Star Formation Histories of Local Group Dwarf Galaxies

Ludwig Biermann Award Lecture

Eva K. Grebel

Astronomisches Institut, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany[1]
Sternwarte der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

Abstract

The star formation histories of dwarf galaxies in the Local Group are reviewed. First the question of Local Group membership is considered based on various criteria. The properties of 31 (36) galaxies are consistent with likely (potential) Local Group membership. To study the star formation histories of these galaxies, a multi-parameter problem needs to be solved: Ages, metallicities, population fractions, and spatial variations must be determined, which depend crucially on the knowledge of reddening and distance. The basic methods for studying resolvable stellar populations are summarized. One method is demonstrated using the Fornax dwarf spheroidal galaxy. A comprehensive compilation of the star formation histories of dwarf irregulars, dwarf ellipticals, and dwarf spheroidals in the Local Group is presented and visualized through Hodge's population boxes. All galaxies appear to have differing fractions of old and intermediate-age populations, and those sufficiently massive and undisturbed to retain and recycle their gas are still forming stars today. Star formation has occurred either in distinct episodes or continuously over long periods of time. Metallicities and enrichment vary widely. Constraints on merger and remnant scenarios are discussed, and a unified picture based on the current knowledge is presented. Primary goals for future observations are: accurate age determinations based on turnoff photometry; detection of subpopulations distinct in age, metallicity, and/or spatial distribution; improved distances; and astrometric studies to derive orbits and constrain past and future interactions.

1 Introduction

L'exploration du monde par l'homme a procédé un peu comme un enfant prend conscience de son entourage: famille, voisins, cité, pays... En fait, ce n'est que l'extension de ce processus en des cercles toujours plus larges qui nous a conduits au cours des âges à reconnaître des organisations cosmiques de plus en plus vastes, distantes et complexes, constituant le système planétaire, le monde des étoiles – notre Galaxie – et finalement l'univers des galaxies lointaines, extérieures à la nôtre.

De Vaucouleurs, L'exploration des galaxies voisines (1958)

The galaxies of the Local Group (LG) are our closest extragalactic neighbours, close enough to be resolved into individual stars and to be studied in detail. These nearby galaxies include different morphological types and their stellar populations cover a wide range of ages and metallicities. Proximity and variety make these galaxies ideal targets for investigations of detailed star formation histories in different environments. Ultimately, these studies will lead to a better understanding of star formation processes in general, the conditions for star formation, and environmental influences such as metallicity, mass, and interactions. Knowledge of

[1] *Present address:* AI Würzburg, grebel@astro.uni-wuerzburg.de

these star formation histories will improve our understanding of formation and evolution of galaxies ranging from our Milky Way to distant, unresolvable galaxies.

The study of resolved stellar populations also yields distances through a variety of methods. The galaxies in the LG provide a convenient laboratory to test the consistency of different methods used to derive the cosmological distance scale and a possibility to investigate their dependence on metallicity and other parameters.

New observational findings on LG dwarf galaxies are being published almost every month and the resulting complex picture provides interesting challenges for the theoretical understanding of how the LG formed and evolves. In this review, the galaxy content of the LG (Section 2) will be discussed first. Then different techniques and problems in population studies (Section 3) are summarized. As an example, one of the methods is applied to the Fornax dwarf spheroidal galaxy (Section 4). In Section 5 star formation histories are presented using population boxes as introduced by Hodge (1989). Some of the currently entertained ideas on origin and evolution of the LG dwarf galaxies are discussed in Section 6, and future needs are summarized in Section 7.

2 Which Galaxies Belong to the Local Group?

SURVEYS OF THE SKY SHOW THAT NEBULÆ ARE SCATTERED SINGLY AND IN GROUPS OF VARIOUS SIZES UP TO THE OCCASIONAL GREAT CLUSTERS. THE SMALL-SCALE DISTRIBUTION RESEMBLES THAT OF STARS IN THE STELLAR SYSTEM. [...] THE GALACTIC SYSTEM IS A MEMBER OF A TYPICAL, SMALL GROUP OF NEBULÆ WHICH IS ISOLATED IN THE GENERAL FIELD. THE KNOWN MEMBERS OF THE "LOCAL GROUP" ARE THE GALACTIC SYSTEM WITH THE MAGELLANIC CLOUDS AS ITS TWO COMPANIONS; M31 WITH M32 AND NGC 205 AS ITS COMPANIONS; M33, NGC 6822 AND IC 1613. THE THREE NEBULÆ, NGC 6946, IC 10 AND 342, MAY BE MEMBERS, BUT THEY ARE SO HEAVILY OBSCURED THAT THEIR DISTANCES ARE INDETERMINATE.

HUBBLE, THE REALM OF THE NEBULÆ (1936)

Both the number of member galaxies of our LG and its size are not yet fully known. Knowledge of which galaxies are members and how distant they are allows us to determine improved mass models for the LG and its two dominant galaxies, the Milky Way and Andromeda. Membership has implications ranging from better dynamical models for the LG to the dark matter problem and cosmological questions (e.g., Sandage 1986, Peebles 1995). Many of the faint member galaxies were discovered only in recent years and there may be more low-surface brightness galaxies in the LG yet to be detected. Proper motions are available only for a few of the nearer LG galaxies. Distances to galaxies at the periphery of the LG are uncertain and there are indications that several galaxies beyond the traditionally assumed boundary of 1 Mpc are LG members as well. To define the sample of galaxies discussed in this review, I will now present arguments for the inclusion or rejection of proposed LG members.

2.1 Radial Velocities as Membership Criterion

A first crude membership criterion is the radial velocity of a galaxy. A low radial velocity (no more than a few hundred km s^{-1}) indicates a nearby possible member of the LG. Apparent proximity deduced only from a radial velocity, however, does not suffice to establish membership, though it warrants further investigation.

In their catalogue of nearby galaxies, Schmidt & Boller (1992: hereafter SB92) list 51 galaxies as certain or probable LG members based solely on their low radial velocities. Van den Bergh (1994a: hereafter vdB94) examines LG membership of

Table 1: Data on eight Local Group suspects from Schmidt & Boller (1992) that I exclude as member galaxies due to their high heliocentric velocities $V_\odot$. These data were extracted in part from NED and SIMBAD. Earlier determinations of low $V_\odot$ were largely due to superposition of foreground stars (NED). All the excluded galaxies are spirals.

Name	α (J2000)	δ (J2000)	l [°]	b [°]	type	m_B [mag]	$V_\odot$ [km/s]	reference
ESO 352-02	$01^h04^m.5$	−33°39′.2	280.38	−82.89	Sb:	14.03	10011	Fairall & Jones 1991
ESO 416-12	$02^h43^m.6$	−31°56′.6	230.90	−65.20	Sc	14.45	4995	Fairall & Jones 1991
IC 1947	$03^h30^m.5$	−50°20′.2	261.42	−51.96	S	15.50	11545	Fouqué et al. 1993
ESO 269-70	$13^h13^m.5$	−43°23′.0	307.17	+19.31	S0	14.48	22300	Fairall & Jones 1991
IC 4739	$18^h40^m.8$	−61°54′.1	333.55	−22.51	Sb:	15.13	4430	Bell & Whitmore 1989
IC 4789	$18^h56^m.3$	−68°34′.1	326.82	−25.55	Sc	13.99	4234	Fairall & Jones 1991
IC 4937	$20^h05^m.3$	−56°15′.3	341.54	−32.39	S0:	13.99	4758	da Costa et al. 1991
IC 5026	$20^h48^m.5$	−78°04′.2	315.27	−32.42	Sc:	15.42	2748	Mathewson et al. 1992

nearby galaxies based on their heliocentric velocities $V_\odot$, angles θ between a given galaxy and the solar apex, and distance moduli. The two studies have 29 galaxies in common as certain LG members. Three galaxies of SB92's LG list (Leo A, Pegasus, IC 5152) are considered possible LG members by vdB94, who furthermore discusses another six galaxies as potential LG members (Sex A, Sex B, SculDIG, NGC 3109, GR 8, Anon 0426+63) that were regarded as non-members by SB92. Of SB92's remaining 19 candidate member galaxies, two are in fact globular clusters (Pal 3, Pal 12), and one appears to be an open cluster or association (And IV: van den Bergh 1972, Jones 1993). I identify the LG suspect ESO 056-19 with the emission nebula DEM 21 (Davies et al. 1976) in the Large Magellanic Cloud (LMC). Its velocity ($V_\odot = 273$ km s^{-1}) supports its being part of the LMC. Eight more candidates – all of them spiral galaxies – can be shown not to belong to the LG due to their high radial velocities published elsewhere in the literature (Table 1). Discrepancies between the low radial velocities adopted by SB92 and other measurements may be explained by superimposed foreground stars for at least five galaxies (ESO 352-02, ESO 269-70, IC 4739, IC 4937, IC 5026) according to the NASA Extragalactic Database (NED).

2.2 Position in the $\cos\theta, V_\odot$ Diagram as Membership Criterion

Lacking distance information for the remaining seven LG suspects from SB92's list, I followed vdB94 in using the location in a cos θ, $V_\odot$ diagram as *preliminary* membership criterion. In Fig. 1 known and suspected LG member galaxies are plotted together with nearby non-members (from the B1 group around IC 342 and the B7a Sculptor group; Kraan-Korteweg & Tammann 1979, SB92). The values for cos θ were calculated using the solar apex (indicated by the solid line) as determined by Karachentsev & Makarov (1996: $l_\odot = 93°, b_\odot = -4°, V_\odot = 316$ km s^{-1}) and the galactic coordinates of each galaxy,

$$\cos\theta = \cos b \cos b_\odot \cos(l - l_\odot) + \sin b \sin b_\odot .$$

Galaxies known to be LG members in Fig. 1 follow the ridge line for the solar apex, while the galaxies at the periphery and outside of the LG generally show higher positive velocity residuals due to the cosmological expansion (Sandage 1986). The dashed lines represent ±60 km s^{-1} mean velocity dispersion envelopes with

Table 2: Data on the remaining seven galaxies from Schmidt & Boller (1992) whose heliocentric velocities $V_\odot$ indicate possible membership in the Local Group. The last two galaxies are suggested Local Group members from Arp (1994). θ is the angle between the solar apex from Karachentsev & Makarov (1996) and a galaxy's l, b. The likelihood of Local Group membership based on the available data is estimated in column "LG".

Name	α (J2000)	δ (J2000)	l [°]	b [°]	type	m_B [mag]	$V_\odot$ [km/s]	$\cos\theta$	LG
Anon 0106+21	$01^h09^m.0$	21°55′.0	128.31	−40.77	Im		−324	0.662	?
Anon 0107+01	$01^h10^m.0$	02°52′.0	132.35	−60.40			−230	0.442	yes?
AM 1001-270	$10^h04^m.1$	−27°20′.5	263.11	22.31	Im		361	−0.936	yes?
ESO 318-13	$10^h47^m.7$	−38°51′.3	278.04	17.96	Sd:	14.97	17	−0.967	no
IC 4247	$13^h26^m.8$	−30°21′.8	311.90	31.89	Sa:	14.37	274	−0.696	no?
Anon 2259+12	$23^h01^m.6$	12°44′.0	85.65	−42.05			−364	0.781	no?
ESO 347-08	$23^h20^m.8$	−41°43′.8	348.85	−66.42	Sm	14.61	16	−0.034	?
NGC 404	$01^h09^m.5$	35°43′.0	127.05	−27.01	E/S0	11.3	−45	0.768	no
IC 342	$03^h46^m.9$	68°06′.0	138.17	10.59	Sc	10.5	289	0.689	no

respect to the central ridge line (Sandage 1986) and include most of the nearby LG member galaxies. It should be remembered that radial velocity is just one projected velocity component, while the tangential velocity is unknown. An object on a highly eccentric orbit and close to the pericenter (i.e., close to the Milky Way or M 31) will have a high radial velocity and yet be bound, while a galaxy at the apocenter of its strongly eccentric orbit would have a quite low velocity.

Table 2 lists cos θ, $V_\odot$, and other parameters for the remaining LG candidate galaxies from SB92. Its $V_\odot$, cos θ values place the LG suspect ESO 318-13 far below the LG locus in Fig. 1. It is therefore excluded as a LG member. Anon 0106+21 and Anon 2259+12 both have negative velocity residuals with respect to the (uncertain) LG envelope, but membership cannot be ruled out completely. The position of Anon 0107+01 in the cos θ, $V_\odot$ diagram almost coincides with that of IC 1613, which is considered a member of the LG. ESO 347-08 lies almost on top of the $V_\odot = -316 \cdot \cos\theta$ line supporting LG membership. Fouqué et al. (1993) consider this galaxy a member of the Sculptor group (Kraan-Korteweg & Tammann 1979) without giving details. IC 4247's and AM 1001-270's positions in Fig. 1 fall well within the adopted LG envelope lines. However, if the $V_\odot = 414$ km s^{-1} measurement of Quintana et al. (1995) is adopted for IC 4247 rather than da Costa et al.'s (1987) value, then this galaxy has such a large positive velocity residual that it unlikely to be a member of the LG. The small angular diameters of the spiral galaxies as given in the NED (IC 4247: 1′.3 × 0′.5; ESO 347-08: 1′.7 × 1′.4; AM 1001-270: 2′.2 × 0′.3) would also seem to exclude LG membership. Most radial velocity determinations quoted by SB92 are based on optical methods. Contamination by foreground stars may have affected the $V_\odot$ measurements for a number of these galaxies. Radio-based methods may be affected by interference with HI of a foreground cloud or in a nearby galaxy. Because of the potential uncertainties in the velocity measurements, the few galaxies in Table 2 whose $\cos\theta$, $V_\odot$ values appear to be compatible with LG membership should not be considered members until more data, and in particular distance determinations, are available. For most of the galaxies, a literature search revealed no additional data at all.

