ASTRONOMY FROM WIDE-FIELD IMAGING

Part Eleven:

LOCAL GROUP DWARF GALAXIES AND LSB GALAXIES

DWARF SPHEROIDAL GALAXIES

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Dwarf Spheroidal (dSph) galaxies are the faintest baryonic systems recognized as galaxies. Understanding the structure and stellar populations of these systems is critical for the modelling of their formation and evolution, and by extension, for understanding the general problem of galaxy formation and evolution. Further, as dSphs are the only available probes of the distant halo of the Galaxy, understanding their structure is a crucial step in the study of the gravitational potential of the halo and the mass of the Galaxy. I will not attempt to review fully all current topics of dSph research. Instead, I will concentrate specifically on those issues that are directly related (as I see it) to the overall topic of wide-field imaging. Recent reviews covering other aspects of dSph research have been written by DaCosta (1988, 1992) and Pryor (1992).

1. Discovery

It is worth realizing that the discovery of the Halo dSph population is due entirely to wide-field techniques. The first of the eight currently known dSphs to be discovered was the Sculptor System (Shapley 1938). It was noticed as an excess of faint, stellar objects on a routine plate taken with the HCO Southern Station Bruce 24" reflector. The field-of-view of this telescope was ~ 4° x 4°. This was quickly followed by the discovery of the Fornax system (Shapley 1939), based on similar plate material. The Leo I, Leo II, Draco and Ursa minor dwarfs were discovered on plates taken for the Palomar Sky Survey (Harrington & Wilson 1950; Wilson 1955). The last of the dwarfs to be discovered by human inspection of plate data was the Carina system, found on a plate taken for the UKSTU Southern Sky survey (Cannon et al. 1977). As noted by Cannon et al., "The low number density and the moderately high foreground number density make it [Carina] very difficult to detect".

The one further object discovered since then, the Sextans dwarf, has a central surface density much lower than that of the other seven. Even knowing where to look, it is very difficult to discern on the (UKSTU) discovery plate. It was detected as part of a project to scan the UKSTU Southern Sky Atlas with the APM machine in Cambridge (Irwin et al. 1990). This form of digital detection is likely to be the way that any still unknown Halo dSphs will be discovered. I would like to remark that the discovery of the Sextans object, combining as it does a very large angular size and low central surface brightness, makes it quite unclear if we have anything like a representative sample of the most extreme dwarf galaxies present in even the Galactic halo.

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2. Stellar Populations

I will discuss only two sorts of probes of the stellar populations of the Halo dSphs; their luminosity functions (LFs) and their color-magnitude (CM) diagrams. Other wide-field techniques include plate-blinking for variable star searches (e.g. Nemec et al. 1988) and investigation of objective prism plates for bright stars with distinctive spectral features (i.e. carbon stars — see e.g. Westerlund et al. 1987).

2.1 LUMINOSITY FUNCTIONS

The sorts of information obtainable on the LFs of the halo dSphs from CCDs and from Schmidt plates are quite complementary. While CCDs offer much deeper samples, and greater photometric accuracy and precision, Schmidt plates offer global samples, and a direct sampling of the 'background' (both background galaxies, and foreground Galactic stars). Neither of these advantages are possible with CCDs in the foreseeable future, due to the large angular size of the dSphs (see Section 3 below). As a rough comparison of the LFs these two sorts of detectors can yield, I compare the B_J LF of Sculptor from Eskridge (1988a, Fig. 6b) with the V LF of Carina from Mighell (1990, Fig. 14). The Sculptor LF is based on UKSTU data, and extends from the bright limit ($B_J \sim 17.5$) to $B_J \sim 22$. There are 7700 ±800 stars in the LF to this limit. The Carina LF includes ~ 3000 stars down to $V \sim 25$, but is cut off at the bright end at $V \sim 18.5$. Ideally, this comparison would be between data sets in the same color, for the same object. But such data are not currently available in the literature. However, the two systems have comparable distance moduli (they differ by ≤ 0.2 mag). Also, the colors of the bulk of the stars sampled are in the range $(B - V) \sim 0.5 - 1.0$. Thus the intrinsic overlap between the two LFs is a very small region just at the top of the subgiant branch (SGB).

