STAR FORMATION HISTORY OF NEARBY DWARF GALAXIES

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This review will take the *linear* view of the history of stellar systems. Thus the last billion years of a dwarf galaxy's development receives no special attention. A considerable amount of information has recently come to light on the intermediate age populations of dwarf galaxies.

EARLY TYPE SYSTEMS

In addition to its rather substantial dwarf irregular companions the Milky Way has a number of dwarf elliptical satellites, commonly termed dwarf spheroidals. These have traditionally been compared with globular clusters (they inhabit the same space), but there are a number of significant differences in their stellar population (see Table 1).

To start with column (2) of Table 1, the existence of red horizontal branches in the HR diagrams of low metallicity systems is termed the "second parameter problem". Two reviewers (Kraft 1979 and Freeman and Norris 1981) have been persuaded that an age difference of 10^9 years is the most likely contender for the second parameter in globular clusters. The best case for an enhanced CNO abundance as the driving influence in globulars was NGC 7006 (McClure and Hesser 1981). But this has recently been disputed by Cohen and Frogel (1982). Note that simply to point to enhanced CNO is not to provide a fundamental explanation. Why should these elements be enhanced in some systems of the outer halo? One explanation offered by Hartwick and McClure (1980) suggests that the inner halo might have formed its stars, before sufficient time had elapsed for nitrogen to be made from intermediate mass stars. In summary, a small age spread in the outer halo seems the best explanation of the HB morphology of the dwarf spheroidals, but the enhanced CNO hypothesis remains a contender (Seitzer and Rood 1981).

Broad giant branches are *prima facie* evidence of a metallicity dispersion. Such a dispersion has been proven spectroscopically in the cases of Draco (Kinman, Kraft and Suntzeff 1981) and Ursa Minor (Zinn

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 179–186.

TABLE 1: Characteristics of the Stellar Population of Dwarf Spheroidals

Dwarf (1)	HB (2)	RGB (3)	AGB (4)	MS (5)	AC (6)	C* (7)
Draco	Red	Broad	Normal	M92-like[9]	Yes	CH[10]
Sculptor	Red	Broad	Normal	?	Yes	CH[11,13]
Ursa Minor	Blue	Broad[2,3]	Extended[15]	?	Yes	CH[2,5]
Carina	Red[1]	?	Extended[6]	?	No?[1]	C+CH[6,12]
Fornax	?	Broad[4]	Extended[7,8]	?	?	C+CH[8,11,13,14]
Leo I	?	?	Extended[15]	?	Many	Yes[5]
Leo II	Red	?	Normal?[15]	?	Yes	Yes[5]

1. Cannon *et al.* 1982.
2. Schommer, Olsewski and Cudworth 1981.
3. Zinn 1981.
4. Demers, Kunkel and Hardy 1979.
5. Olsewski, Aaronson and Hodge 1982.
6. Mould *et al.* 1982.
7. Demers and Kunkel 1980.
8. Aaronson and Mould 1980.
9. Da Costa and Mould, in preparation.
10. Aaronson, Liebert and Stocke 1982.
11. Frogel *et al.* 1982.
12. Cannon, Niss and Norgaard-Nielson 1981.
13. Richer and Westerlund 1982.
14. Westerlund, 1979.
15. Aaronson and Mould, unpublished data.

1981a). This observation suggests that the star formation history in these systems extends for more than one generation (although this could be a short time on the scale we are currently considering).

According to asymptotic giant branch (AGB) evolution theory reviewed by Iben and Renzini (1982) and observations of Magellanic Cloud globular clusters (of which more later), the extended AGB's in some dwarf spheroidals imply the presence in these systems of stars up to 1.5 M_o. The most straightforward interpretation of these observations is an extended history of star formation in these dwarf systems. Aaronson and Mould (1981) have estimated that 10% of the stellar population of the Fornax galaxy is of intermediate age. However it's not impossible that stars as massive as this could be made by mass transfer in binaries, as has been suggested for the anomalous cepheids.