Arp (1994) suggests LG membership for the peculiar galaxy NGC 404 (con-

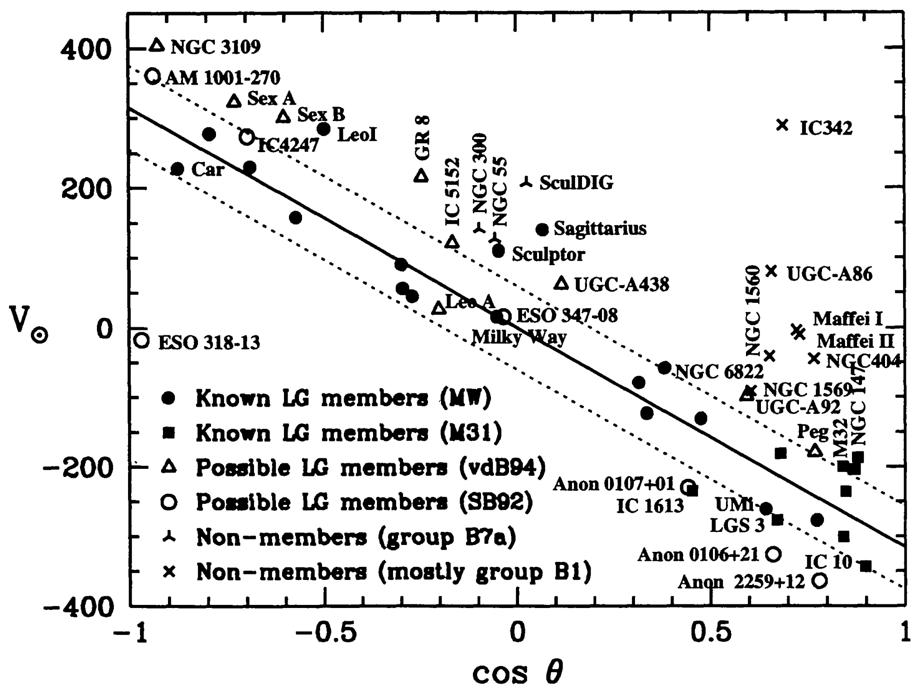

Figure 1: Heliocentric velocity $V_{\odot}$ versus the cosine of the angle θ between the solar apex and l, b of galaxies listed in Tables 2, 3, and van den Bergh's (1994a) Table 1. Filled squares indicate galaxies possibly bound to M 31, and filled circles stand for possible Milky Way companions and "isolated" galaxies in the Local Group (Karachentsev 1996). Non-members are from the B1 galaxy group around IC 342 and the B7a Sculptor group (Kraan-Korteweg & Tammann 1979, Schmidt & Boller 1992). The solid line represents the adopted solar motion of $V_{\odot} = 316$ km s^{-1} toward $l_{\odot} = 93°, b_{\odot} = -4°$ of Karachentsev & Makarov (1996). Dashed lines are ± 60 km s^{-1} envelopes (Sandage 1986) that enclose most known Local Group member galaxies. The known non-members of the Local Group generally have positive velocity residuals due to the cosmological expansion (Sandage 1986).

sidered a field galaxy by SB92) and for IC 342, a galaxy that is regarded as the dominant galaxy in the B1 group (Kraan-Korteweg & Tammann 1979). Figure 1 shows that both galaxies have large positive velocity residuals as compared to the adopted LG locus (see also Table 2). A radio study indicates that NGC 404 is situated at a distance of about 10 Mpc (Wiklind & Henkel 1990) excluding LG membership. Due to the high obscuration at low Galactic latitudes distance determinations for galaxies in the B1 group are particularly difficult and have been a matter of debate (see discussion in Krismer et al. 1995). Following Krismer et al. (1995) IC 342 is not a member of the LG, though a definite decision has to wait until reliable distance determinations are available.

In Table 3 the currently known and probable LG member galaxies are listed. The 29 galaxies from vdB94's Table 2 are supplemented by the recently discovered Sagittarius dwarf galaxy (Ibata et al. 1994). Fig. 1 shows that their locations are well-constrained by the ± 60 km s^{-1} envelopes around the solar apex ridge line. Unless noted otherwise, heliocentric velocities were taken from SB92, vdB94, and Karachentsev & Makarov (1996). The $V_{\odot}$ values of LGS 3, Leo A, GR 8, DDO 187, SagDIG, DDO 210, and Pegasus were adopted from Lo et al. (1993).

Some of the known LG members deviate from the mean locus of LG galaxies in Fig. 1. Sagittarius is in the process of merging with the Milky Way, and it is offset in mean velocity by $\approx$ 150 km s^{-1} from Galactic bulge stars (Ibata et al. 1997). With the radial velocity determined by Zaritsky et al. (1989), Leo I is found 67 km s^{-1} above the adopted envelope, while the earlier measurement by Suntzeff et al. (1986: $V_\odot = 185$ km s^{-1}) places this LG member galaxy close to the solar apex ridge line. Zaritsky et al.'s value is used here because of their higher measurement accuracy. Byrd et al. (1994) suggest a scenario that can account for the position and radial velocity of Leo I if it once belonged to M 31. For the Sculptor dwarf spheroidal galaxy $V_\odot = 110$ km s^{-1} (Queloz et al. 1995). Sculptor is a known member of the Local Group and close to the Milky Way but has a positive velocity residual of 36 km s^{-1} with respect to the upper envelope of the LG locus. The position of DDO 210 almost coincides with the solar apex line rather than lying above the LG locus as found by vdB94. While in both studies the same $V_\odot$ was used, vdB94's Table 1 gives an incorrect cos θ value. LG membership is also supported for vdB94's LG suspects IC 5152, Pegasus, and Leo A through the cos θ, $V_\odot$ diagram. Some of the LG non-members in the groups B1 (NGC 1569) and B7a (NGC 300, NGC 55) are similarly close to the upper boundary line as are vdB94's LG candidates NGC 3109, Sex A, Sex B, GR 8, UGC-A438, and UGC-A92, which all lie a little above the upper LG envelope line as noted earlier by vdB94.

2.3 Proximity As a Membership Criterion

Assuming a mass of $\approx 4.8 \cdot 10^{12}$ M$_\odot$ for the LG (e.g., Peebles 1995) yields a distance to the zero-velocity surface of the LG to be $\approx$ 1.8 Mpc using the formalism laid out in Sandage (1986). Uncertainties in the mass estimate aside, galaxies more distant than 1.8 Mpc would seem unlikely to be members of the LG. Unfortunately, for almost all galaxies orbits are still unknown. Many of the distances are very uncertain, and conflicting measurements have been published (see vdB94 for an extensive discussion). In Table 3 distances from the barycenter of the LG (D_{LG}) are given. These were calculated from heliocentric distances based on de-reddened distance moduli when available in the recent literature (Table 4 & 5) or else adopted from vdB94's compilation. To estimate the location of the barycenter, the mass ratio for the Milky Way and M 31 in Peebles (1995) and the distance to M 31 derived by Freedman & Madore (1990) were used. This yields a distance of 0.44 Mpc of the Milky Way from the assumed center of mass of the LG in the direction of M 31.

UGC-A92 is considered a member of the B1 group by Krismer et al. (1995; but see discussion in vdB94). For Leo A and GR 8 (distances from Hoessel et al. 1994 and Tolstoy et al. 1995 (only 1 Cepheid)) to be members the mass of the LG would need to be more than twice as much as assumed above ($\approx 11 \cdot 10^{12}$ M$_\odot$ and $13 \cdot 10^{12}$ M$_\odot$, resp.) requiring M$_\odot/L_\odot > 200$ for the two dominant LG galaxies. Leo A and GR 8 LG are rejected as members although the location of Leo A in the cos θ, $V_\odot$ diagram is fully consistent with LG membership.

As noted by vdB94, all presumably known LG members except for Tucana and SagDIG have $D_{LG} < 0.9$ (first three panels of Table 3). Distances between $\approx$ 1.3 and $\approx$ 1.7 Mpc make LG membership possible for NGC 3109, UGC-A438, Sextans A and B, and IC 5152, though they all have positive velocity residuals with

Table 3: Known and possible members of the Local Group. Coordinates were taken from SIMBAD. Morphological types follow the definition given in Section 2.4 or were adopted from van den Bergh (1994). M_B values are mostly from Schmidt & Boller (1992) and were not corrected for more recent distance and reddening determinations. D_{LG} denotes the distance from the barycenter of the Local Group (Section 2). A colon indicates a highly uncertain distance. The first two parts of this table contain galaxies assumed to be companions of the Milky Way and M 31 (Karachentsev 1996). The third panel gives presumably isolated members of the LG. The fourth panel contains more distant potential LG members, and the last one galaxies that should be considered non-members.

Name	α (J2000)	δ (J2000)	l [°]	b [°]	type	M_B [mag]	$V_\odot$ [km/s]	$\cos\theta$	D_{LG} [Mpc]
Milky Way	$17^h45^m.7$	−29°00	0.00	0.00	Sb/Sc	−20.5	16	−0.052	0.440
Sagittarius	$19^h00^m.0$	−30°30	6.00	−15.00	dSph	−13.0	140	0.068	0.448
LMC	$05^h23^m.6$	−69°45	280.46	−32.89	Ir III-IV	−18.5	278	−0.793	0.469
SMC	$00^h52^m.6$	−72°48	302.80	−44.30	Ir IV-V	−17.4	158	−0.571	0.468
Ursa Minor	$15^h08^m.8$	67°12	104.95	44.80	dSph	−7.8	−261	0.643	0.419
Draco	$17^h20^m.0$	57°50	86.37	34.72	dSph	−8.9	−277	0.775	0.413
Sextans	$10^h13^m.0$	−01°37	243.50	42.27	dSph	−8.0	230	−0.689	0.497
Sculptor	$00^h59^m.9$	−33°42	287.54	−83.16	dSph	−10.0	110	−0.046	0.426
Carina	$06^h41^m.6$	−50°58	260.11	−22.22	dSph	−10.2	228	−0.874	0.502
Fornax	$02^h40^m.0$	−34°27	237.29	−65.65	dSph	−11.9	45	−0.270	0.437
Leo II	$11^h13^m.5$	22°10	220.17	67.23	dSph	−8.9	90	−0.298	0.561
Phoenix	$01^h49^m.0$	−44°52	272.49	−68.82	dIr/dSph	−8.9	56	−0.295	0.591
NGC 6822	$19^h44^m.9$	−14°48	25.34	−18.39	dIr	−15.8	−58	0.382	0.653
M 31	$00^h42^m.7$	41°16	121.18	−21.57	Sb I-II	−21.0	−301	0.843	0.329
M 32	$00^h42^m.7$	40°52	121.15	−21.98	dE	−15.6	−200	0.842	0.326
NGC 147	$00^h33^m.1$	48°31	119.82	−14.25	dE	−14.6	−187	0.880	0.331
And I	$00^h45^m.7$	38°00	121.69	−24.85	dSph	−10.6	–	0.823	0.374
And III	$00^h35^m.3$	36°31	119.31	−26.25	dSph	−10.6	–	0.833	0.376
NGC 185	$00^h39^m.0$	48°19	120.79	−14.48	dE	−15.1	−204	0.872	0.191
NGC 205	$00^h40^m.3$	41°41	120.72	−21.14	dE	−15.6	−236	0.849	0.411
And II	$01^h16^m.3$	33°25	128.87	−29.17	dSph	−10.5	–	0.740	0.170
M 33	$01^h33^m.8$	30°39	133.61	−31.33	Sc II-III	−19.0	−181	0.683	0.436
IC 10	$00^h20^m.4$	59°18	118.97	−3.34	Ir	−17.4	−344	0.899	0.433
LGS 3	$01^h03^m.9$	21°54	126.75	−40.90	dIr/dSph	−9.2	−277	0.673	0.423
IC 1613	$01^h05^m.0$	02°09	129.82	−60.54	dIr	−14.4	−235	0.453	0.426
Leo I	$10^h08^m.5$	12°18	225.98	49.11	dSph	−10.4	285	−0.498	0.610
DDO 210	$20^h46^m.9$	−12°51	34.05	−31.35	dIr	−12.2	−131	0.476	0.85:
Tucana	$22^h41^m.8$	−64°25	322.91	−47.37	dSph	−8.9	–	−0.384	1.100
WLM	$00^h02^m.0$	−15°28	75.85	−73.63	dIr	−14.4	−123	0.336	0.771
Pegasus	$23^h28^m.6$	14°45	94.77	−43.55	dIr	−13.1	−179	0.771	0.621
SagDIG	$19^h30^m.0$	−17°41	21.06	−16.28	dIr	−9.9	−79	0.316	1.25:
NGC 3109	$10^h03^m.1$	−26°10	262.10	23.07	dIr	−16.4	404	−0.943	1.607
UGC-A438	$23^h26^m.5$	−32°23	11.86	−70.86	dIr	−12.7	62	0.116	1.28:
Sex B	$10^h00^m.0$	05°20	233.21	43.78	dIr	−15.1	301	−0.602	1.587
Sex A	$10^h11^m.0$	−04°43	246.17	39.87	dIr	−13.7	324	−0.728	1.723
IC 5152	$22^h02^m.7$	−51°18	342.92	−50.19	dIr	−14.8	121	−0.166	1.71:
Leo A	$09^h59^m.4$	30°45	196.90	52.42	dIr	−13.3	26	−0.201	2.336
GR 8	$12^h58^m.7$	14°13	310.76	76.98	dIr	−12.0	216	−0.246	2.51:
UGC-A92	$04^h32^m.0$	63°36	144.71	10.51	dIr	−15.1	−99	0.595	3.30:

respect to the upper LG envelope in Figure 1. Thus the current census of known and potential LG members comprises at least 36 nearby galaxies.

2.4 Morphological types

THE SIMPLEST PROCEDURE IS TO SORT OUT THE NEBULÆ [...] INTO GROUPS OF OBJECTS SHOWING SIMILAR FEATURES. THE MORE CONSPICUOUS MEMBERS OF EACH GROUP CAN THEN BE STUDIED IN DETAIL AND THE RESULTS USED FOR THE COMPARISON OF THE GROUPS THEMSELVES. THE DEGREE OF SUCCESS ATTAINED BY THE METHOD DEPENDS LARGELY UPON THE SIGNIFICANCE OF THE FEATURES SELECTED AS THE BASIS OF CLASSIFICATION.

HUBBLE, THE REALM OF THE NEBULÆ (1936)

Several classification schemes for galaxies have been developed (e.g., Sandage & Binggeli 1984, de Vaucouleurs et al. 1991, van den Bergh 1960). For the purpose of this review, four basic galaxy types are distinguished (Fig. 2) – large spiral (S), irregular (Ir) or dwarf irregular (dIr), dwarf elliptical (dE), and dwarf spheroidal (dSph) galaxies. Gallagher & Wyse (1994) define a dSph as a galaxy with $M_B > -14$ mag, low surface brightness ($V \geq 22$ mag arcsec^{-2}), no well-defined nucleus, and very little gas, while a dE is elliptical in appearance, shows a dense, globular-cluster-like nucleus, and may contain larger amounts of gas. DIrs usually are at least a few magnitudes brighter than dSphs, "irregular" in appearance, gas-rich, and show recent star formation (e.g., Lee 1995a). A galaxy is considered intermediate between dSphs and dIrs when it contains predominantly old (or intermediate-age) populations, does not show recent star formation, but contains more than $10^5 M_\odot$ HI. See Table 3 for examples.

Let us briefly recall the distribution of morphological types in the LG: The distribution of morphological types with distance (e.g., Table 3) shows the well-known clustering of dEs and dSphs around the dominant spiral galaxies in the LG, while the Irs and dIrs are found at larger distances (except for LMC and SMC). Due to their low surface brightness, more distant dSphs may not yet have been detected. While both dSphs and dEs can be seen around M 31, the Milky Way does not have dEs as companions. Thirteen dSphs are currently known, 2 dIr/dSphs, and 14 Irs and dIrs, while there are only 4 dEs. M 33 does not seem to have close companions. Two of the three spirals, M 31 and the Milky Way, contain almost the entire mass of the LG. Consistent with findings for more distant galaxy clusters, dwarf galaxies are the most frequent type of galaxy.

3 Methods to Study Resolved Stellar Populations

HET ONDERZOEK IS VRIJ: DOCH, WAT GIJ VINDEN MOET –
EN ANDERS HEBT GIJ 'T ZWAAR IN DIT EN 'T ANDRE LEVEN! –
IS BIJGAAND REZULTAAT; WANT DIT ALLEEN IS GOED,
EN AL DE REST WORDT DOOR DEN DUIVEL INGEGEVEN.

P.A. DE GÉNESTET (1860)

In order to derive the star formation history of a galaxy, or parts thereof, one needs to explore the ages, metallicities, fractions, and spatial distribution of the stellar populations it contains. The distance to the target galaxy as well as foreground and internal extinction must be determined as accurately as possible.

