1/r^n$, where n lies in the range 1–1.5. Alternatively, if the dark matter were warm, i.e. composed of particles which had a non-negligible intrinsic velocity dispersion, then this would lead to a shallow or uniform density core, whose size depends on the actual velocity dispersion of the particles. The presence or absence of a cusp, as well as its precise steepness is one of the most direct measurements of the nature of dark matter. There is already evidence of cored haloes in some dSphs (e.g. Kleyna et al. 2003; Goerdt et al. 2006) but the identification of a property of the dark matter requires a universal result. The global stellar kinematics of all the dSphs have not yet been defined sufficiently well to yield definitive results on the inner slope of their dark matter distributions. Our Carina data set will be sufficiently large to place robust constraints on the profile of a dSph dark-matter halo, while our modelling will further the analyses of the data from all the dSphs.

Observations of the Carina dSph

The Carina dSph has previously attracted attention due to its unusual, bursty star-formation history, with the most recent peak occurring around 3 Gyr ago (e.g. Monelli et al. 2003). Its central velocity dispersion is 6.8 km/s (Mateo et al. 1993), implying a mass-to-light ratio of about 30–40 (solar units). Majewski et al. (2005) provide evidence of irregularity in the outer regions of the light profile, perhaps associated with tidal disturbance. Our Carina data were obtained as part of VLT Large Programme 171.B-0520 (PI: Gilmore). The targets were selected to lie on the red giant branch of the colour-magnitude diagram of Carina and span the magnitude range V = 17.5 to 20 (see Figure 2 of Koch et al. 2006a). The photometric and astrometric data for the input catalogue were obtained by the ESO Imaging Survey (EIS) as part of the Wide-Field Imager Pre-FLAMES survey. The spectroscopic data were taken in visitor mode and reduced using the standard GIRAFFE reduction software, with sky subtraction performed using our own in-house software (see Wilkinson et al. 2006 [in prep.] for more details on the data processing). Median velocity errors are 1.2 km/s for the entire data set and 1.5 km/s for the faintest stars (V = 20–20.5).

A total of 1257 targets in Carina were observed. Of these, 535 are probable members of Carina (based on their radial velocities). The remainder are foreground Milky Way stars which can be used to investigate the properties of the velocity distribution of our own Galaxy (see below). Of the probable members, some 437 stars have spectra with sufficient signal-to-noise to enable chemical abundances to be determined using the Calcium triplet estimator (Koch et al. 2006b). The spatial distribution of Carina members from our survey is shown in Figure 1. As our primary goal in this survey is to map out the velocity structure of Carina, it is particularly important to observe stars at large projected radii as these place the strongest constraints on the mass and extent of the galaxy. As can be seen in the figure, our targets probe to the nominal tidal radius of Carina (around 28.8 arcmin). Our sample increases the number of measured stellar velocities for Carina members by almost an order of magnitude and extends to radii at which both the effects of an extended halo as well as the tidal effects of the Milky Way may be observable.

The histogram in Figure 2 shows the distribution of velocities for our full sample of stars along the line of sight to Carina. The members of Carina are clearly visible as the narrow peak centred at about 223.8 km/s. The systemic velocity of Carina is not well separated from the velocities of Milky Way stars along the line

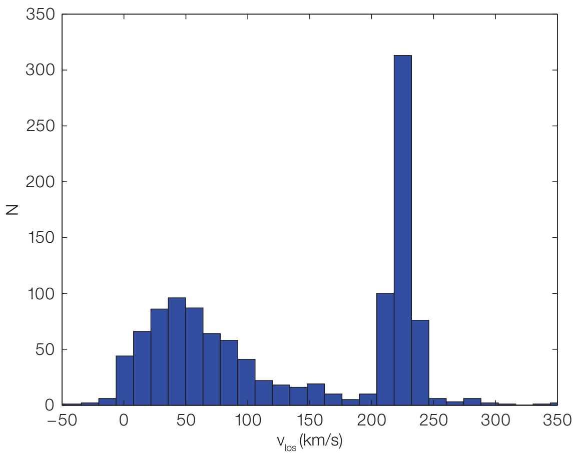

Figure 2: Velocity distribution of all stars observed along the line of sight to Carina. The peak due to Carina members at around 223.8 km/s is clearly visible.