Skipping over the main sequence observations (which are the difficult solution to this whole problem), we should recall Zinn and Searle's (1976) demonstration that (at least the Draco) anomalous cepheids have masses 2 to 3 times that of regular RR Lyrae stars. The AC's could also be evidence of a minority population of intermediate age. The alternative theory, however, postulates that the ACs are

https://doi.org/10.1017/S1539299600005104 Published online by Cambridge University Press

evolved close binary systems in which considerable mass has been transferred to the secondary (see Hirshfeld 1980 and references therein). Can this theory also explain the extended AGBs in dwarf spheroidals? The poor correlation between columns (4) and (6) in Table 1 suggests otherwise. The lifetimes of ACs may be 30 times longer than those of upper AGB stars, however. So it is possible that this situation arises by chance. Variability studies of Fornax and Carina are critical to the resolution of this issue.

Finally, column (7) of Table 1 gives the tally of carbon stars so far discovered in dwarf spheroidals. It is worth making the distinction between carbon stars with $M_{bol} < -4.5$, which can be understood as thermal-pulsing AGB stars (Iben and Renzini 1982) and carbon stars at or below the red giant branch tip, which I would term CH stars for historical (rather than spectroscopic) reasons. Two suggestions that have been made in respect of the CH stars are that they are the product of mixing at the He coreflash and that they are the Population II equivalent of the binary Ba stars (McClure, Fletcher and Nemec 1980). Neither suggestion has been substantiated for CH stars as yet. Note that the latter theory requires mass transfer when the original primary is on the AGB, and will produce subgiant and main sequence CH stars too.

An interesting correlation has been noted (Frogel *et al.* 1981, Richer and Westerlund 1982) between the incidence of carbon stars in nearby systems and metallicity. This correlation can be partially understood to the extent that carbon star formation is a mixing process, in that there is less oxygen to neutralize in low metallicity systems. Also, in the case of the AGB C stars, Wood (1982, private communication) finds that dredge-up is more efficient in stars of low metallicity and helium abundance. On the other hand, it is surprising that systems such as the Magellanic Clouds in which the carbon stars are primarily AGB C stars, should fall on the same relation with a system like Draco which has only CH stars. It is hard to see how this correlation represents a fundamental property of stellar systems, since typical intermediate age clusters in the Clouds lie off the relation at 10^{-3} C stars/$M_{\odot}$ and typical galactic globular clusters have less than 10^{-5} C stars/$M_{\odot}$.

We can turn briefly to the dwarf elliptical systems, because, owing to their larger distances, less work has been done. The outer parts of NGC 147, however, have recently been studied by Mould, Kristian and Da Costa (1982). From an (I, V-I) color-magnitude diagram they conclude: 1) that the stellar population in the selected (outlying) field is similar to that of Galactic globular clusters, 2) that the giant branch is broad with a mean metallicity of -1.2 ± 0.2, 3) that NGC 147 occupies the middle ground in the mass/metallicity relation for ellipticals, 4) that the outer parts of NGC 147 do not show an extended AGB. Preliminary analysis suggests similar conclusions for the outer parts of NGC 185 and NGC 205, the other two dwarf elliptical companions of M31.

These results should be contrasted with the situation in the

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centers of the latter two galaxies, in which star formation is clearly still occurring. According to Gallagher and Hunter (1982) NGC 185 can be fuelled for star formation at the rate of 3 x 10^{-4} $M_{\odot}$/year on recycled gas. Gallagher and Mould (1980) have shown preliminary evidence for an intermediate age population in the center of NGC 205.

THE MAGELLANIC CLOUDS

In recent years it has become apparent that the star clusters of the Clouds are not simply divided into young and old by color. Rather, a continuous distribution of ages is present. This age spread has been delineated by a variety of different techniques, including integrated photometry (Searle, Wilkinson and Bagnuolo 1980), integrated spectroscopy (Rabin 1980), photometry on the AGB (summarized by Mould and Aaronson 1982) and main sequence photometry (summarized by Hodge 1982).

In principle, the age distribution of clusters is an excellent guide to the star formation history of the Clouds. In practice, however, there are a number of problems. First of all, only the main sequence dating technique has a really well-established age calibration. Hodge (1982) has pointed to what may be a large scale error in the AGB tip calibrations given by Mould and Aaronson (1982) and Iben and Renzini (1982). Second, there is the matter of the luminosity evolution of clusters. Mould and Aaronson have modelled the cluster formation history of the Clouds in a simple way and find that the distribution of AGB tip luminosities is not incompatible with a steady rate of cluster formation. Third, it should be stressed that there is no information on the rate of destruction of clusters in the Clouds.