Stellar populations resolvable into individual stars can be studied with much higher accuracy than the integrated light of distant, unresolved populations, but there are still many difficulties to overcome. Observational results are constrained by the limiting magnitudes attainable, by resolution and crowding effects, and by

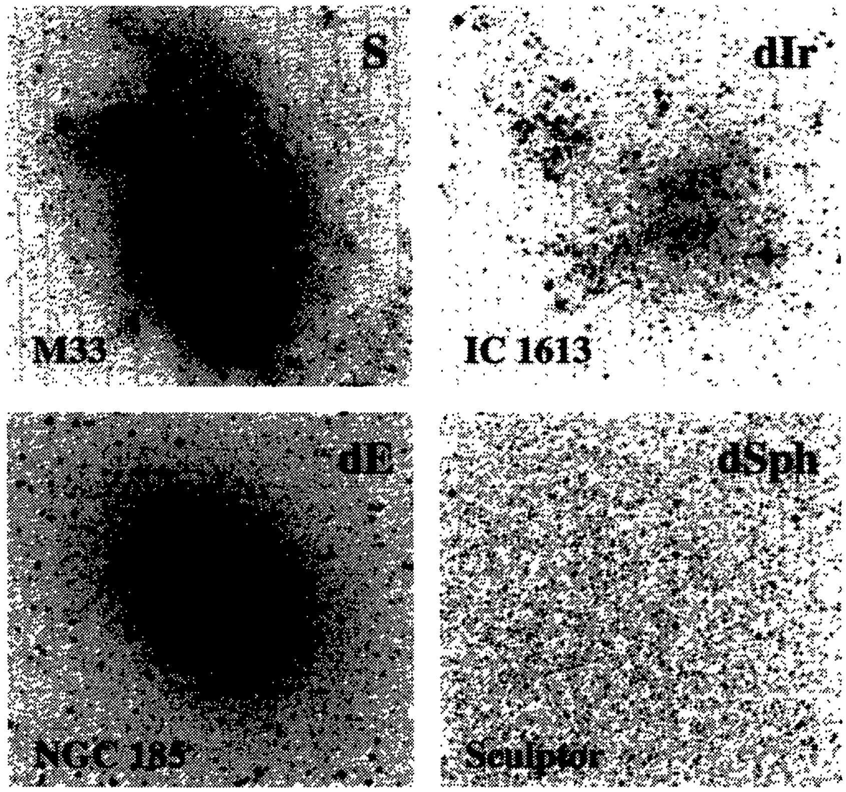

Figure 2: Examples for the four basic morphological types of galaxies found in the Local Group (see also Table 3 and the definitions in Section 2.4) – spirals (S), irregulars (Ir), dwarf ellipticals (dE), and dwarf spheroidals (dSph). Note how little central concentration and density a dSph shows in comparison to a dE, while the dIr has prominent regions of high gas concentration and young massive stars.

dust obscuration. Interpretation of the observations suffers from problems such as disentangling a mix of populations, the age-metallicity degeneracy, and potentially inadequate theoretical models. The usefulness of methods employed in stellar population studies depends on their ability to deal with these problems.

The *combination* of different, independent approaches helps to yield a more comprehensive and consistent picture of the star formation history of a galaxy. This holds not only for different methods for detailed studies of the stellar content, but ideally also involves supplementary data on the gas content, internal kinematics and overall dynamics, chemical enrichment, the extragalactic neighbourhood, past and future interactions, etc. Once such a truly comprehensive picture is available, an understanding the evolutionary history of the LG will be forthcoming.

Methods for the study of resolved stellar populations rely primarily on CCD photometry and, to a lesser extent, on spectroscopy. Spectroscopy yields abundances, radial velocities, or spectral types. Studies in other wavelength ranges, such as the UV or the infrared, often have a survey nature and tend to concentrate on special types of stars.

Derived ages of stellar populations are often loosely referred to as young, intermediate-age, and old. In this review, "young" will generally denote an age range from 10^6 to 10^8 years, "intermediate-age" some 10^9 years, and "old" $> 10^{10}$ years.

3.1 Stellar Content: What Can Different Types of Stars Tell Us?

Certain types of stars may serve as indicators of distance, age, and/or metallicity. This type of information is independent of isochrone fitting techniques or the modeling of the observed populations through different population synthesis methods and can be used either as supplementary information or for consistency checks. In the following subsections, examples will be given for information attainable through observations of certain types of stars, and groups of stars.

3.1.1 Distances

Distances may be obtained through period-luminosity relations of variable stars or the brightness of individual stars or stellar groups. Classical Cepheids and RR Lyr stars are excellent primary distance indicators if the metallicity dependence is considered (e.g., Madore & Freedman 1991, Carney et al. 1992, Nemec et al. 1994, Sasselov et al. 1997). The absolute magnitude of the zero-age horizontal branch (ZAHB), also metallicity-dependent, is a distance indicator for old populations.

The I magnitude of the tip of the first-ascent red giant branch (TRGB) has been calibrated as a distance indicator for populations in the age-range of 7 to 17 Gyr and more metal-poor than 47 Tuc (Lee et al. 1993a). The TRGB method requires less telescope time, is less affected by internal extinction problems than Cepheids, is based on stars 4 magnitudes brighter than RR Lyr stars, and quite insensitive to metallicity variations for $-2.2 < [Fe/H] < -0.7$ dex. Crowding effects and other potential problems are discussed in Madore & Freedman (1995).

In this review, preference is given to the above described photometric distance indicators. Other methods such as the brightest red or blue stars, C stars, planetary nebulae, surface brightness fluctuations, etc. (see Jacoby et al. 1992 for a review) are not considered. Apart from their metallicity dependence, distance determinations depend critically on the adopted extinction. For a given interstellar extinction $A_{V,0}$, the amount of reddening that a specific star suffers in a given filter depends on its effective temperature, surface gravity, and metallicity (Grebel & Roberts 1995).

3.1.2 Metallicities

A short red horizontal branch (HB) indicates a metal-rich population, while extended blue HBs are found in old, metal-poor populations. However, HB morphology in old populations depends on more parameters than just metallicity, and many suggestions have been made to explain the unknown "second parameter(s)" (e.g., Lee et al. 1994, Stetson et al. 1996, Buonanno et al. 1997). The colours of AGB stars also depend on metallicity but are poor indicators since often it is difficult to disentangle their position from that of the blue portion of the RGB.

The ratio of carbon (C) stars to evolved M stars, and the ratio of late to early M stars, are strong functions of parent galaxy luminosity and are indicative of metallicity changes in intermediate-age stars (Cook et al. 1986). Also the ratio of WC/WN stars depends to a certain extent on metallicity (e.g., Armandroff & Massey 1991). The blue-to-red supergiant ratio in galaxies is a function of metallicity (Langer & Maeder 1995) as are evolution and winds of massive OB stars (e.g., Walborn et al. 1995).

Spectroscopic abundance determinations are usually more accurate than photometric methods. However, due to the large amounts of telescope time required, spectroscopic abundances are often measured only for very few stars that may or may not be representative for an entire population, a caveat that may be overcome with multiple-object spectroscopy. A comparison of spectroscopic and photometric methods for young stars and reasons for discrepancies is given in Grebel (1995). Special care has to be taken when converting oxygen abundances measured in HII regions into stellar iron abundances (Richer & McCall 1995).

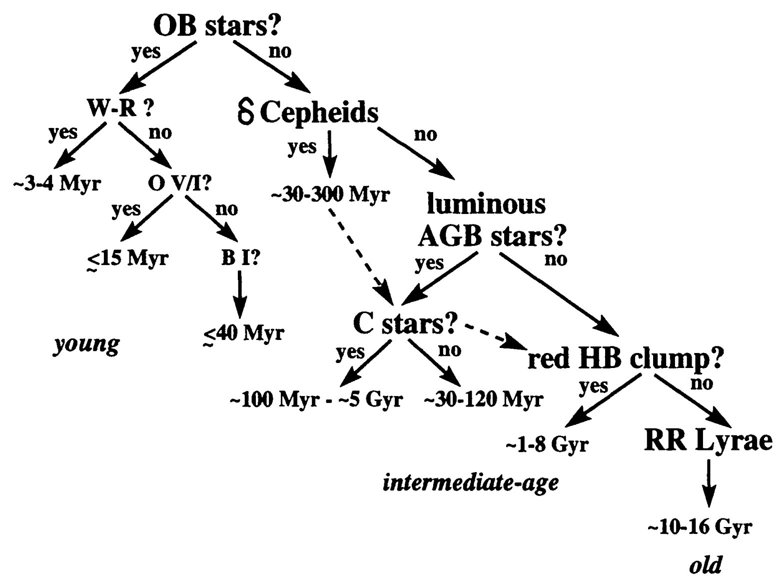

Figure 3: Flow chart illustrating how crude age estimates can be derived from special types of stars for a single population. Age ranges were in part taken from Maeder & Meynet (1994), Frogel et al. (1990), Caputo et al. (1995), and Ibata et al. (1997). The ages always depend on the masses, luminosities, and metallicities of the stars involved. Finally, the presence of a certain star type is a sufficient criterion for population in the corresponding age range, while the absence of this type does not necessarily imply a lack of a stellar population in this age range (e.g., RR Lyr).

3.1.3 Ages

As certain types of stars exist only in certain age ranges, their lack or presence can be used for crude age estimates as illustrated in Figure 3. For instance, OB and Wolf-Rayet stars are unmistakable tracers of recent star formation (e.g., Armandroff & Massey 1991, Maeder & Meynet 1994). The presence of OB stars but absence of W-R stars helps to detect regions of recent star formation – either before the formation of W-R stars or more than ≈ 4 Myr ago so that W-R stars are no longer visible. Total number and fractions of Be stars are largely a function of spectral type and thus of age (Mermilliod 1982, Grebel 1997).

The proportion of stars of a certain type may be translated into the fraction of the subpopulation whose age they represent. Since the mean luminosities of C stars in a galaxy are a function of age, the mean fractional C star contribution to the V magnitude of a galaxy can be used to derive the fraction of the intermediate-age population (Aaronson & Mould 1985). Anomalous Cepheids may be indicators of an intermediate-age population unless they result from binary mass transfer or coalescence and are coeval with the underlying population. Blue stragglers are probably not tracers of a younger population but instead the result of binary evolution (e.g., Stryker 1993, Bailyn & Pinsonneault 1995).

Morphological age criteria based on certain types of stars include the magnitude difference between the intermediate-age red HB clump (core-helium burning stars) and the main-sequence turnoff, which was calibrated as an age indicator by Caputo et al. (1995). The magnitudes of the ZAHB and of the main-sequence turnoff serve as age indicators for old populations (see Stetson et al. 1996 for a comprehensive review of methods). Mighell & Rich (1996) apply different morphological age indicators to Leo II. The resulting ages range from ≈ 7 Gyr to ≈ 11 Gyr. A very reliable age indicator is a well-defined main-sequence turnoff position, which requires uncrowded photometry extending well below the turnoff.

3.2 Deciphering Colour-Magnitude Diagrams

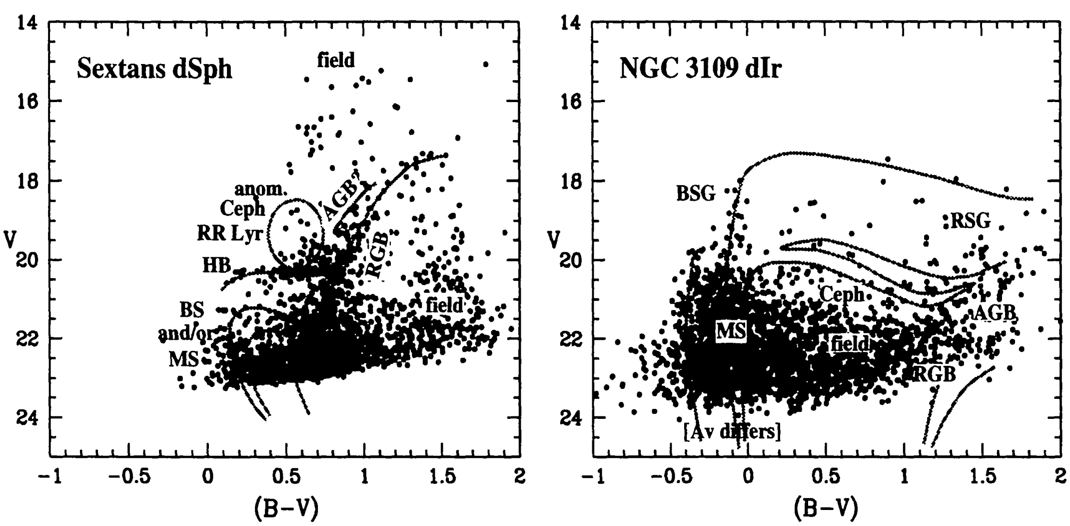

Figure 4: B, V colour-magnitude diagram for the dSph Sextans (left panel, taken from Mateo et al. 1995a) and for the dIr NGC 3109 (right panel, taken from Greggio et al. 1993). The main morphological features are indicated qualitatively by hand-drawn lines. The abbreviations stand for the following: MS = main sequence, BSG = blue supergiants, BS = blue stragglers, RSG = red supergiants, AGB = asymptotic giant branch, RGB = red giant branch, anom. Ceph = anomalous Cepheids, RR Lyr = RR Lyrae stars, HB = horizontal branch, field = foreground stars. For NGC 3109, the interpretation follows in part Lee (1993) and Davidge (1993).

Colour-magnitude diagrams (CMDs) of stellar populations in LG dwarf galaxies usually show a mix of populations. Owing to the relative proximity of dSphs, their CMDs show less scatter and reach fainter absolute magnitudes than CMDs of composite populations in dIrs. The most conspicuous feature of a dSph CMD is a wide red giant branch (RGB) coupled with a more or less pronounced HB, or a red HB clump, or both (Figure 4). Ideally, the main-sequence turnoff will be visible. CMDs of dIrs usually show the upper portion of an RGB/AGB region, red supergiants (RSGs) on top of it, and an upper main sequence plus blue supergiants (BSGs). Due to crowding and the faintness of the stars, the main sequence/BSG region and the RGB/AGB/RSG region both exhibit wide scatter, which makes the interpretation of dIr CMDs more difficult (Figure 4). Often different approaches are chosen for the analysis of CMDs of predominantly intermediate/old populations and populations with a high fraction of young stars.

3.2.1 Morphological Criteria

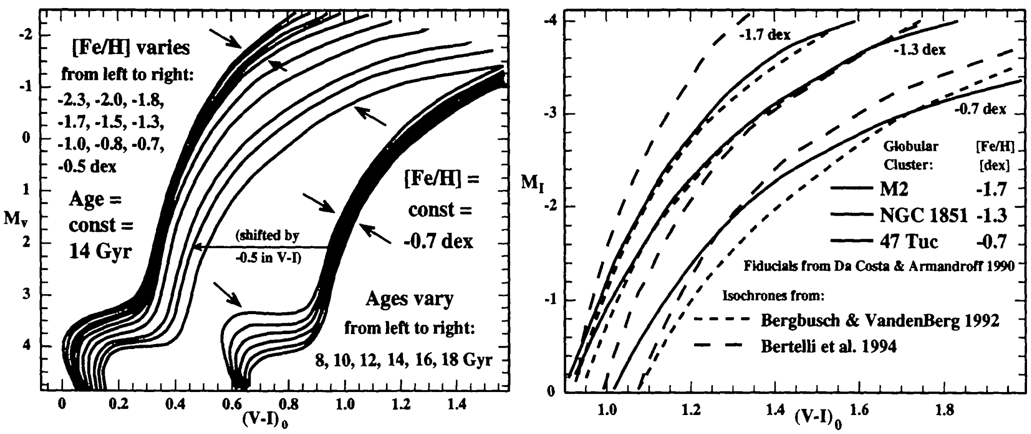

Figure 5: Left panel: Effects of metallicity and age on the red giant branch (RGB). All isochrones are from Bergbusch & VandenBerg (1992). The left-hand set of isochrones was shifted by -0.5 mag in $V-I$ so that both sets of isochrones could be displayed in the same diagram. While the locus and slope of the RGB are sensitive to *metallicity*, the RGB is a poor *age* indicator for old populations. Note how the metallicity resolution decreases with decreasing metallicity. Right panel: Comparison of isochrones from different groups to globular cluster fiducials from Da Costa & Armandroff (1990: solid lines). Location and slopes of the fiducials agree better with the Bergbusch & VandenBerg (1992: short dashes) isochrones than with Bertelli et al. (1994: long dashes). All isochrones have an age of 14 Gyr. For a more detailed comparison, see Grebel (1995).