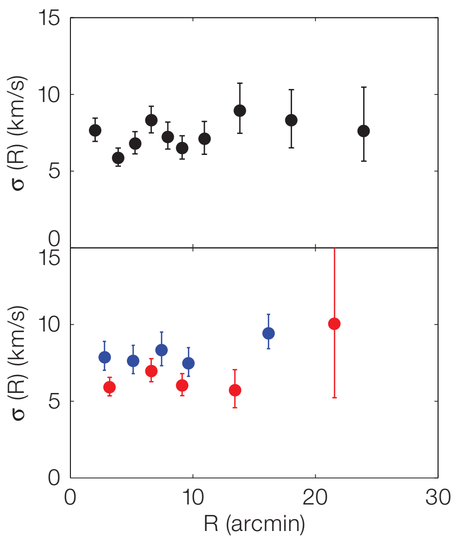

Figure 3: **Top:** Velocity dispersion profile for all stars in Carina. **Bottom:** Velocity dispersion profiles for stars with [Fe/H] < –1.68 (blue) and [Fe/H] > –1.68 (red).

of sight. This makes it more difficult to establish membership, as simple criteria (e.g. the standard velocity cut of three times the internal velocity dispersion) may include a non-negligible level of foreground contamination.

Dark matter in Carina

The large central velocity dispersions in dSphs are usually interpreted as evidence of significant amounts of dark matter. Much stronger constraints on the amount of dark matter in a dSph, as well as its spatial distribution, can be obtained from knowledge of the variation of the velocity dispersion with position in the dSph. In Figure 3 we present the dispersion profile for Carina, plotted as a function of projected radius. To calculate the dispersion in each radial bin of this profile, we assume that the projected velocity distribution in each bin is a Gaussian convolved with the stellar velocity errors (which are also assumed to be Gaussian). We also introduce a power-law interloper velocity distribution to take account of the presence of foreground Milky Way stars in our velocity samples.

The dispersion profile of Carina based on the complete data is remarkably flat, with an amplitude of about 7–8 km/s out to the edge of the data at a radius of approximately 45 arcmin. Koch et al. (2006b) showed that if the stellar population is divided at a metallicity of [Fe/H] = –1.68, the 'metal-rich' sample is slightly more centrally concentrated than the 'metal-poor' population. The lower panel of Figure 3 shows the dispersion profiles for the metal-rich and metal-poor stars in Carina based on the above definition. The amplitude of the dispersion profile of the metal-rich stars appears to be systematically lower than that of the metal-poor stars. This is consistent with their relative spatial distributions, since the more extended metal-poor population would be expected to exhibit a larger velocity dispersion. The observation by Harbeck et al. (2001) that the younger stellar populations in Carina are more centrally concentrated than the older stars, combined with the age-metallicity relation for Carina stars identified by Koch et al. (2006b), would then suggest an interpretation of the kinematic data in terms of a secondary, more recent burst of star formation concentrated towards the centre of Carina.

The flatness of the velocity dispersion profile has important implications for the dark-matter density profile of Carina. For a stellar system in virial equilibrium, the Jeans equations provide a simple estimator of the halo mass distribution once the spatial distribution of the stars and their velocity-dispersion profile are known. Figure 4 shows the density profile inferred from our Carina data set. We have used the surface-density profile determined by Majewski et al. (2005) to determine the stellar-density distribution and have assumed that the gravitational potential is everywhere dominated by the dark matter. Spherical symmetry is assumed and we have simplified the form of the Jeans equations by assuming that the velocity distribution is everywhere isotropic. The black line in the density plot shows the form of the density

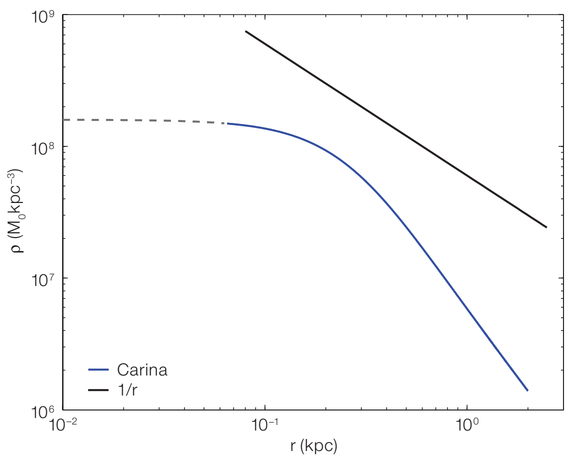

Figure 4: Mass density profile of Carina as inferred from the velocity dispersion profile using Jeans equations and assuming velocity isotropy. The black curve shows the expected relation for a standard cusped halo.

profile expected from cosmological simulations of galaxy formation in the cold dark-matter paradigm. In contrast to the profiles of the haloes seen in simulations, in the central regions of Carina it appears that the dark-matter density is close to uniform.