The CCD data contains information on the main sequence (MS) and turn-off (TO) populations that is simply unobtainable from Schmidt plates. However, there is basically *no* information on the evolved stellar population from the CCD data. The Schmidt plate LF of Sculptor contains a complete sample of the evolved stars, telling us that Sculptor has (among other things) the following:

1) 210 ±80 stars brighter (in B_J) than the RGB tip;
2) 2440 ±340 HB stars;
3) an *intrinsic* HB width of ≈ 0.38 mag (B_J);
4) a Helium abundance of Y ≈ 0.23 ±0.05 from N_{HB}/N_{GB}.

(see Eskridge 1988a for details). None of this would be determinable from a CCD observing project of reasonable scope.

2.2 COLOR-MAGNITUDE DIAGRAMS

For CM diagrams, CCDs and Schmidt plates offer the same basic set of trade-offs as for LFs. In this case, I make the more exact comparison of Schmidt plate and CCD CM diagrams of the Sextans dwarf from Irwin et al. (1990, Fig. 3) and Mateo et al. (1991a, Fig. 19) respectively. The Irwin et al. CM diagram is a 'quick-look', showing a large sample of stars down into the SGB. It is heavily contaminated by Galactic foreground (shown in their comparison Color-apparent magnitude diagram), and this limits its usefulness. This raises a critical point of advantage that Schmidt plate data have over CCD data — there IS a comparison sample of ~pure foreground, obtained in the SAME image as the galaxy data that could have been used to statistically correct for foreground contamination, as discussed, for instance by Hodge et al. (1991). The Mateo et al. (1991a) CM diagram looks much cleaner than that of Irwin et al., but the superior outlining of the CM locus was obtained by merging two different data sets into a composite. The data for $V \leq 21$ were obtained from short exposures over a much larger area than the data for $V \geq 21$.

3. Structure

3.1 RADIAL PROFILES

The need for wide-field (Schmidt plate!) imaging for the study of the global structure of the halo dSphs is pointed out most convincingly by the work of Irwin & Hatzidimitriou (1993a, 1993b — hereafter IH). They give angular sizes (tidal diameters) ranging from ~ 17′.5 (for Leo II) up to ~ 320′ (≈ 5°.3!) (for Sextans). A 2048^2 CCD, with good pixel sampling (≈ 0″.3/pixel) still will not include all of even Leo II, although it is getting close: Demers & Irwin (1993) claim to include ~ 70% of Leo II in the field of just such a detector in their recent study.

The first systematic study of the structure of the dSphs was done by Paul Hodge in the early 1960s (Hodge 1961a, 1961b, 1962, 1963, 1964a, 1964b, 1966). Various one-shot studies were done over the next 25 years (Hodge & Smith 1974; Demers et al. 1980; Godwin 1985), but the lack of a comprehensive study of all known objects with modern emulsions and data analysis techniques led to Mark Aaronson's call for "another hero" in his 1986 ST symposium talk (Aaronson 1986). I was at that time analyzing the structure of Sculptor and Fornax with modern emulsions and analysis techniques. One major result of this work was that my values for the tidal radii were both much larger than those found by Hodge (Eskridge 1988b, 1988d). More importantly, in neither case was I able to find a 'really good' fit to either a King (1966) model or an exponential law. There is a significant excess at large radii in both objects on all the plates I analyzed (Eskridge 1988b, Fig. 7, 1988d, Fig. 4). This actually recalled the initial discovery by van Agt (1978) that ~ 10% of Sculptor's RR Lyrae stars were 'extra-tidal'.