The simplest approach for deriving the parameters of galaxies dominated by old and/or intermediate-age populations, such as found in dSphs, is through morphological criteria. For instance, the tip of the RGB or the HB can be used for distance determinations, and HB and main-sequence turnoff for age estimates as mentioned earlier. For a given age, slope and position of the RGB are strong functions of metallicity. The metallicity resolution decreases toward lower abundances (see left set of isochrones in Figure 5). For a fixed metallicity, in turn, the position of the RGB shows little variation with age while the main-sequence turnoff is sensitive to both age and metallicity. Ground-based CCD photometry often does not reach the turnoff region, which makes age determinations highly uncertain or impossible.

Metallicities are estimated by comparing the slope and width of the composite RGBs to fiducials of Galactic globular clusters of known metallicity (Da Costa & Armandroff 1990), or with isochrones, assuming that most of the width of the RGB is caused by metallicity effects rather than variations in age. For old populations with well-defined RGBs, reddening and metallicity can be determined simultaneously through the shape of the RGB, the HB magnitude, and the colour at the HB level (Sarajedini & Norris 1994, Sarajedini 1994).

3.2.2 Luminosity Functions

Mighell (1990, Mighell & Butcher 1992) developed a technique to derive star formation histories of intermediate-age populations by fitting their observed luminosity functions (LFs) with theoretical LFs covering a range of parameters and distance moduli. The theoretical LFs primarily are functions of age, metallicity, He abundance, and IMF. Correct interpretation of complicated star formation histories of older populations requires large numbers of stars in the LF to minimize the age-metallicity-distance degeneracy. If this condition is fulfilled, this method allows one to derive age, metallicity, and distance modulus simultaneously for single or composite populations.

A pronounced discontinuity in the LF at the RGB tip may be indicative of an old population (e.g., Minniti & Zijlstra 1996). Comparing observed LFs of globular clusters to the LF of a dSph, Mateo et al. (1991, 1995a) found an excess in the RGB portion possibly caused by AGB stars from an intermediate-age population. An apparent overabundance of stars in a dSph's main-sequence LF may imply the presence of a younger population in the dSph rather than an unusually high blue straggler content. For young populations, the LF consists of a blue plume of inseparable massive blue main-sequence stars and blue supergiants (e.g., Marconi et al. 1995), possibly mixed with intermediate-age blue-loop stars.

3.2.3 Isochrones and Metallicity Distribution Functions

Grebel and collaborators (Grebel et al. 1994, Grebel 1995) developed a technique to simultaneously determine ages, abundances, reddening, and distance moduli through simultaneous isochrone fits to multi-colour photometry in at least four filters. Four filters formally suffice to avoid degeneracy. The fits are done for a range of values in all four parameters and statistically evaluated.

The use of a metallicity-sensitive photometric system allows one to determine the metal abundances of a large number of stars, and the metallicity-sensitive Washington broadband system (Harris & Canterna 1977, Geisler et al. 1991) allows it to be done with reasonable exposure times. Studying mixed old and intermediate-age populations in dSphs, one can determine the metallicities of red giants from their $M - T_2$, $C - M$ colours, independently of age and isochrones. The resulting metallicity distribution functions enable one to detect subpopulations distinct in metallicity (Section 4) while avoiding the age-metallicity degeneracy.

3.2.4 Synthetic CMDs

Tosi, Greggio, and collaborators (e.g., Tosi et al. 1991) compared observed CMDs of composite stellar populations with synthetic CMDs. The synthetic CMDs are based on evolutionary tracks combined with Monte-Carlo simulations assuming an IMF and a given star formation rate. In addition, scatter was introduced in accordance with the standard error of the magnitudes. Completeness and blending effects also were evaluated. An independent consistency check was introduced by comparing observed LFs to simulated ones. In comparison to the methods described earlier, this method also accounts for stochastic and crowding effects, and allows the derivation of a complete picture of the star formation history of the observable populations. Codes taking into account chemical enrichment and observed metallicities are in preparation (Marconi et al. 1995).

Aparicio, Gallart, and collaborators (e.g., Aparicio et al. 1996) included comprehensive simulations of crowding effects as a function of completeness, colour, and magnitude in their synthetic CMDs. The intermediate-age and old populations were modeled from the observed distribution in two features in the CMD termed "red tail" and "red tangle" by Aparicio & Gallart (1995). The red tail contains old and intermediate-age AGB stars, and the red tangle consists of old RGB stars, old and intermediate-age AGB stars, and intermediate-age blue-loop stars. Chemical enrichment was also considered (Gallart et al. 1996).

Statistical evaluations can help to decrease degeneracy in synthetic CMDs. Tolstoy (1995; Tolstoy & Saha 1996) developed a quantitative technique to compare observational data to synthetic CMDs of mixed populations investigating the likelihood that model and observed CMDs are drawn from the same distribution.

3.3 Possible Tests of Different Methods

An obvious consistency check is to compare the results of one's method of choice to independent age indicators such as certain types of stars, or independent metallicity indicators such as spectroscopically determined abundances or globular cluster fiducials. Figure 5 (right panel) shows a comparison of isochrones from theoretical models to fiducials of globulars with well-established metallicity. All methods that use theoretical models (stellar evolutionary tracks and/or isochrones, Kurucz models, etc.) depend on how closely these models match the actual physical properties of the stars. Many models are frequently updated and improved.

The Carina dSph is a well-suited object to test the age sensitivity of different methods. Carina shows several main-sequence turnoffs while the spread in metallicity is very small (Smecker-Hane et al. 1996). Thus the subpopulations of this galaxy as well as their ages are quite well known. The existing data could be artificially truncated at different absolute magnitudes and then subjected to various analysis methods. Differences between the analysis of Carina based on LF fitting by Mighell & Butcher (1992) and Smecker-Hane et al.'s results may be caused largely by the different quality of the input data.

3.4 Some of the Remaining Problems

Smecker-Hane et al.'s (1996) data underline the need for photometry below the turnoff region to derive ages. Generally, reliable interpretation of resolvable stellar populations requires high-quality data extending to faint magnitudes. Observationally, the excellent resolution attainable with the Hubble Space Telescope needs to be combined with large-area coverage. With respect to theory, the quality of the available models and our understanding of stellar evolution strongly constrain the correct interpretation of star formation histories.

While models like those of Bergbusch & VandenBerg (1992) for old populations agree well with observations for metal-poor systems, the shape of the upper RGB still can not be satisfactorily reproduced for old, metal-rich systems (e.g, Grebel et al. 1996a), though progress is being made (e.g., Tripicco et al. 1995). There is also progress in understanding and reproducing HB morphology (e.g., Mazzitelli et al. 1995, Caputo & Degl'Innocenti 1995, Caputo et al. 1995, Castellani & Degl'Innocenti 1995), but neither the second-parameter problem is solved (e.g., Stetson et al. 1996) nor are "diagonal", metal-rich HBs well understood.

For young populations, the main sequence is quite insensitive to metallicity, which makes metallicity derivations through synthetic CMDs difficult. The location of the supergiants and the extension of the blue loops is a more sensitive function of metallicity, but theoretical models from different groups arrive at different results depending on the input physics (discussed in, e.g., Bertelli et al. 1994). What affects the blue-to-red supergiant ratio is still poorly understood (e.g., Langer & Maeder 1995). The upper main sequence for massive stars overlaps with the blue supergiant locus (nice discussion in Massey et al. 1995). The determination of the main-sequence turnoff is made harder by effects of binary evolution and rapid rotation, which also lead to significant main-sequence widening, and mimic crowding effects and age spreads (e.g., Grebel et al. 1996b, Grebel 1997). Patchy or differential extinction may have similar effects. Although synthetic CMDs appear to be the best approach for understanding the complicated population mix in the poorly resolved dIrs, they suffer from ambiguity caused by the degeneracy of the locations of main sequence(s), blue supergiants, blue-loop stars, and binaries on the one hand and AGB stars of various ages superposed on RGBs on the other. The age resolution depends directly on crowding and faintness of magnitudes reached. Uncertainties and ambiguities of results based on synthetic CMDs with different input models are illustrated in the discussion in Greggio et al. (1993). Problems with the red-tail, red-tangle approach are discussed in Gallart et al. (1996).

4 Example: The Fornax dSph Galaxy

Fornax was the second dSph galaxy to be discovered (Shapley 1938). Fornax and Sagittarius are the brightest, largest, and most massive dSphs known, and the only two known to contain globular clusters. The field populations and the globular clusters span a range of metallicities (Buonanno et al. 1985, Sarajedini & Layden 1995, Da Costa & Armandroff 1995). I will use Fornax to illustrate metallicity distribution functions (MDF) and simultaneous isochrone fitting.

In order to determine the abundances of individual red giants in dSphs with good number statistics, Washington colours were calibrated in metallicity using the full set of Kurucz's synthetic spectra, standard filter passbands, and a library of stars with $\log g$, $T_{\rm eff}$, and [Fe/H] from high-resolution spectroscopy and well-observed Washington-photometric colours. This yields metallicities for any red giant with $C-M$, $M-T_2$ colours. Using Washington CCD photometry of a field in Fornax including globular cluster (GC) #3 kindly made available by Doug Geisler, Metallicities were determined for red giants with small photometric errors (Grebel et al. 1994, Grebel 1995). The left panel of Figure 6 shows the two-colour diagram (TCD) with iso-abundance curves and observed red giants in Fornax. The right panel of Figure 6 shows the resulting MDF. The pronounced central peak corresponds to the dominant component of the field population. A small, more metal-rich subpopulation also is found. The metal-poor peak in the MDF consists mostly of red giants in GC #3. Gaussians were fitted to the peaks in order to

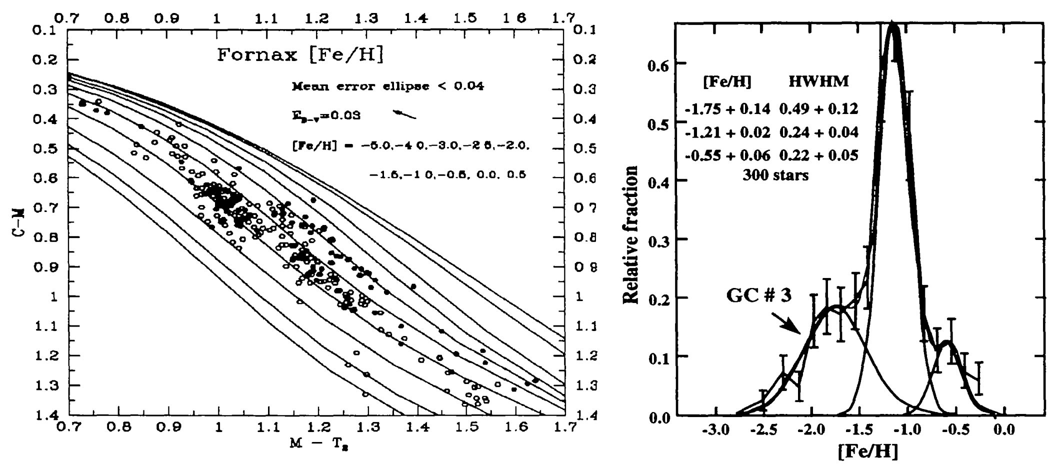

Figure 6: Two-colour diagram (left) of red giants in Fornax with superimposed iso-abundance curves. Filled circles represent stars probably belonging to GC #3, while open circles correspond to likely field stars. The resulting metallicity distribution function (right) shows three peaks. The most metal-poor one consists mainly of globular cluster members, while the other two are field stars.

estimate the abundance spread. As long as the spread is 0.5 dex or less a Gaussian in [Fe/H] will also be a Gaussian in Z within the precision of the data.

The result of the simultaneous isochrone fitting in four colours with a range of metallicities, ages, reddening, and distance moduli is listed in the upper left panel of Figure 7. The metallicities agree well with the findings from the MDF. The potential small metal-rich subpopulation has too few members to be discernible by isochrone fits. The dominant field population is found to be younger than the globular cluster (8 Gyr vs. 11 Gyr) though not extending to as young an age as the dominant field population found in the center of Fornax by Beauchamp et al. (1995). While these age determinations are uncertain owing to photometry not extending below the turnoff, a comparison of Beauchamp et al.'s CMD to Grebel's (1995) results (upper right panel in Figure 7) shows that star formation appears to have continued for a longer period of time in the central areas, while it ceased a few Gyr earlier in the outer parts. Judging from the 1987 Yale isochrones superimposed on Beauchamp et al.'s CMD, part of the central field population may contain more metal-rich populations than present in Grebel's (1995) outer region, which would be indicative of enrichment during the extended central star formation episode. A small, underlying, old population indicated by potential blue HB stars may exist in the outer field. Indications for a sparsely populated old blue HB have also been found by Demers et al. (1994). The absence of an old population would be surprising particularly with regard to the globular clusters, most of which appear to have formed well before the intermediate-age field population. For an extensive discussion of the results see Grebel (1995). Large-area coverage with Washington photometry reaching below the main-sequence turnoff is needed to resolve the star formation history of Fornax spatially, in age, and in metallicity.

