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Substructure in dwarf spheroidals – a star cluster connection?

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Abstract. The observational evidence for kinematic substructure in Local Group dSphs is reviewed. The properties of these substructures are consistent with their being disrupted star clusters. The persistence of cold substructure argues strongly against the presence of dark matter cusps in the haloes of dSphs. A formation scenario for dSphs is described involving the merger of star clusters in the potential well of a low-mass dark matter halo.

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1. Observations of kinematic substructure in Local Group dSphs

Dwarf spheroidal galaxies (dSphs) provide a valuable opportunity to test theories of dark matter and of galaxy formation and evolution. An increasing body of data on the kinematics of individual stars in Local Group dSphs appears to confirm early suggestions that these objects contain significant quantities of dark matter (e.g. Aaronson 1983; Evans – this proceedings). However, recent observations have shown that the internal kinematics of these apparently simple stellar systems are more complicated than was first thought (e.g. Wilkinson *et al.* 2004; Tolstoy *et al.* 2004) with distinct stellar populations exhibiting different kinematic signatures.

Observations of Ursa Minor and Sextans in particular have revealed the presence of kinematically cold substructures near the centres of both these dSphs. The left panel of Figure 1 shows the stellar isophotes of Ursa Minor which display a secondary peak offset from the centre of the galaxy (corresponding to the origin of this plot). The velocity distribution of the stars in the vicinity of this secondary peak is significantly narrower than that of the main body of Ursa Minor. If we assume that the velocity distribution in this region can be represented as the combination of two Gaussian components we find that the cold population can be represented by a Gaussian of width $0.5\mathrm{km\,s^{-1}}$ and velocity offset of $1.0\mathrm{km\,s^{-1}}$. In the aperture in which the likelihood ratio of a two-component model compared to a single component model is maximal, approximately 70 per cent of the stars are found to be associated with the cold component (see Kleyna *et al.* 2003 for details). The total luminosity of the component is then roughly $1.5 \times 10^4 \mathrm{L}_\odot$, which corresponds to the luminosity of a low-mass star cluster.

A similar kinematic feature has been identified in the centre of the Sextans dSph, where the velocity distribution inside 10 arcmin (250 pc) is dominated by a kinematically cold component (see Figure 1 and Kleyna *et al.* 2004). The total luminosity of this feature is about $1.3 \times 10^5 \mathrm{L}_\odot$, comparable to the luminosity of Milky Way globular clusters. Kleyna

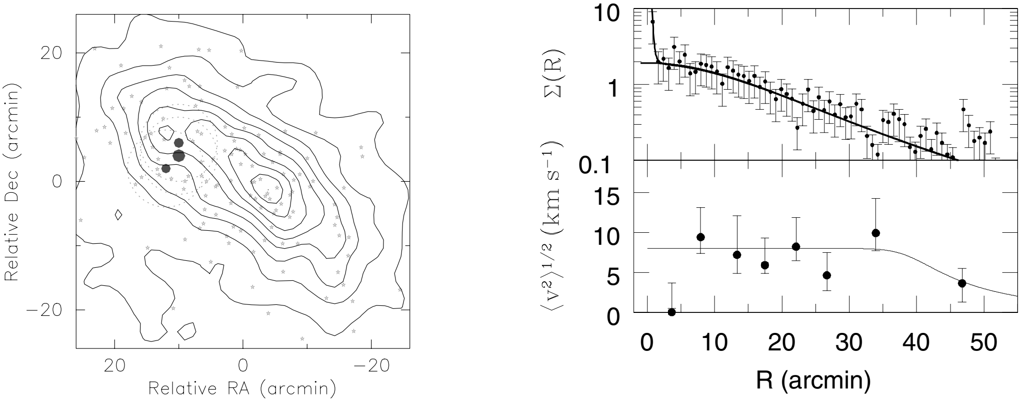

Figure 1. Left: Isophotes of Ursa Minor. The largest dot indicates the aperture in which a velocity distribution which includes a kinematically cold component is 4.7×10^4 times more likely than a single component model (statistical significance 99.94 per cent). (From Kleyna *et al.* 2003). Right: Surface brightness profile (top) and velocity dispersion profile (bottom) of the Sextans dSph. The low dispersion at small radii indicates the presence of cold substructure. (From Kleyna *et al.* 2004).