Table 1. Structural parameters for the halo dSphs

Galaxy	α(1950)	δ(1950)	r_c ′	r_t ′	e	PA (1950) °
Carina	$06^h40^m.6$	-50°56′	8.8±1.2	28.8±3.6	0.33±0.05	65±5
Draco	$17^h19^m.5$	+57°58′	9.0±0.7	28.3±2.4	0.29±0.01	81±1
Fornax	$02^h37^m.8$	-34°44′	13.7±1.2	71.1±4.0	0.30±0.01	41±1
Leo I	$10^h05^m.6$	+12°33′	3.3±0.3	12.6±1.5	0.21±0.03	79±3
Leo II	$11^h10^m.8$	+22°26′	2.9±0.6	8.7±0.9	0.13±0.05	12±10
Sculptor	$00^h57^m.7$	-33°59′	5.8±1.6	76.5±5.0	0.32±0.03	99±1
Sextans	$10^h10^m.5$	-01°22′	16.6±1.2	160.0±50.0	0.35±0.05	56±5
Ursa Minor	$15^h08^m.4$	+67°25′	15.8±1.2	50.6±3.6	0.56±0.05	53±5

As hinted at above, Aaronson's challenge has recently been answered by IH. Table 1 is taken from their study. My finding that there are significant excesses at large radii above that predicted by the 'best-fit' King models is confirmed by IH for Sculptor and Fornax, and extended to all six other dSphs. However, their values for the structural parameters of Sculptor and Fornax disagree with mine by a good bit more than our combined errors. It appears that this is because of problems with the older image deblending software (from 1986) that I used for my analysis (Hatzidimitriou, private communication). Regardless of this, I would like to recommend the community adopt the IH numbers if for no other reason than that they are complete set of internally consistent values.

The issue of the appropriate structural description of the dSphs is critical for correct mass models for both the dSphs and for the Galactic halo. A *highly* simplified equation that demonstrates this is as follows:

$$\frac{M_d}{L_d} \approx \frac{(3+e)\,M_{MW}}{L_d} \left(\frac{r_t}{R_p}\right)^3$$

(for a King 1966 model, adapted from Cuddeford & Miller 1990). Subscript 'd' refers to the dwarf, e is the orbital eccentricity, r_t is the tidal radius of the dwarf, and R_p is the perigalacticon of the dSph orbit. Note that the M/L for a dSph goes as r_t^3! This equation is only strictly true for an object that is truly tidally truncated, so probably does not hold in detail for the Halo dSphs, however the basic point holds that the total masses of the dSphs depend quite sensitively on their profiles at large radii. In fact, both the two dimensional form of the profile and a two dimensional velocity dispersion map are required for proper mass modelling and neither the data nor the theoretical tools exist for this at present. Pryor & Kormendy (1990) provide an exposition of the problem, along with detailed 1-D models. However, without proper 3-D mass modelling of the 2-D profiles, it will not really be possible to demonstrate that the dSphs are even bound systems. For an alternative viewpoint, see the work of Kuhn & Miller (1989) and Kuhn (1993).

3.2 2-D STRUCTURE

Traditionally, the dSphs have been assumed to be smooth, elliptically symmetric objects. Indications that this might not be so go back to the observation by Hodge (1961a) that the profile of Fornax is asymmetric. On a much smaller scale, Olszewski & Aaronson (1985) concluded that the distribution of stars in a CCD field of Ursa Minor was too clumpy to be described as a statistical fluctuation of an underlying smooth density distribution.

Schmidt plate studies of both Sculptor and Fornax find significant deviations (at the 30-35% level) from smooth elliptical symmetry on angular scales of 3′ - 6′, corresponding to spatial scales of 100-200 pc (Eskridge 1988c, Fig. 5, 1988e, Fig. 4). The origin of such structures remains a mystery. They have crossing times of $t_{cross} \sim 10^8$ yrs, implying that they are either at least marginally bound or disconcertingly young. The dissipation time scale from the interaction of a nominally bound clump with the overall gravitational potential of the dSph is, of course, quite model dependent, but $t_{dis} \sim 10^{9\rightarrow 10}$ yrs for reasonable numbers (see Eskridge 1988c, 1988e for details). This leaves either the possibility that these features are relic associations left over from the formation of the dSphs, or that they are the sites of intermediate-age star formation events. The critical test of these possibilities would be to examine the LFs and CM diagrams of these regions, compared to 'normal' regions, to search for possible differences in their stellar populations. This work is currently underway (Eskridge 1994), but as yet, no results are available. It would also be very interesting to see if any of the other six Halo dSphs have similar structure.