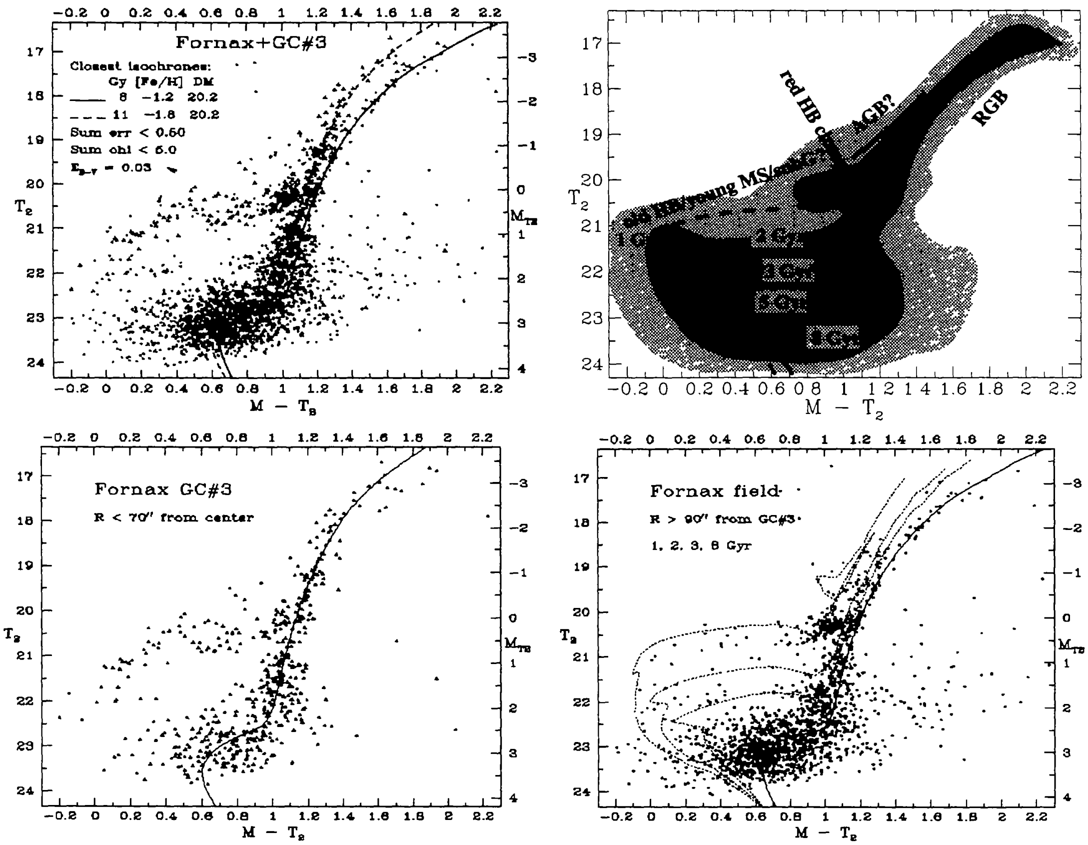

Figure 7: A subset of Washington CMDs of the region around globular cluster (GC) #3 in Fornax. The upper left panel shows the results of isochrone fits to the dominant field population and GC #3. In the CMD in the lower left panel only stars within 70″ around the cluster center are plotted. In contrast to the field star population in the lower right panel, the metal-poor globular cluster shows an extended red and blue HB and RR Lyrae strip. The field star population around GC#3 is predominantly of intermediate-age (≈7–8 Gyr) and features a short red HB clump. Dotted younger isochrones from Schaller et al. (1992) with a metallicity of −1.3 dex are plotted for illustrative purposes. While the stars within the range delineated by the 1–3 Gyr isochrones may indeed be "young" intermediate-age stars, they might alternatively be blue stragglers. Stars located along the 1 Gyr isochrone might instead be blue HB stars belonging to an old field population with very few members (compare with position of the HB of the globular cluster in the lower left panel). The upper right panel shows a hand-drawn sketch of the population components observed in our field compared to data for the center of Fornax (Beauchamp et al. 1995: Figure 20). The amount of shading gives a crude representation of the stellar density in the Beauchamp et al.'s CMD, while solid lines indicate features identified in our field. In the central region of Fornax younger populations (8–3 Gyr) are strongly represented and star formation may have continued until 1 Gyr ago, while it mostly ceased > 6 Gyr ago in the outer region around GC #3. This indicates a radius-dependent age gradient.

5 Star Formation History of Local Group Dwarf Galaxies

IF WE INDULGE IN FANCIFUL IMAGINATION AND BUILD WORLDS OF OUR OWN, WE MUST NOT WONDER AT OUR GOING WIDE ASTRAY FROM THE PATH OF TRUTH AND NATURE... ON THE OTHER HAND, IF WE ADD OBSERVATION TO OBSERVATION, WITHOUT ATTEMPTING TO DRAW NOT ONLY CERTAIN CONCLUSIONS, BUT ALSO CONJECTURAL VIEWS FROM THEM, WE OFFEND AGAINST THE VERY END FOR WHICH OBSERVATIONS OUGHT TO BE MADE.

WILLIAM HERSCHEL

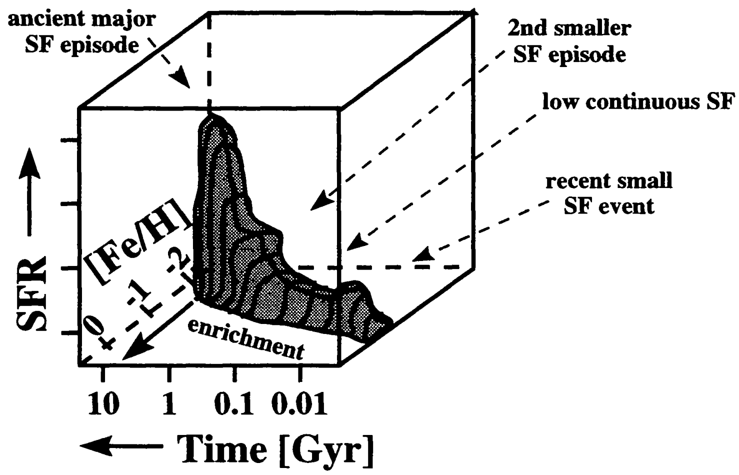

Figure 8: Example of a population box (Hodge 1989) to visualize the overall star formation history of a (fictitious) galaxy. The three axes show star formation rate (SFR), metallicity, and time. For convenience, a logarithmic time axis is used, which corresponds best to the common distinctions between "old", "intermediate-age", and "young" populations. Each galaxy is depicted as an isolated system. Spatial variations are not represented.

Our knowledge about the star formation histories (SFHs) of LG galaxies is growing rapidly as more and better data are becoming available. I have surveyed the available literature to attempt to give a comprehensive overview of our current knowledge (as of November 1996).

To facilitate inter-comparison, SFHs are summarized in table format and population boxes. Hodge (1989) introduced the concept of population boxes (Figure 8) to visualize the SFHs of galaxies. For many LG galaxies our knowledge is still incomplete. In particular, star formation rates (SFRs) usually are known poorly. Thus the representation of SFRs in population boxes presented here only illustrates relative ratios and is not to scale. Modeling observed CMDs as described in Section 3 provides a good means to estimate SFRs.

Figures 9 & 10 show that SFHs of galaxies may differ strongly even within the same morphological type in terms of star formation times, rates, and enrichment. In all LG galaxies studied to-date with sufficiently deep photometry, old and intermediate-age populations (whose fractions vary) have been found. Thus the dSph galaxies that seem devoid of gas today must have lost their remaining gas a few Gyr ago, possibly through the winds of massive stars and supernova explosions (e.g., Fornax, Leo I?), or through tidal effects or ram pressure stripping caused by neighbouring massive galaxies like the Milky Way (e.g., Draco, Ursa Minor?). NGC 205 and M 32 may be bulge remnants of disrupted companions who had much of their gas and possibly their disk removed by M 31 through ram pressure stripping (Sofue 1994). Van den Bergh (1994b) pointed out that ages of the dominant populations in low-mass galaxies seem to decrease with increasing Galactocentric distance. The distant LG galaxies that are intermediate between dIrs and dSphs (Phoenix, LGS 3) may represent a transition between these two types (e.g., Kormendy 1985).

By heating the gas in a dSph, Type Ia supernovae from the first star formation episode might delay the next episode by a few Gyr (Burkert & Ruiz-Lapuente 1997). While the different populations in Carina do not show the predicted enrichment (Smecker-Hane et al. 1996), the two old populations in Sculptor that are distinct in metallicity (Grebel 1995) make this dSph a candidate for temporary deactivation through Type Ia supernovae. Photometry extending below the main-sequence turnoff is needed for a reliable age determination.

More massive galaxies (dIrs, dEs) can retain much of their gas in spite of strong stellar winds and supernovae (De Young & Heckman 1994). Modeling with synthetic CMDs indicates that star formation in dIrs often occurs slowly and continuously over very long time scales while being interrupted by short, inactive periods (Aparicio & Gallart 1995: "gasping" star formation). Depending on the feedback from newly formed stars and critical mass densities (Hunter & Plummer 1996) small frequent star formation episodes can maintain a young population over a Hubble time through gas recycling (Welch et al. 1996). External triggers (i.e., interactions) are not required for this mechanism.

A simplified scenario for the possible evolutionary history of dwarf galaxies is given in Figure 11. Many details, especially the differing enrichment histories, are not yet taken into account.

6 Where Do They Come From, Where Do They Go?

LIKE BUBBLES ON THE SEA OF MATTER BORN,
THEY RISE, THEY BREAK, AND TO THAT SEA RETURN.
ALEXANDER POPE

Gerola et al. (1983) proposed that dE or dSph galaxies are bound remnants of more massive parent galaxies or unbound tidal debris from the interaction of giant galaxies. Dwarf galaxies have been found to form in tidal tails of interacting galaxies (e.g., Mirabel et al. 1992). If this scenario holds for the Local Group, the Milky Way and M 31 should have accreted or merged with the progenitor galaxies. Galaxy mergers may lead to the formation of, or contribute, globular clusters. Globulars with retrograde orbits may be contributed by an incoming galaxy with retrograde motion. Indeed, Milky Way dwarf companions and so-called "young" (red HB morphology) globular clusters with presumably retrograde orbits (Rodgers & Paltoglou 1984, van den Bergh 1993, Lee et al. 1994) were found to lie on two great circles (Kunkel 1979, Lynden-Bell 1982, Majewski 1994), possibly indicating two major merger events. DSphs should have been more numerous in the past. The Sagittarius dSph is currently merging with the Milky Way, and the gaseous Magellanic Stream may be accreted by the Milky Way within 1 Gyr (Sofue 1994). Mergers with, and ram pressure stripping of, dwarf companions of M 31 may be responsible for its disrupted inner gaseous disk and its double nucleus (Sofue 1994).

New data on kinematics and ages show that several of the above mentioned clusters are neither young nor have retrograde orbits. Judging from the few globular clusters with known angular momenta and space motions (Dauphole et al. 1996),

Table 4. Properties of (dwarf) irregular galaxies in the Local Group. Surface brightness σ_B and HI mass log $M_{\rm HI}$ are from Melisse & Israel (1994). All other references are denoted by superscripts. Underneath each distance modulus "DM" the method is specified. Column "SFR" contains the star formation rate. HIIR = HII regions, Cep = Cepheids, YSG/BSG = yellow/blue supergiants, SF = star formation, cont. = continuous, decr. = decreasing, MS = main sequence, WR = Wolf-Rayet stars, C = carbon stars, BSS = brightest blue stars, TRGB = tip of the RGB, gasps = continuous star formation with short inactive periods.

Name	σ_B mag/□′	log $M_{\rm HI}$ log $M_\odot$	E_{B-V} mag	*DM* mag	12+log(O/H) or [Fe/H]	SFR $10^{-7}M_\odot$/yr	Populations	References
IC 10	13.1	8.96	≈0.94[1]	24.59 ± 0.30[1]	8.20[2]	0.8[3]	> 15 WR, HIIR, starburst[4]	[1]Saha &al.1996,[2]Lequeux &al.1979
				(Cepheids)			Cep, TRGB[1]	[3]Thronson et al.1990
NGC 6822	13.2	7.82	0.41[5]	23.47 ± 0.11[6]	8.20[7]	0.5-1[5]	> 4WR[8], OB assoc. 7–12Myr[9],	[4]Massey & Armandroff 1995
			var.	(Cepheids)			gasps < 1 Gyr[5]	[5]Marconi & al. 1995
					−1–−0.8[10]		9 − 6 Gyr group[10], C[15]	[6]McAlary & al. 1983
					−2.3–−1.7[10]		< 15 − 12Gyr,gasps[10],≈2GC[30]	[7]Skillman & al. 1989a
IC 1613	14.9	7.74	≈0.02[11]	24.10 ± 0.27[11]	7.86[12]		> 1 WR[8], HIIR, 5 − 100Myr[13]	[8]Armandroff & Massey 1991
				(RR Lyrae)	−1.3,±0.8[14]		Cep, YSG[14], C[15]	[9]Wilson 1992,[10]Gallart & al.1996
							RR Lyr, > 15% old[11]	[11]Saha & al.1992,[12]Talent 1980
WLM	14.6	7.84	0.02[16]	24.80 ± 0.05[16]	−1.2[17]	0.017[17]	HIIR, BSG[17]	[13]Hodge&al.1991,[14]Freedman1988
				(TRGB)	low[18]		C[18], low cont. SF > 1 Gyr[19]	[15]Cook & Aaronson 1988
					−1.4 ± 0.2[16]		1 GC[20], > 10 Gyr halo[16]	[16]Minniti & Zijlstra 1996
Sex B	14.3	7.80	0.03[21]	≈ 25.6[22]	7.56[23]	0.03-0.35[22]	HIIR[24],gasps[22]	[17]Hodge & Miller 1995
				(synth.)	−1.3[22]		> 1 Gyr[22]	[18]Cook & al. 1986
Sex A	14.6	7.97	0.04[25]	25.85 ± 0.15[25]	7.48[23]	0.006[24]	HIIR, 5 − 10[24] Myr,	[19]Ferraro & al. 1989
				(Cepheids)			30 − 60 Myr, low cont. SF[27]	[20]Ables & Ables 1977
							Cep, TRGB[25], "old" halo[26]	[21]Ratnatunga & Bahcall 1985
DDO 210	15.3	6.82	0.03[21]	24.6[28]		0.02-0.16[5]	no HIIR, low SF < 80 Myr[29],	[22]Tosi & al. 1991
				(comparison)			more 0.1 − 1 Gyr[29]	[23]Skillman & al. 1989b
NGC 3109			0.04[31]	25.45 ± 0.15[31]		0.03-0.83[29]	HIIR, >10Myr[32],gasps<1Gyr[29],	[24]Strobel & al. 1991
			var.	(TRGB)			100Myr SF≃ 2.5×400Myr SF[29]	[25]Sakai & al.1996
					−1.6 ± 0.2[31]		Cep[33], TRGB[31], AGB	[26]Hunter & Plummer 1996
					< −1.6[34]		old halo[31], 20 GCs[35]	[27]Aparicio & al. 1987
SagDIG		6.74	0.01[24]	25.3 ± 0.5[36]	7.42[7]		HIIR[24]	[28]van den Bergh 1994a
				(BBS)			C[15]	[29]Greggio & al.1993,[30]Hodge 1989
LGS 3		5.48	0.024[37]	24.54 ± 0.21[37]			few blue MS[37]	[31]Lee 1993, [32]Bresolin & al.1993
				(TRGB)			TRGB, few AGB[37], C[38]	[33]Capaccioli & al. 1992
					−2.10 ± 0.22[37]		strong RGB[37]	[34]Davidge 1993, [35]Harris 1991
Phoenix		5[39]	0.02[40]	23.1 ± 0.1[40]			few blue MS < 150 Myr[40]	[36] Cook 1987, [37]Lee 1995
				(TRGB)			C?[40]	[38]Cook & Olszewski 1989
					−1.4 – −2.5[40]		strong RGB[40]	[39]Carignan & al. 1991
IC 5152	13.9	8.33		26.0[41]	8.36[12]		HIIR[12]	[40]van de Rydt & al. 1991
				(Cepheids)			Cep[41]	[41]Caldwell & al. 1988
Pegasus	14.5	6.76	0.02[42]	24.9 ± 0.1[42]			1 HIIR,few>25Myr,80–100Myr[42]	[42]Aparicio 1994
				(TRGB)	−0.4,−0.7[43]		2.5 − 4 Gyr[43], Cep?[44]	[43]Aparicio & Gallart 1995
					−1.1[42]		strong RGB > 10 Gyr[43]	[44]Hoessel & al. 1990