et al. (2004) suggested that this feature is the remnant of a disrupted star cluster. In addition to explaining the cold kinematics of the centre of Sextans, this picture also explains the surprising observation by Lee *et al.* (2003) that the blue straggler population of Sextans appears to be mass segregated. While this is difficult to understand in the context of a dSph with surface brightness as low as that of Sextans, the disruption of a star cluster within which mass segregation has already taken place would naturally produce the observed difference in the spatial distributions of low and high mass blue stragglers as the high mass objects would typically be found close to the centre of the star cluster and would therefore be the last objects to be removed by tidal disruption.

In Sextans, the spatial scale of the velocity feature matches closely the scale on which the nature of the stellar populations changes, as indicated by the radial variation of the horizontal branch ratio (see e.g. Lee *et al.* 2003; Harbeck *et al.* 2001). Recently, Tolstoy *et al.* (2004) have found that in the Sculptor dSph, differences in the spatial distribution of the stellar populations are mirrored by variations in the velocity dispersions of the populations. A preliminary analysis of our VLT-FLAMES data for the Carina dSph (see Koch – this proceedings – for a discussion of these data) provides hints of velocity substructure in this galaxy also. In the core of Carina, the velocity distribution of the more metal-rich population is noticeably narrower than that of the metal-poor population. This may indicate that at small radii the stellar distribution (and hence the observed kinematics) is dominated by a more concentrated population with smaller velocity dispersion, possibly corresponding to the red clump population identified by Harbeck *et al.* (2001). Thus, kinematic substructure appears to be a common feature in dSphs.

2. Implications of substructure I: cored haloes

The presence of long-lived, cold substructure in Ursa Minor has important implications for the shape of its dark matter halo. If the halo has a cusped density distribution, as expected on the basis of cosmological simulations, then any cold substructure would disperse on a short time-scale. Kleyna *et al.* (2003) presented the evolution of such a substructure on a radial orbit and showed that after 1 Gyr no discernible structure remained. By contrast, substructure in a cored halo can persist for up to 12 Gyrs, due

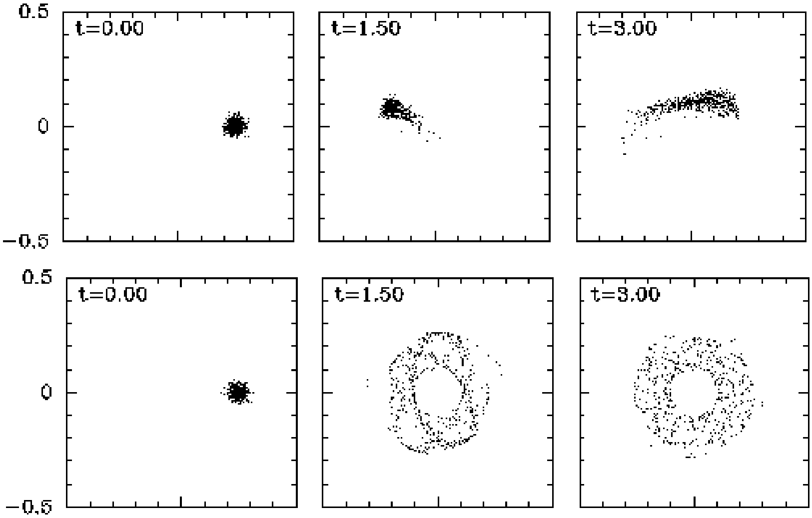

Figure 2. Evolution of cold substructure on orbits with initial tangential velocity equal to half the local circular speed. Results for a cored halo (core radius 0.6 units: top) and a cusped halo ($\rho \sim 1/r$: bottom) up to 3 Gyr are shown. The initial velocity dispersion for the substructure is 1 $\mathrm{km\,s^{-1}}$ in the cored halo and 0.1 $\mathrm{km\,s^{-1}}$ in the cusped halo.

to the fact that orbits in a harmonic gravitational potential are harmonically bounded and therefore orbits remain coherent for a long time. Figure 2 presents the evolution for substructures on more circular orbits, for which the tangential velocity at apocentre is half the local circular velocity. As in the case of a radial orbit, the localised substructure disperses in under 3 Gyr in the cusped potential while in a cored potential localised structure remains (up to 12 Gyr).