4. Beyond the Halo

Our knowledge of dSphs beyond the Galactic halo is also entirely dependent on wide-field optical observations. The first such discoveries were reported by van den Bergh (1972), who found three dSphs (And I, II, III) associated with M 31 from searches of IIIa-J Palomar Schmidt plates. There are also a large number of dSphs known in the M 81 group (some quite distant from M 81), largely due to the work of Börngen et al. (1984) based on plates from the 2 m Tautenburg Schmidt.

There have been a number of programs continuing throughout the 1980s searching for dwarf galaxies in nearby clusters and the nearby field, all using either Schmidt plates, or wide-field direct plates from Las Campanas (e.g. Impey et al. 1988; Ferguson & Sandage 1989; Ferguson 1989; Eder et al. 1989; Binggeli et al. 1990; Evans et al. 1990; Binggeli & Cameron 1991). The majority of this work has focused on the Virgo and Fornax clusters, although some work has been done on loose groups and the field. It is clear from the work that careful analysis of plate data allows for the detection of dSphs as faint as Sculptor out to the distance of the Virgo cluster, and should yield complete samples of objects as faint as Fornax to these distances.

Finally, coming back to a point I brought up in Section 1, we are still discovering dSphs in the Local Group. An object in Tucana, first noted by Corwin et al. (1985) from inspection of the UKSTU southern sky survey, and then forgotten, was recently rediscovered (see Lavery & Mighell 1992). Based on CCD photometry down to $V \sim 23$, the Tucana dwarf appears to be a dSph at a distance of ~ 900 kpc, in an otherwise isolated part of the sky. I must conclude, once again, that we simply do not have an adequate census of the galaxian population of the Local Group. Further, I expect that analysis of the second Palomar sky survey will yield the discovery of at least a few more extreme dwarf galaxies within 1 Mpc.

5. Wide-Field CCD Studies

I am aware of a number of studies begun recently (Pryor, private communication) that attempt to transcend the traditional dependence on Schmidt plates for the study of the structure of the Halo dSphs. None of these are published yet, so I simply outline the problems and benefits available from the two main sorts of approaches.

5.1 CCD SCHMIDT CAMERAS

A growing number of Schmidt telescopes throughout the world are now equipped with large format (2048^2) CCD cameras. These provide a roughly 2° x 2° fov with ≈ 3.″5 sampling. This grossly under-samples the resolved stellar component, and is thus of limited use for studies of the bright stars. But such instruments can potentially provide excellent data on the unresolved component that should dominate the (baryonic) mass of the objects. The improvement in linearity of CCDs over photographic emulsions should lead to greatly improved surface photometry and integrated magnitudes for the Halo dSphs. As an example of the severity of the problem of determining these (very basic!) quantities for the halo dSphs, in a recent study of Fornax, Mateo et al. (1991b) review data in the literature, and note that the two existing determinations of the central surface brightness of Fornax differ by half a magnitude ($\Sigma_{o,\,V}$ = 23.9 or 23.4: de Vaucouleurs & Ables 1968; Hodge & Smith 1974). The integrated magnitudes are even a bit more discrepant (V_{tot} = 8.4 or 7.8: de Vaucouleurs & Ables 1968; Hodge 1971). Such large uncertainties dramatically restrict the power of modelling to describe the physical state of the halo dwarfs and their interaction with the Galactic halo.

One must keep in mind that even a 2° x 2° fov is *still* too small to include all of Fornax, Sculptor, Sextans, or Ursa Minor and cleanly reach the background. Possibly, such a fov will work for Carina and Draco. It will quite clearly work for Leo I and II (although Regulus may prove to be a problem for Leo I observations!).