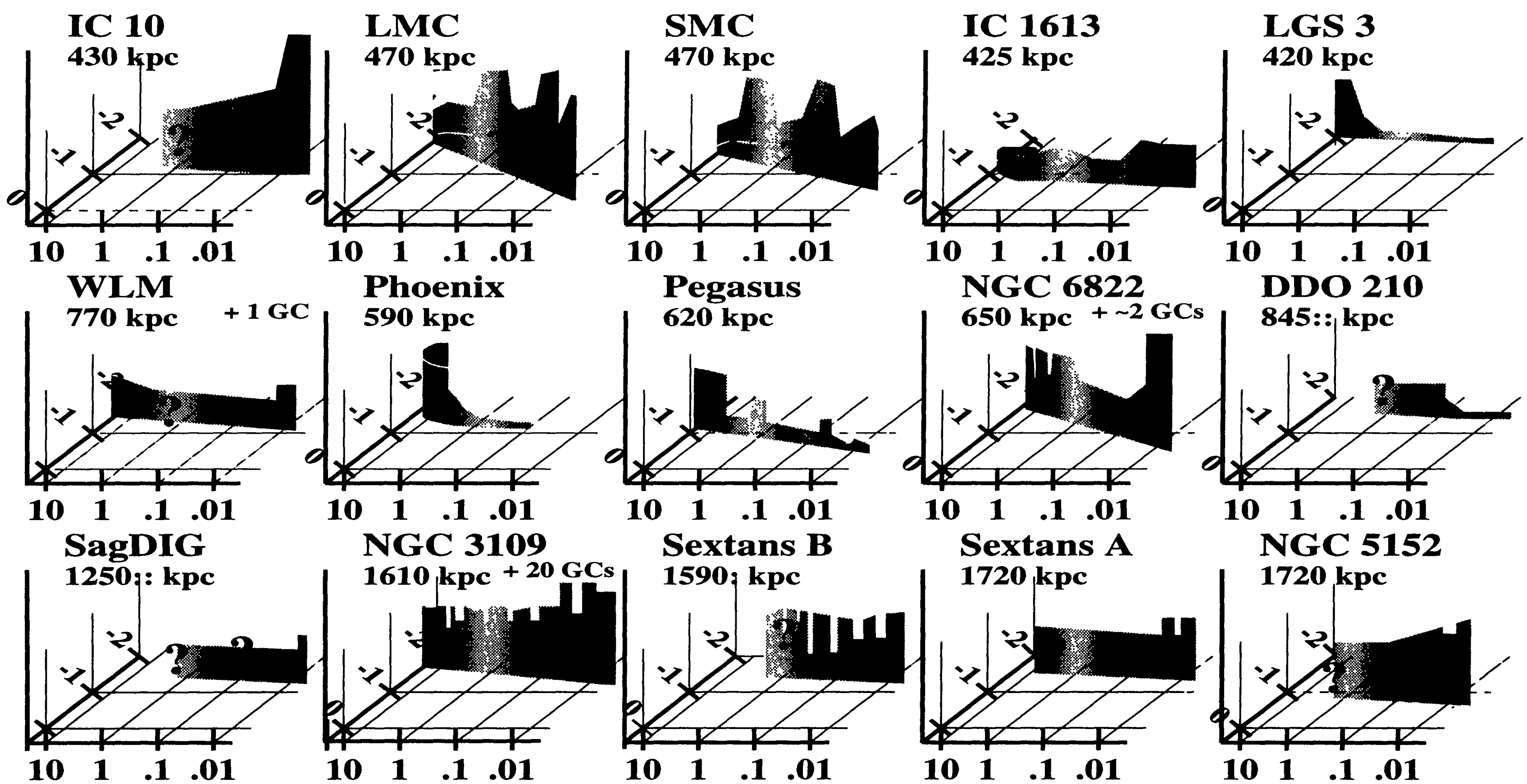

Figure 9: An attempt to depict the approximate star formation histories of Local Group irregular galaxies based on Table 4. Axes are as in Figure 8 with ages in Gyr. For many galaxies, little information is available on the old populations. Some galaxies contain globular clusters (GCs). The distances refer to the barycenter of the Local Group. Note how differently star formation proceeded in these galaxies. Star formation took place at different times and with differing intensity. Some galaxies show a large amount of chemical enrichment, while others have changed very little. LGS 3 and Phoenix are intermediate between dIrs and dSphs.

Table 5. Properties of dwarf spheroidal and dwarf elliptical galaxies in the Local Group. Surface brightness σ_B and HI mass log $M_{\rm HI}$ are from Lee (1995a). All other references are denoted by superscripts. See Table 4 for a description. BHB/RHB = blue/red horizontal branch, GC = globular cluster, pop. = population, met. = metallicity, grad. = gradient, disp. = dispersion. Note that results from different methods are not always consistent or comparable.

Name	σ_V mag/□′	log $M_{\rm HI}$ log $M_\odot$	E_{B-V} mag	DM mag	[Fe/H] dex	Populations	References
Sagittarius	25.4	> 4[1]	0.2 – 2[2]	16.7–17.2[2]	−0.52±.09[3]	clump[3],AGB,C[4],small 7Gyr pop.[5]	[1]Koribalski &al.1994,[2]Alcock &al.1997
			variable	(RR Lyr)	−0.8; −1.2[6]	bulk 10 – 14[6], RR Lyr[2,5]	[3]Sarajedini & Layden 1995
					−0.4,−1.7,−1.6,−2.0[8]	Ter7,Arp2,M54,Ter8:7–16Gyr[7]	[4]Whitelock &al.1996,[5]Mateo &al.1995b
Ursa Minor	25.1	2.4[9]	≈ 0.03[10]	19.25[10]		C[12],anom.Cep[13],small intermed.pop.	[6]Fahlman &al.1996,[7]Chaboyer &al.1996
				(RR Lyr)	−1.9 to −2.2[15]	RR Lyr, BHB, RHB, bulk old[11]	[8]Da Costa & Armandroff 1995
Draco	25.2	1.8[9]	0.03±.01[14]	19.51[10]		C[12], anom.Cep[13], RHB, 8 Gyr[14]	[9]Knapp &al.1978,[10]Nemec &al.1994
				(RR Lyr)	−1.6±.2;−2.3±.2[16]	RR Lyr[10], 2 old pop.?[16]	[11]Olszewski & Aaronson 1985
Sextans	25.5		0.04±.03[17]	19.67±.15[17]	low	anom.Cep,MS,25% 2 – 4 Gyr[17]	[12]Aaronson & Mould 1985
				(RR Lyr)	−1.6±.2[17]	RR Lyr,RHB,>8Gyr[17],12Gyr[18]	[13]van Agt 1967,[14]Carney&Seitzer1986
Sculptor	24.1	< 5[9]	0.04±.01[19]	19.71[22]	−1.8,−1.9,−2.2;±.3[20]	anom.Cep[22], C[21]	[15]Bell 1985,[16]Lehnert & al.1992
				(RR Lyr)	−1.6,±.4;−2.1,±.2[19]	RR Lyr,RHB,BHB,13 – 15 Gyr[19]	[17]Mateo & al.1995a, [18]Mateo & al.1991
Carina	25.2	3[23]	0.03[25]	20.12±.04[25]	−1.9,±.2[25]	clump, MS, 2 Gyr, 3 – 6 Gyr[25]	[19]Grebel 1995,[20]Smith & Stryker 1986
				(CMD)		RR Lyr[10],RHB,BHB,MS 11–13Gyr[25]	[21]Azzopardi & al.1986
Fornax	23.2	< 4[9]	0.03±.02[19]	20.45 ± .1[26]	−0.6, ±.2; −1.2, ±.3[19]	many C[28],1–8Gyr,bulk>5Gyr[19,27]	[22]Kalużny & al.1995
				(HB)		age grad.,weak BHB[19,24],≈4% old[24]	[23]Mould & al.1990,[24]Demers & al.1994
					−2.0,−1.7,−1.9,−1.4,−1.9[19,29]	GC#1–5, old[19,30]	[25]Smecker-Hane & al.1996
Leo II	24.0	< 4[9]	0.0[31]	21.66 ± .21[31]		C[12],AGB,clump[31],few<7Gyr[32]	[26]Rodgers & Harding 1989
				(TRGB)	−2.0, ±.2[31]	RHB[31],14–7Gyr, bulk 9 Gyr[32]	[27]Beauchamp&al.1995,[28]Azzopardi1994
Leo I	22.3	< 4[9]	0.02[33]	22.18 ± .11[33]	−2.0, ±.2[33]	C[12], clump, AGB, bulk 3 Gyr[33]	[29]Minniti&al.1996,[30]Buonanno&al.1985
				(TRGB)		no SF 3–20Gyr, 10%>12Gyr[35]	[31]Lee 1995b, [32]Mighell & Rich 1996
Tucana		none[34]		24.72 ± .2[36]	−1.6 ± .2[36]	AGB? clump? no HB, > 5Gyr[36]	[33]Lee & al.1993,[34]Oosterloo & al.1996
And I	24.9	4.9[37]	0.04±.02[38]	24.55 ± .08[38]	−1.45, ±.3[38]	RHB,few>3Gyr,bulk 10Gyr[38]	[35]Mateo&al.1994,[36]Castellani&al.1996
					radial met.grad.[38]	RRLyr,BHB,few old,radial grad.[38]	[37]Thuan & Martin 1979
And III	25.3	4.9[37]	0.05[39]	24.2 ± .2[39]	−2.0 ± .2[39]	bulk old, ≈ 10% intermed.[39]	[38]Da Costa &al.1997
And II	24.8		0.08[40]	23.8 ± .3[40]	−1.6, ±.3[40]	C[41],≈10% intermed.[39],bulk old[40]	[39]Armandroff &al.1993
M 32			0.08[42]	≈ 24.42[42]	−0.3[42]	AGB 2–4Gyr[43],50% 8.5 Gyr[42]	[40]König&al.1993,[41]Aaronson&al.1985
				(CMD)	−2.2 to −0.5[44]	age&met.grad.[44],2–5Gyr,13Gyr[45]	[42]Grillmair & al.1996
NGC 147	21.6		0.18[46]	24.4[48]	-0.9,±.7;-1.0,±.3[48]	radial age grad.,few AGB,clump[48]	[43]Elston& Silva 1992
				(CMD)	disp.varies radially	RR Lyr, bulk old[46]	[44]Davidge & Jones 1992
					−1.9, −1.5[47]	4 GCs	[45]Bertola & al. 1995,[46]Davidge 1994
NGC 185	20.9	5.1[52]	0.19±.03[49]	23.96 ± .21[49]		ongoing SF[50], AGB[49]	[47]Da Costa & Mould 1988
				(TRGB)	−1.23, ±.8[49]	RR Lyr[51], strong RGB[49]	[48]Han & al.1996, [49]Lee & al.1993c
					−1.4,−1.2,−1.7,−2.5,−1.8[48]	GCs #1–5, total: 8[48]	[50]Welch & al.1996
NGC 205	20.2	5.6[52]	0.04[53]	> 24.7 ± .3[53]		100–500Myr[56],small central burst[55]	[51]Saha & Hoessel 1990
				(RR Lyr)	solar	C[54], AGB, strong 0.5 – 1.5Gyr[55]	[52]Johnson & Gottesman 1983
					−1.0 to −0.5[56]	RR Lyr[53], RGB	[53]Saha & al.1992b,[54]Richer & al.1984
					−1.5,−1.5,−1.4,−1.3,−1.4,−2.0[48]	8 GCs[48]	[55]Davidge 1992, [56]Bica & al.1990

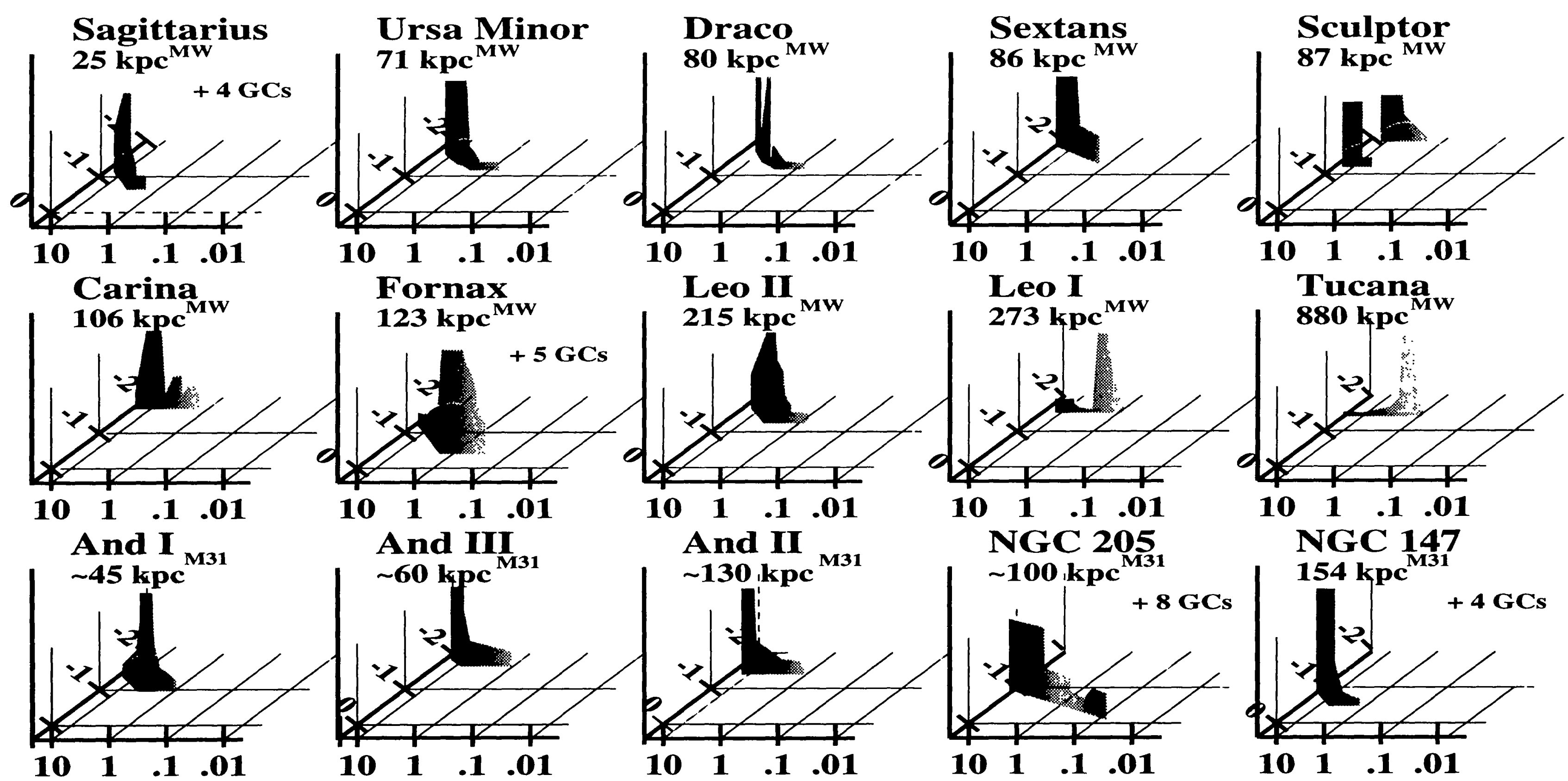

Figure 10: An attempt to depict the approximate star formation histories of Local Group dwarf spheroidal galaxies based on Table 5. Axes are as in Figure 8 with ages in Gyr. The distances in the upper two rows refer to the Milky Way, while distances to M 31 are given for the companions of Andromeda in the lower row. Note how differently star formation proceeded in these galaxies as compared to the irregular galaxies. Old and intermediate-age populations dominate, though large differences in star formation times and chemical enrichment exist between the dSphs. Abundance spreads are indicated by curved white lines. For the Milky Way companions, the mean age may decrease with increasing distance as suggested by van den Bergh (1994b). NGC 205 and NGC 147 are dwarf ellipticals.