We emphasise, however, that the dark-matter density profile presented here is based on strong assumptions about the stellar spatial and velocity distributions which may not be justified, particularly at very large radii. By assuming velocity isotropy, we are prey to the strongest degeneracy of this problem, namely that a flat dispersion profile in an isolated dSph can be produced either by the presence of large amounts of mass at large radii, or by radially varying anisotropy in the velocity distribution. In our modelling of the Draco dSph (Wilkinson et al. 2002), we constructed a family of dynamical models which included dark matter haloes of varying extent, as well as radially varying velocity anisotropy. We are currently extending this methodology to new dynamical models appropriate for the (multi-population) case of Carina (Wilkinson et al. 2006, in prep.). These models will enable us to quantify the properties of the dark-matter density profile of Carina. Our models incorporate multiple tracer populations, to enable us to use the metal-rich and metal-poor sub-populations of Carina (and other dSphs) as independent tracers of the underlying dark-matter potential.

In addition to their value in constraining models of the dark matter, it has become apparent that our kinematic data can also be used to investigate the properties of the Milky Way velocity distribution along the line of sight to Carina. Two recent papers have investigated this novel possibility. Wyse et al. (2006) compared the velocity distributions along the line of sight to three dSphs (Carina, Draco and Ursa Minor) and found an excess of stars with an azimuthal velocity of about 100 km/s relative to the predictions of smooth Galaxy models. They conclude that this kinematic structure, which is seen along widely separated lines of sight, may be the remains of an object which fell into the Milky Way at early times, and may even have contributed to the formation of the Thick Disc. In their investigation of our Carina data, and a velocity sample towards M31, Martin et al. (2006) provided an alternative interpretation, namely that they detect the velocity signature of the Monoceros ring, another large stellar structure which is suggested to surround the Milky Way disc at low latitude.

In order to gain a better understanding of what the internal kinematics of dSphs can tell us about the nature of the dark matter, it is important to consider the properties of these objects as a class. In Figure 5, we plot the mass-to-light ratios of the local group dSphs against their absolute V-band magnitudes. The figure is based on that given in Mateo et al. (1998) but includes more recent mass determinations where these are available – the mass for Carina is based on the simple dynamical modelling presented above. The solid curve shows the expected relation for a population of objects with a stellar mass-to-light ratio of unity (solar units) and a total halo mass of 4×10^7 solar masses. In this case, the total mass-to-light ratio, $(M/L)_{Tot}$ is simply given by $(M/L)_{Tot} = (M/L)_{Stars} + M_{DM}/L_V$, where M_{DM} is the mass in dark matter and L_V is the total V-band luminosity. Notwithstanding the significant scatter about this relation, it appears that most observations to date are consistent with dSphs having a common halo mass scale of around 4×10^7 solar masses, generally cored mass distributions, and a low central dark-matter density. It is important to note that this mass scale refers to the mass *interior* to the edge of the stellar distribution, since this is the region which is probed by kinematic observations. Further, several of the dSph mass estimates presented in this plot are based only on the central velocity dispersion – the mass scale may therefore be somewhat different once detailed dynamical models are completed for all dSphs. However, this plot demonstrates that it is possible to interpret the velocity dispersions of dSphs in terms of the intrinsic properties of the dark matter.

Future work

Now that velocities have been measured as far out as the nominal tidal radii in most dSphs, the next major advance will be to obtain usefully large samples of stars at much larger radii. Although Wilkinson et al. (2004), and Munoz et al. (2005) have taken the first steps in this direction, the results are still controversial and larger data sets are needed. The key difficulties are the large areas of sky which must be surveyed, and the preselection of targets in regions where the expected surface density of dSph members is extremely low. However, stars in these regions will provide extremely useful information about dSph haloes. We expect that at some level all dSphs must be affected by the tidal field of the Milky Way. However, thus far there is no definitive *kinematic* evidence of this process in any dSph. Constraining the radii at which the Milky Way begins to disturb dSphs will make it possible to derive the current total mass and extent of their dark haloes. Of course, identifying fundamental properties of the dark matter re-