5.2 SPOT-SAMPLING AND MOSAICS

The idea here is to use either multiple exposures with one CCD, or use a CCD mosaic in order to image a large region with 'good' sampling ($\lesssim$ 0″.3 for a site with ~ 1" seeing). The Kiso instrument discussed at this meeting is a first step toward the kind of mosaic required for this sort of research. But one must keep in mind the following issues: a 2048^2 CCD with ≈ 0″.3 sampling will require ~ 20 fields to cover an object such as Draco (per filter!); it will be necessary to develop analysis software to deal with (possibly quite significant) variations in the PSF, both within and between frames, in order to sample the object in question down to a uniform limit.

6. Outside the Optical

Although nearly all the flux from dSphs is photospheric emission, studies at wavelengths dominated by flux from other sources may prove invaluable for our understanding of these systems. Below I discuss two such sorts of observations — HI line data and ROSAT X-ray data (although my talk did not include any discussion of X-ray observations).

6.1 HI OBSERVATIONS

It is common knowledge that dSphs do not contain HI gas. In fact, this knowledge is not simply folklore. Seven of the eight dSphs (Sextans currently excepted) have been subject to HI studies that have put quite low limits on their HI contents (Knapp et al. 1978; Mould et al. 1990). The results of these studies put limits on the HI masses of the dSphs that are **quite** low. The range is as follows:

$$M_{HI} \lesssim 10^4 M_{\odot} \quad \text{(Leo II)}$$

$$M_{HI} \lesssim 70 M_{\odot} \quad \text{(Draco).}$$

However, a crucial constraint on these conclusions is that they are based on centrally pointed observations with beams of ~ 10′ - 20′. Given the angular sizes of the dSphs, and recent HI mapping projects showing extended HI shell structures associated with extreme dI galaxies (e.g. Carignan et al. 1991), it is a not unreasonable idea to attempt HI observations of the Halo dSphs at radii comparable to their limiting radii. Such a project is, in fact, in progress (Carignan, private communication).

Dr. Carignan has allowed me to discuss some preliminary results of this project, but I must emphasize that the analysis of the data is ongoing. Observations were made at Parkes of

Sculptor, Fornax, and Tucana. Of these, only Sculptor was clearly detected. Green Bank observations of the northern sky objects turned up no clear detections. Follow-up observations of Sculptor with the Australia Telescope appear to show two clouds, both ~ 20′ from the center of Sculptor, containing a total of ~ $10^4 M_\odot$ of HI. A subsequent VLA mapping program is in progress.

Although these results are still too sketchy to justify lavish theoretical interpretation, I cannot emphasize their importance enough. It is clear to me that they will be crucial in advancing our understanding of the evolution of dSph systems.

6.2 X-RAY OBSERVATIONS

I did not have time to mention this work in my talk, but there are approved (or existing) ROSAT observations for four of the halo dSphs (Carina, Fornax, Sculptor and Sextans). Indeed, a paper on the Fornax observations was published just after the symposium (Gizis et al. 1993). Knowledge of the stellar X-ray sources (mainly XRBs) provides information on the IMF and the binary frequency in environments much different than the Solar neighborhood, nearby galactic disks, or globular clusters. Gizis et al. find no evidence for any XRBs associated with Fornax down to a flux level of $L_X \approx 10^{35}$ ergs/sec in the ROSAT band. This is consistent with simple scaling from 'normal' ellipticals and bulges, indicating that Fornax (at least) did not have an IMF weighted heavily to massive stars. If one scales the results from globular clusters, one finds an expectation of ~ 8 sources above the detection limit. This implies that Fornax (and, by extension the other dSphs) has too low a stellar density to generate stellar X-ray sources through neutron star-star interactions.

7. Some Questions

I would like to close with a few of what I believe to be the most pressing (and currently answerable) questions related to the study of dSphs using wide-field imaging techniques:

1) is the census of the *Halo* dSphs complete?
2) is that of the Local Group?
3) do dSphs have HI shell structures resembling those now being found associated with extreme dIs?
4) do the other six Halo dSphs have the sorts of non-axisymmetric features found in Sculptor and Fornax?
5) what are the relationships of these last two questions to the overall star formation histories, stellar populations, and structures of the Halo dSphs?
6) does anyone have any further questions to add to this list?

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