The orbits shown in Figure 2, and those presented in Kleyna *et al.* (2003), are all in the plane of the sky. This is driven by the observation that the substructure in Ursa Minor has no significant offset in mean velocity from the bulk velocity of the dSph. Independent of the shape of the potential, any orbit has to be close to face-on in order to avoid giving rise to a measurable line of sight velocity component. The radii of the near-circular orbits were chosen to correspond to the approximate current location of the observed Ursa Minor structure. Given that the timescale for a cluster at large radii to move close to the centre due to dynamical friction is less than a Hubble time, we would typically expect any substructure to have spent several Gyr close to its current location. If the halo had a central cusp there has thus been sufficient time for disruption to occur.

3. Implications of substructure II: origin of dSphs

We have seen that the properties of the kinematic substructure identified in Ursa Minor and Sextans are consistent with those expected for disrupted star clusters. This leads us to consider the possibility that dSphs were built up from the remnants of disrupted clusters. In the Local Universe, it is now well established that all stars form in cluster environments, which range in size from OB associations up to masses comparable to the old Milky Way globular clusters and most of which dissociate within a short time of their formation due to a combination of gas loss and external tidal fields. Given the broad range of star forming environments in which clusters are observed, it is reasonable to suppose that this was also the dominant mode of star formation at the time when the dSphs formed most of their stars. For example, Fellhauer & Kroupa (2002) investigated the merger of star clusters as a possible origin for ultra-compact dwarf galaxies. The merger time for star clusters formed in a small volume is very short – if this merger takes place within the gravitational potential of a dSph galaxy, then dynamical friction will further reduce this time scale. A violent merger at the centre of a halo is likely to produce a significant population of stars on highly radial orbits. In the pure-stellar models of Fellhauer & Kroupa (2002), such stars would be removed by the tidal field of a parent galaxy when they moved to the outer parts of the satellite. Within a dSph halo, however, a large fraction of these stars may remain bound to the galaxy. This population might then explain the sudden fall-off seen in the velocity dispersion profiles of Ursa Minor, Draco and Sextans which would then be properly viewed as arising from the presence of two distinct populations in each dSph each with their own spatial distribution and velocity anisotropy. Surviving cold substructures correspond to later accretions.

4. Conclusions

Recent kinematic observations in Local Group dSphs have shown us that kinematic substructure is relatively common and that the different stellar populations within dSphs often have differing velocity distributions. The survival of cold substructure can be used to infer the shape of the dark matter density distribution and, in particular, can rule out the presence of a cusp in the halo of Ursa Minor. The properties of the substructure are also consistent with a formation scenario in which dSphs are formed through the merger of star clusters in a dark matter halo. Further numerical simulations are underway to confirm that this picture is fully consistent with the observed properties of the dSphs.

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Discussion

TOLSTOY: The abundance differences (e.g. deep mixing patterns) between “globular cluster” stars and “field” stars in dSphs might suggest that it is difficult to build an entire dSph from globular clusters.

WILKINSON: The star clusters which contributed to the bulk population of the dSphs were probably more akin to Milky Way open clusters in terms of their densities and survival times. Thus, one would not necessarily expect to observe deep mixing in dSphs.

LIN: How would the external perturbation produced by the Milky Way tidal field affect the survival of the substructure in Ursa Minor?

WILKINSON: We performed a number of simulations in which we included the tidal field of the Milky Way (modelled as an isothermal sphere with $10^{12}\mathrm{M}_{\odot}$ inside 50 kpc) for a range of Ursa Minor orbits with periods ~ 1.6 Gyr. In no instance did this tidal force significantly affect the survival of substructure either in a cored or cusped halo.