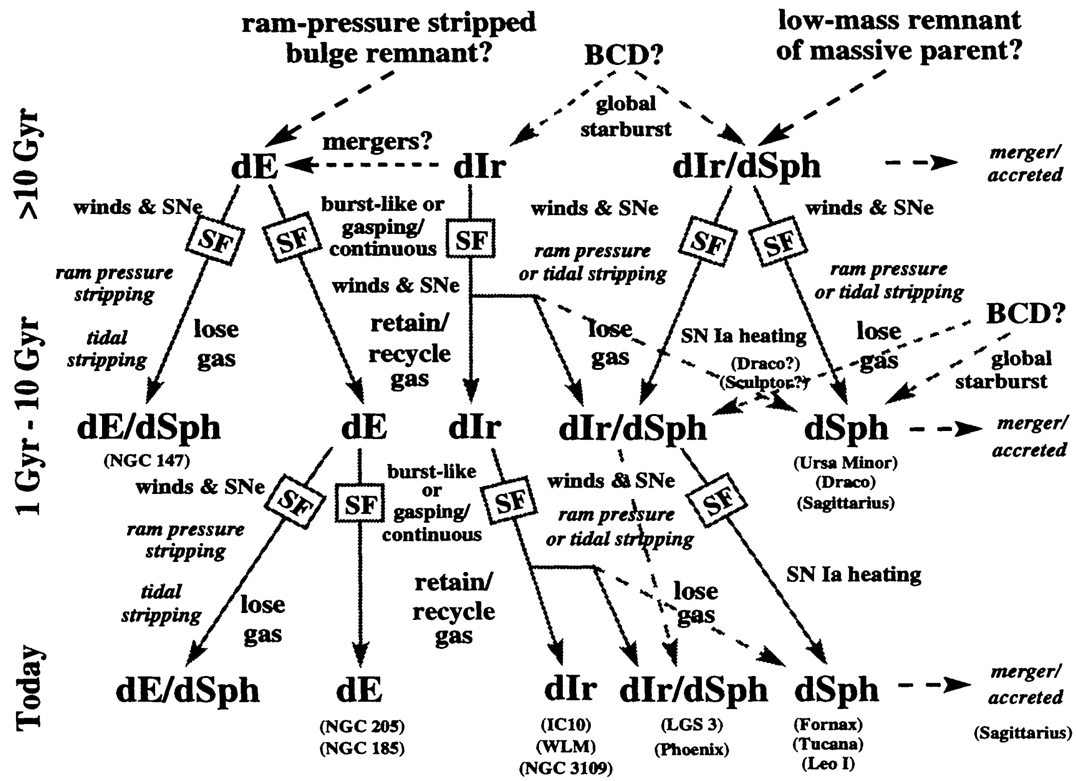

Figure 11: A simplified scenario for the evolutionary history of Local Group dwarf galaxies taking into account effects of massive star formation ("SF", grey arrows) and interactions (italics, black arrows). "BCD" stands for blue compact dwarf galaxy. To what extent (if at all) the various effects contribute depends on mass, location, and (gas) content of each individual dwarf galaxy. I list possible examples for certain processes among Local Group galaxies in brackets.

and turnoff ages (Chaboyer et al. 1996) in Figure 12, a merger that contributed previously formed globular clusters with retrograde motion could have taken place 14 Gyr ago or less. Most of these clusters would have had blue HBs. Chaboyer et al. suggest that the inner Galactic halo formed in rapid collapse, while the outer formed over an extended period of time possibly in part through accretion.

Studying stellar populations in the Galactic halo in search for merger signatures, Unavane et al. (1996) found that mergers must have been rare within the past 10 Gyr. They estimate that at most 40 small, metal-poor Carina-like dSphs could have been accreted or up to 5 Fornax-like dSphs to account for the more metal-rich stars. Majewski et al. (1996) report possible subpopulations with common proper motion and metallicity among north Galactic pole halo stars that might be left from merger events longer ago than the one with Sagittarius.

Since the massive Fornax and Sagittarius dSphs are the only ones that contain globular clusters, mergers may have contributed only few globular clusters to the Milky Way. The four globular clusters possibly belonging to Sagittarius have [Fe/H] = −0.4 to −2.0 dex (Da Costa & Armandroff 1995), while the 10 – 14 Gyr field population ranges from −0.8 to −1.2 dex (Fahlmann et al. 1996). Two of the globulars are "young" (Ter 7: 7.2 Gyr, Arp 2: 12.3 Gyr); the other two (M 54;

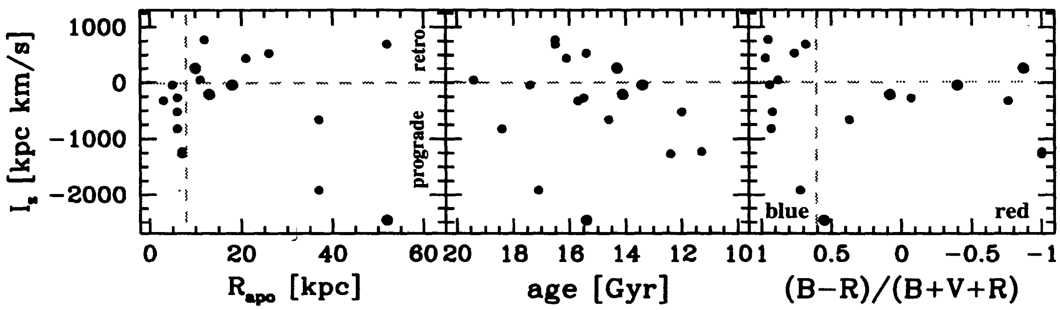

Figure 12: The z-component of the angular momentum I_z of 18 Galactic globular clusters (Dauphole et al. 1996) plotted vs. apogalactic distance R_{apo}, age, and morphological horizontal branch index (B-R)/(B+V+R) (data from Dauphole et al. 1996 and Chaboyer et al. 1996). Due to small-number statistics, the following preliminary conclusions should be considered with caution: Clusters with retrograde orbits appear to lie beyond the solar circle and to show a smaller range of ages. Clusters with blue HB morphology exhibit a higher scatter in angular momenta than the rest. Globular clusters on retrograde orbits are more metal-poor than −1.2 dex (plot not shown here). Four bona-fide "young" globular clusters suggested to be possibly associated with the great circles (Majewski 1994; fat dots) have in part prograde, in part retrograde orbits.

Ter 8: 16.9 Gyr) are old (Chaboyer et al. 1996).[2] Fornax's globulars range from −1.3 to −2.0 dex and appear to be older than the intermediate-age field population. Mergers can thus contribute both old and "young" globular clusters (Da Costa & Armandroff 1995) of different HB morphology. Second-parameter effects, age and metallicity spreads among Galactic halo globular clusters should have been caused mostly by effects other than mergers with dwarf galaxies. The age-metallicity relation discovered by Chaboyer et al. (1996) indicates formation of halo globular clusters over a time period of more than 5 Gyr with progressive enrichment.

Lynden-Bell & Lynden-Bell (1995) pointed out that any two points in the sky have a great circle passing through them, and there are plenty of possible "streams" with at least three members. Apparently isolated dSphs (Tucana) exist as well, indicating that at least some dSphs may not be remnants of more massive galaxies. The abundance differences between dSphs do not exclude an origin in the same parent galaxy if a positive mass-metallicity relation (Gerola et al. 1983) exists. Due to their (possibly) high dark matter content, masses of dSphs are poorly known

[2]The high metallicity and young age of Ter 7 would let it appear unlikely that this globular cluster initially formed in Sagittarius (Sgr). Formation elsewhere and subsequent capture is one possibility. Renzini (1996) suggested Ter 7 might be a bulge globular cluster in chance superposition with Sgr. If so, both its young age and large distance from the bulge ($\approx$ 26 kpc as opposed to $\approx<$ 3 kpc) are atypical for bulge globulars. Ibata et al. (1997) demonstrate that Sgr has an orbital period of $\leq$ 1 Gyr and survived many orbits around the Milky Way. If the bulk of Sgr's field population formed before it began to merge with the Milky Way, the merger should have started < 10 Gyr ago. Triggered through the interaction Ter 7 might have formed from enriched gas in Sgr or possibly through collision with a Galactic high-velocity cloud.
On the other hand, the above quoted ages and metallicities were obtained using different methods so that *an absolute comparison may be misleading.* Adopting Sarajedini's & Layden's (1995) result of −0.5 dex for one of Sgr's field subpopulations and considering that Whitelock et al. (1996) found an intermediate-age population of AGB and C stars, both comparable in age to Ter 7, it is conceivable that Ter 7 may have formed in Sgr with no need for external influences after all. Consistent methods are paramount when making absolute comparisons.

(e.g., Gallagher & Wyse 1994).

Absolute proper motions and space motions are needed for dwarf galaxies and globular clusters to unambiguously determine their orbits and potential affiliation with great circles. Dauphole et al. (1996) derived space motions of globular clusters and show that three of Majewski's (1994) bona-fide "young" globular clusters are not associated with the proposed Fornax-Leo-Sculptor stream. The space motion for Sculptor (Schweitzer et al. 1995) does not confirm its motion along the Fornax-Leo-Sculptor stream, but neither is it ruled out. Sculptor was found to be on an elliptical orbit with little eccentricity around the Milky Way. Ursa Minor was shown to move along the Magellanic stream in the same sense as the Large Magellanic Cloud (Schweitzer & Cudworth 1996).

7 Outlook

HOE'T NIET IS, ZEGGEN ONS DE HEEREN;
MAAR HOE HET IS, MIJN GOEDE LÎEN,
DE TIJD OF DE EEUWIGHEID ZAL'T LEEREN –
MISSCHIEN. P.A. DE GÉNESTET (1859)

This review started with a discussion of membership in the LG. Then I presented methods used for population studies, summarized the star formation histories of LG dwarf galaxies, and discussed which internal and external effects may have influenced their evolution.

Despite the large body of observations available today, we have only a crude and simplistic picture of the history of our nearest neighbours and our own Galaxy. All galaxies appear to have old and intermediate-age populations. Whether they also have recent star formation seems to depend on their mass and their distance from the massive spirals. Sufficiently massive dIrs and dEs may be capable of sustaining a moderate amount of star formation over long periods by recycling processed gas. Less massive dIrs, dEs, and dSphs lose their gas through their own star formation processes, or external influences, and may all end up as dSph-like galaxies. Dwarf galaxies may be remnants of initially much more massive galaxies and may eventually merge with the massive spirals. Such mergers may contribute both old and young globular clusters.

Nearby galaxies in the Local Group and beyond will constitute prime targets for the coming generation of large ground-based and space-based telescopes with their high-resolution imaging capabilities, large infrared arrays, efficient multi-object spectroscopy, and coverage of different wavelength ranges. Accurate ages through photometry extending below the turnoff are needed. We should study spatial variations in star formation and subpopulations through large-area coverage with metallicity-sensitive photometry, and spectroscopy. Obtaining accurate distances, studying highly obscured LG galaxies, completing the census of LG group members, and solving the the missing gas and dark matter mysteries are some of the key issues for the coming years. Astrometry and space motions are paramount to calculate past and future orbits, and to investigate to what extent interactions took place and to estimate their impact on global star formation processes and the evolution of the LG. In all these important studies, we must take care to apply methods and theoretical models correctly – and consistently – both in our own analyses and when carrying out intercomparisons.

Acknowledgements
I am indebted to Wolfgang Brandner for his help and many useful discussions. I thank Grant Miller for a critical reading of the text. Doug Geisler kindly allowed me to use his Washington data for my analysis. I thank Klaas de Boer, Wilhelm Seggewiss, and the award committee of the German Astronomical Society for their much appreciated support. Support by the German Space Agency (DARA) under grant 05 OR 9103 0 and by the German Research Foundation through the Graduiertenkolleg "The Magellanic System and Other Dwarf Galaxies" of the Universities of Bonn and Bochum are gratefully acknowledged.

This research has made extensive use of NASA's Astrophysics Data System Abstract Service (ADS), of the SIMBAD database, operated at CDS, Strasbourg, and of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, CalTech, under contract with NASA.

References

Aaronson, M., Mould, J. 1985, ApJ 290, 41
Aaronson, M., Gordon, G., Mould, J., Olszewski, E., Suntzeff, N. 1985, ApJ 296, L7
Ables, H.D., Ables, P.G. 1977, ApJS 34, 245
Alcock, C., Allsman, R.A., Alves, D.R., et al. 1997, ApJ, submitted
Aparicio, A. 1994, ApJ 437, L27
Aparicio, A., García-Pelayo, J.M., Moles, M., Melnick, J. 1987, A&AS 71, 297
Aparicio, A., Gallart, C. 1995, AJ 110, 2105
Aparicio, A., Gallart, C., Chiosi, C., Bertelli, G. 1996, ApJ 469, 97
Armandroff, T.E., Massey, P. 1991, AJ 102, 927
Armandroff, T.E., Da Costa, G.A., Caldwell, N., Seitzer, P. 1993, AJ 106, 986
Arp, H. 1994, ApJ 430, 74
Azzopardi, M., Lequeux, J., Westerlund, B.E. 1986, A&A 161, 232
Azzopardi, M., 1994, CTIO/ESO Workshop *"The Local Group"*, Eds. A. Layden, R.C. Smith, J. Storm, La Serena, p. 129
Bailyn, C.D., Pinsonneault, M.H. 1995, ApJ 439, 705
Beauchamp, D., Hardy, E., Suntzeff, N.B., Zinn, R. 1995, AJ 1995, 1628
Bell, R.A. 1985, PASP 97, 219
Bell, M., Whitmore, B.C. 1989, ApJS 70, 139
Bergbusch, P.A., VandenBerg, D.A. 1992, ApJS 81, 163
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., Nasi, E. 1994, A&AS 106, 275
Bertola, F., Bressan, A., Burstein, D., et al. 1995, ApJ 438, 680
Bica, E., Alloin, D., Schmidt, A.A. 1990, A&A 228, 23
Bresolin, F., Capaccioli, M., Piotto, G. 1993, AJ 105, 1779
Buonanno, R., Corsi, C., Fusi Pecci, F., Hardy, E., Zinn, R. 1985, A&A 152, 65
Buonanno, R., Corsi, C., Bellazini, M., Ferraro, F.R., Fusi Pecci, F. 1997, AJ, in press
Burkert, A., Ruiz-Lapuente, P. 1997, ApJ, submitted
Byrd, G., Valtonen, M., McCall, M., Innanen, K. 1994, AJ 107, 2055
Caldwell, N., Schommer, R.A., Graham, J.A. 1988, PASP 100, 1217
Capaccioli, M., Piotto, G., Bresolin, F. 1992, AJ 103, 1151
Caputo, F., Degl'Innocenti, S. 1995, A&A 298, 833
Caputo, F., Castellani, V., Degl'Innocenti, S. 1995, A&A 304, 365
Carignan, C., Demers, S., Côté, S. 1991, ApJ 381, L13
Carney, B.W., Seitzer, P. 1986, AJ 92, 23
Carney, B.W., Storm, J., Jones, R.V. 1992, ApJ 386, 663
Castellani, V., Degl'Innocenti, S. 1995, A&A 298, 827
Castellani, M., Marconi, G., Buonanno, R. 1996, A&A 310, 175
Chaboyer, B., Demarque, P., Sarajedini, A. 1996, ApJ 459, 558
Cook, K.H. 1987, PhD Thesis, University of Arizona