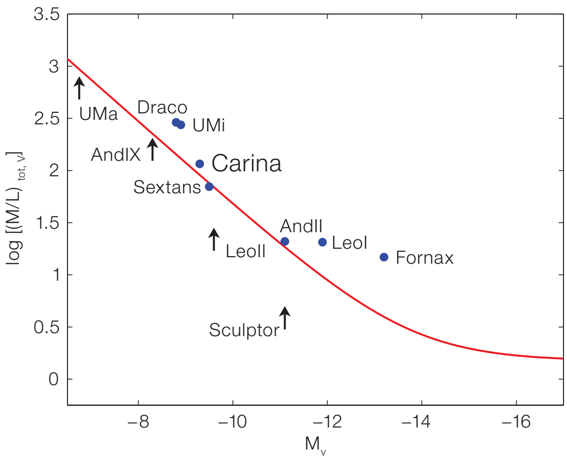

Figure 5: Mass-to-light ratios versus absolute V magnitude for Local Group dSphs. The solid curve shows the relation expected if all dSph haloes contain about 4×10^7 solar masses of dark matter interior to their stellar distributions. Arrows indicate mass estimates which are lower limits based on central velocity dispersions only.

quires that common properties in all the dSphs be identified – we must therefore carry out similar studies of all dSphs.

Finally, in the area of dynamical modelling, identifying correlations between the kinematics and abundances of the stellar populations in dSphs (e.g. Tolstoy et al. 2006) is likely to provide important new information about the formation and evolution of these objects, which in turn will further constrain models of any astrophysical feedback on their dark matter.

Acknowledgements

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A Three-Planet Extrasolar System

Using the ultra-precise HARPS spectrograph on ESO's 3.6-m telescope at La Silla, a team of astronomers[1] has discovered that a nearby star is host to three Neptune-mass planets. The innermost planet is most probably rocky, while the outermost is the first known Neptune-mass planet to reside in the habitable zone. This unique system is likely further enriched by an asteroid belt.

Planetary System around HD 69830 (Artist's Impression).

Over more than two years, the team carefully studied HD 69830, a rather inconspicuous nearby star slightly less massive than the Sun. Located 41 light years away towards the constellation of Puppis, it is, with a visual magnitude of 5.95, just visible with the unaided eye. The team's precise radial-velocity measurements allowed them to discover the presence of three tiny companions orbiting their parent star with periods of 8.67, 31.6 and 197 days.

"Only ESO's HARPS instrument installed at the La Silla Observatory, Chile, made it possible to uncover these planets", said Michel Mayor, from Geneva Observatory, and HARPS Principal Investigator. "Without any doubt, it is presently the world's most precise planet-hunting machine."

The detected velocity variations are between two and three metres per second. Such small signals could not have been distinguished from noise by most of today's available spectrographs.

The newly found planets have minimum masses between 10 and 18 times the mass of the Earth. Extensive theoretical simulations favour an essentially rocky composition for the inner planet, and a rocky/gas structure for the middle one. The outer planet has probably accreted some ice during its formation, and is likely to be made of a rocky/icy core surrounded by a quite massive envelope. Further calculations have also shown that the system is in a dynamically stable configuration.

The outer planet also appears to be located near the inner edge of the habitable zone, where liquid water can exist at the surface of rocky/icy bodies. Although this planet is probably not Earth-like due to its heavy mass, its discovery opens the way to exciting perspectives.

With three roughly equal-mass planets, one being in the habitable zone, and a possible asteroid belt, this planetary system shares many properties with our own Solar System.

(Based on ESO Press Release 18/06)

[1] Lovis et al. 2006, Nature 441, 305. The team is composed of Christophe Lovis, Michel Mayor, Francesco Pepe, Didier Queloz, and Stéphane Udry (Observatoire de l'Université de Genève, Switzerland), Nuno C. Santos (Observatoire de l'Université de Genève, Switzerland, Centro de Astronomia e Astrofisica da Universidade de Lisboa and Centro de Geofisica de Evora, Portugal), Yann Alibert, Willy Benz, Christoph Mordasini (Physikalisches Institut der Universität Bern, Switzerland), François Bouchy (Observatoire de Haute-Provence and IAP, France), Alexandre C. M. Correia (Universidade de Aveiro, Portugal), Jacques Laskar (IMCCE-CNRS, Paris, France), Jean-Loup Bertaux (Service d'Aéronomie du CNRS, France), and Jean-Pierre Sivan (Laboratoire d'Astrophysique de Marseille, France).