Cook, K.H., Aaronson, M., Norris, J. 1986, ApJ 305, 634
Cook, K.H., Olszewski, E. 1989, BAAS 21, 775
Cook, K.H., Aaronson, M. 1988, PASP 100, 1218
da Costa, L.N., Willmer, C., Pellegrini, P.S., Chincarini, G. 1987, AJ 93, 1338
da Costa,L.N,Pellegrini,P.S,Davis,M,Meiksin,A,Sargent,W.L.W,Tonry,J.L.1991,ApJS 75,935
Da Costa, G.S., Mould, J.R 1988, ApJ 334, 159
Da Costa, G.S., Armandroff, T.E. 1990, AJ 100, 162
Da Costa, G.S., Armandroff, T.E. 1995, AJ 109, 2533
Da Costa, G.S., Armandroff, T.E., Caldwell, N., Seitzer, P. 1997, AJ, in press
Dauphole,B,Geffert,M,Colin,J,Ducourant,C,Odenkirchen,M,Tucholke,H-J.1996,A&A 313,119
Davidge, T.J., 1992, ApJ 397, 457
Davidge, T.J., 1993, AJ 105, 1392
Davidge, T.J., 1994, AJ 108, 2123
Davidge, T.J., Jones, J.H. 1992, AJ 104, 1365
Davies, R.D., Elliott, K.H., Meaburn, J. 1976, MemRAS 81, 89
Demers, S., Irwin, M.J., Kunkel, W.E. 1994, AJ 108, 1648
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G., Buta, R.J., Paturel, G., Fouqué, P. 1991, "Third Reference Catalogue of Bright Galaxies", Springer-Verlag, Heidelberg
De Young, D.S., Heckman, T.M. 1994, ApJ 431, 598
Elston, R., Silva, D.R. 1992, AJ 104, 1360
Fahlman, G.G., Mandushev, G., Richer, H.B., Thompson, I.B., Sivaramakrishnan, A. 1996, ApJ 459, 65
Fairall, A.P., Jones, A. 1991, Publ. Dept. Astron., U. Cape Town No. 11
Ferguson, H.C., Binggeli, B. 1994, A&ARv 6, 57
Ferraro, F.R., Fusi Pecci, F., Tosi, M., Buonanno, R. 1989, MNRAS 241, 433
Fouqué, P., Proust, D., Quintana, H., Ramírez, A. 1993, A&AS 100, 493
Freedman, W.L. 1988, AJ 96, 1248
Freedman, W.L., Madore, B.F. 1990, ApJ 365, 186
Frogel, J.A., Mould, J., Blanco, V.M. 1990, ApJ 352, 96
Gallagher, J.S., Wyse, F.G. 1994, PASP 106, 1225
Gallart, C., Aparicio, A., Bertelli, G., Chiosi, C. 1996, AJ 112, 1950
Geisler, D., Clariá, J.J., Minniti, D. 1991, AJ 102, 1936
Gerola, H., Carnevali, P., Salpeter, E.E. 1983, ApJ 268, L75
Grebel, E.K. 1995, PhD Thesis, University of Bonn
Grebel, E.K. 1997, A&A 317, 441
Grebel, E.K., Roberts, W.J., van de Rydt, F. 1994, CTIO/ESO Workshop *"The Local Group"*, Eds. A. Layden, R.C. Smith, J. Storm, La Serena, p. 148
Grebel, E.K., Roberts, W.J. 1995, A&AS 109, 293
Grebel,E.K.,Brandner,W.,Richtler,T.,Subramaniam,A.,Sagar,R. 1996a, BAAS 27, 1404
Grebel, E.K., Roberts, W.J., Brandner, W. 1996b, A&A 311, 470
Greggio, L., Marconi, G., Tosi, M., Focardi, P. 1993, AJ 105, 894
Grillmair, C.J., Lauer, T.R., Worthey, G., et al. 1996, AJ 112, 1975
Han, M., Hoessel, J.G., Gallagher, J.S., Stetson, P.B. 1996, BAAS 189, 906
Harris, W.E. 1991, ARA&A 29, 543
Harris, H.C., Canterna, R. 1977, AJ 82, 798
Hodge, P.W. 1989, ARA&A 27, 139
Hodge,P.W.,Smith,T.R.,Eskridge,P.B.,MacGillivray,H.T.,Beard,S.M. 1991, ApJ 369, 372
Hodge, P.W., Miller, B.W. 1995, ApJ 451, 176
Hoessel, J.G., Saha, A., Danielson, G.E. 1988, PASP 100, 680
Hoessel, J.G., Abbott, M.J., Saha, A., Mossman, A.E., Danielson, G.E. 1990, AJ 100, 1151
Hoessel, J.G., Saha, A., Krist, J., Danielson, G.E. 1994, ApJ 108, 645
Hunter, D.A., Plummer, J.D. 1996, ApJ 462, 732
Ibata, R.A., Gilmore, G., Irwin, M.J. 1994, Nature 370, 194
Ibata, R.A., Wyse, R.F.G., Gilmore, G., Irwin, M.J., Suntzeff, N.B. 1997, AJ, in press
Jacoby, G.H., Branch, D., Ciardullo, R., et al. 1992, PASP 104, 599

Johnson, D.W., Gottesman, S.T., 1983, ApJ 275, 549
Jones, J.H. 1993, AJ 105, 933
Kałużny,J,Kubiak,M,Szymański,M,Udalski,A,Krzemiński,W,Mateo,M.1995,A&AS 112,407
Karachentsev, I.D. 1996, A&A 305, 33
Karachentsev, I.D., Makarov, D.A. 1996, AJ 111, 794
Knapp, G., Kerr, F., Bowers, P. 1978, AJ 83, 360
König, C.H.B., Nemec, J.M., Mould, J.R., Fahlman, G.G. 1993, AJ 106, 1819
Koribalski, B., Johnston, S., Otrupcek, R. 1994, MNRAS 270, L43
Kormendy, J. 1985, ApJ 295, 73
Kraan-Korteweg, R.C., Tammann, G.A. 1979, AN 300, 227
Krismer, M., Tully, R.B., Gioia, I.M. 1995, AJ 110, 1584
Kunkel, W.E. 1979, ApJ 228, 718
Langer, N., Maeder, A. 1995, A&A 295, 685
Lehnert, M.D., Bell, R.A., Hesser, J.E., Oke, J.B. 1992, ApJ 395, 466
Lee, M.G. 1993, ApJ 408, 409
Lee, M.G. 1995a, AJ 110, 1129
Lee, M.G. 1995b, AJ 110, 1155
Lee, M.G., Freedman, W., Madore, B.F. 1993a, ApJ 417, 553
Lee, M.G., Freedman, W., Madore, B.F. 1993c, AJ 106, 964
Lee,M.G.,Freedman,W.,Mateo,M.,Thompson,I.,Roth,M.,Ruiz,M.-T.1993b,AJ 106,1420
Lee, Y.-W., Demarque, P., Zinn, R. 1994, ApJ 423, 248
Lequeux,J.,Peimbert,M.,Rayo,J.F.,Serrano,A.,Torres-Peimbert,S. 1979, A&A 80, 155
Lo, K.Y., Sargent, W.L.W., Young, K. 1993, AJ 1993, 507
Lynden-Bell, D. 1982, Observatory 102, 202
Lynden-Bell, D., Lynden-Bell, R.M. 1995, MNRAS 275, 429
Madore, B.F., Freedman, W.L. 1991, PASP 103, 933
Madore, B.F., Freedman, W.L. 1995, AJ 109, 1645
Maeder, A., Meynet, G. 1994, A&A 287, 803
Majewski, S.R. 1994, ApJ 431, L17
Majewski, S.R., Munn, J.A., Hawley, S.L. 1996, ApJ 459, 73
Marconi, G., Tosi, M., Greggio, L., Focardi, P. 1995, AJ 109, 173
Massey, P., Armandroff, T.E. 1995, AJ 109, 2470
Massey, P., Lang, C.C., Degioia-Eastwood, K., Garmany, C.D. 1995, ApJ 438, 188
Mateo, M., Nemec, J., Irwin, M., McMahon, R. 1991, AJ 101, 892
Mateo, M., Olszewski, E.W., Lee, M.-G., et al. 1994, BAAS 185, 5103
Mateo, M., Fischer, P., Krzemiński, W. 1995a, AJ 110, 2166
Mateo,M,Kubiak,M,Szymański,M,Kałużny,J,Krzemiński,W,Udalski,A.1995b,AJ 110,1141
Mathewson, D.S., Ford, V.L., Buchhorn, M. 1992, ApJS 81, 413
Mazzitelli, I., D'Antona, F., Caloi, V. 1995, A&A 302, 382
McAlary,C.W.,Madore,B.F.,McGonegal,R.,McLaren, R.A.,Welch,D.L.1983,ApJ 273,539
Melisse, J.P.M., Israel, F.P. 1994, A&A 285, 51
Mermilliod, J.C. 1982, A&A 109, 48
Mighell, K.J. 1990, A&AS 82, 207
Mighell, K.J., Butcher, H.R. 1992, A&A 255, 26
Mighell, K.J., Rich, R.M. 1996, AJ 111, 777
Minniti, D., Zijlstra, A.A. 1996, ApJ 467, L13
Minniti, D., Meylan, G., Kissler-Patig, M. 1996, A&A 312, 49
Mirabel, I.F., Dottori, H., Lutz, D. 1992, A&A 256, L19
Mould,J.R.,Bothun,G.D.,Hall,P.J.,Staveley-Smith,L.,Wright,A.E. 1990, ApJ 362, L55
Nemec, J.M., Nemec, A.F.L., Lutz, T.E. 1994, AJ 108, 222
Olszewski, E.W., Aaronson, M. 1985, AJ 90, 2221
Oosterloo, T., Da Costa, G.S., Staveley-Smith, L. 1996, AJ 112, 1969
Peebles, P.J.E. 1995, ApJ 449, 52
Queloz, D., Dubath, P., Pasquini, L. 1995, A&A 300, 31
Quintana, H., Ramírez, A., Melnick, J., Raychaudhury, A., Slezak, E. 1995, AJ 110, 463

Ratnatunga, K.U., Bahcall, J.N. 1985, ApJS 59, 63
Renzini, A. 1996, priv. communication
Richer, H.B., Crabtree, D.R., Pritchet, C.J. 1984, ApJ 287, 138
Richer, M.G., McCall, M.L. 1995, ApJ 445, 642
Rodgers, A.W., Paltoglou, G. 1984, ApJ 283, L5
Rodgers, A.W., Harding, P. 1989, PASP 101, 563
Saha, A., Hoessel, J.G. 1990, AJ 99, 97
Saha, A., Hoessel, J.G., Krist, J. 1992b, AJ 103, 84
Saha, A., Freedman, W.L., Hoessel, J.G., Mossman, A.E. 1992a, AJ 104, 1072
Saha, A., Hoessel, J.G., Krist, J., Danielson, G.E. 1996, AJ 111, 197
Sakai, S., Madore, B.F., Freedman, W.L. 1996, ApJ 461, 713
Sandage, A. 1986, ApJ 307, 1
Sandage, A., Binggeli, B. 1984, AJ 89, 919
Sarajedini, A. 1994, AJ 107, 618
Sarajedini, A., Norris, J.E. 1994, ApJS 93, 161
Sarajedini, A., Layden, A.C. 1995, AJ 109, 1086
Sasselov, D.D., Beaulieu, J.P., Renault, C., et al. 1997, A&A, submitted
Schaller, G., Schaerer, D., Meynet, G., Maeder, A. 1992, A&AS 96, 269
Schmidt, K.-H., Boller, T. 1992, AN 313, 189
Schweitzer, A.E., Cudworth, K.M., Majewski, S.R., Suntzeff, N.B. 1995, AJ 110, 2747
Schweitzer, A.E., Cudworth, K.M. 1996, BAAS 188, 901
Shapley, H. 1938, Harvard College Obs. Bull. 908, 1
Skillman, E.D., Terlevich, R., Melnick, J. 1989a, MNRAS 240, 563
Skillman, E.D., Kennicutt, R.C., Hodge, P.W. 1989b, ApJ 347, 875
Smecker-Hane, T.A., Stetson, P.B., Hesser, J.E., VandenBerg, D.A. 1996, in "From Stars to Galaxies: The Impact of Stellar Physics on Galaxy Evolution", Eds. C. Leitherer, U. Fritze-von Alvensleben, & J. Huchra, ASP Conf. Series, San Francisco, in press
Smith, H.A., Stryker, L.L. 1986, AJ 92, 328
Sofue, Y. 1994, ApJ 423, 207
Stetson, P.B., VandenBerg, D.A., Bolte, M. 1996, PASP 108, 560
Strobel, N.V., Hodge, P., Kennicutt, R.C. 1991, ApJ 383, 148
Stryker, L.L. 1993, PASP 105, 1080
Suntzeff, N.B., Aaronson, M., Olszewski, E.W., Cook, K.H. 1986, AJ 91, 1091
Talent, D.L. 1980, PhD Thesis, Rice University
Thronson, H.A., Hunter, D.A., Casey, S., Harper, D.A. 1990, ApJ 355, 94
Thuan, T.X., Martin, G.E. 1979, ApJ 232, L11
Tolstoy, E. 1995, PhD Thesis, University of Groningen
Tolstoy, E., Saha, A., Hoessel, J.G., Danielson, G.E. 1995, AJ 109, 579
Tolstoy, E., Saha, A. 1996, ApJ 462, 684
Tosi, M., Greggio, L., Marconi, G., Focardi, P. 1991, AJ 102, 951
Tripicco, M.J., Bell, R.A., Dorman, B., Hufnagel, B. 1995, AJ 109, 1697
Unavane, M., Wyse, R.F.G., Gilmore, G. 1996, MNRAS 278, 727
van Agt, S.L.T.J. 1967, Bull. Astron. Inst. Neth. 19, 275
van de Rydt, F., Demers, S., Kunkel, W.E. 1991, AJ 102, 130
van den Bergh, S. 1960, Publ. David Dunlop Obs. 2, 159
van den Bergh, S. 1972, ApJ 171, L31
van den Bergh, S. 1993, AJ 105, 971
van den Bergh, S. 1994a, AJ 107, 1328
van den Bergh, S. 1994b, ApJ 428, 617
Walborn,N.R.,Lennon,D.J.,Haser,S.M.,Kudritzki,R.-P.,Voels,S.A. 1995, PASP 107, 104
Welch, G.A., Mitchell, G.F., Yi, S. 1996, ApJ 470, 781
Whitelock, P.A., Irwin, M., Catchpole, R.M. 1996, New Astronomy 1, 57
Wiklind, T., Henkel, C. 1990, A&A 227, 394
Wilson, C.D. 1992, AJ 104, 1374
Zaritsky,D.,Olszewski,E.W.,Schommer,R.A.,Peterson,R.C.,Aaronson,M. 1989, ApJ 345, 759