For these reasons we turn to the field to learn about the star formation history of the Clouds. (The clusters may still, of course, prove invaluable for calibration purposes). Recent results on the main sequence luminosity function of the LMC (Stryker and Butcher 1981) and the SMC (Hawkins and Brück 1981) have amply confirmed Butcher's (1977) result that the major epoch of star formation in the LMC was 3-5 Gyrs ago. I would just add one word of caution amidst all this concord, and that is to note that these results come from photographic or electronographic photometry at V = 22, just a magnitude above the limit with these techniques. It remains an interesting exercise to perform deeper imaging in the Clouds.

The question that naturally arises now is whether there is a population in the Clouds as old as the Galactic globular clusters. There are, to be sure, some similar globular clusters in the Clouds, but Stryker, Butcher and Jewell (1981) have shown that at a large distance from the center of the LMC the "halo" population is of intermediate age.

The RR Lyrae stars in the Clouds are often cited as evidence of a 10 Gyr or older population. A complete survey is really required to determine the space distribution of these stars. However, if an exponential disk is fitted to the LMC, using it to estimate the central surface density and scale length from the *two* available data points due to Graham (1977) and Kinman, Stryker and Hesser (1976), one estimates that less than 1% of the mass of the Cloud belongs to a population as prolific in RR Lyrae stars as M3. If the distribution were more centrally concentrated, of course, a larger old population would be inferred. The distribution of old clusters in the LMC (van den Bergh 1981) does nothing to support this objection, however.

The spatial distribution of the *intermediate age* population in the Clouds is currently receiving very thorough attention in the work of Blanco, McCarthy and Blanco (1980) on the Magellanic Cloud carbon stars. An interesting consistency check on a number of assumptions we like to make in discussing the star formation history of the LMC can be had as follows.

Dennefeld and Tammann (1980) have examined the statistics of luminous and massive stars in the LMC and find a birthrate of between 0.9 and 1.5 x 10^{-3} stars/year in the range 9 to 25 $M_\odot$. (1) If we use the slope of the mass function they find for the LMC (which is not very different from that of the Milky Way), and (2) if the star formation rate has remained constant since the carbon stars were formed, and (3) if all stars between 1 and 2 $M_\odot$ become carbon stars (these limits are suggested by the bolometric luminosity function determined by Cohen *et al.* [1981]), then the number of carbon stars in the LMC can be estimated (using a 10^6 year lifetime for carbon stars on the AGB) as approximately 7000 in total. This is close to the result of Blanco's (private communication) integration for the LMC.

IS THERE A CONNECTION BETWEEN EARLY AND LATE TYPE SYSTEMS?

Evidence that some apparently moribund early type dwarf galaxies may have been more active in the not-too-distant past gives nourishment to the frequent speculation about an evolutionary connection with late type systems. One can imagine a number of different scenarios, of which the first that should be described is that there is *no* real connection. Early type systems and late type systems were formed quite distinctly during the epoch of galaxy formation, and never the twain shall meet. On this hypothesis one would argue either that the evidence for intermediate age stars in the dwarf spheroidals is an illusion produced by binaries or that the extended history of star formation in these systems is simply the recycling of mass lost by the original and priviliged generation of old stars. The latter possibility can certainly be supported for the Fornax galaxy, using the mass loss rate adopted by Faber and Gallagher (1976), which would make available 1.5 x 10^6 M_o in 10 Gyrs - enough to provide the observed intermediate age population.

A second possibility which has been contemplated is that early and

https://doi.org/10.1017/S1539299600005104 Published online by Cambridge University Press

late type systems exchange identities from time to time due to galaxy wide bursts of star formation. In the stochastic self-propagating star formation theory of Gerola, Seiden and Schulman (1980) such bursts become more and more conspicuous as one works down the Hubble sequence to dwarf galaxies. For burst separations greater than 1 Gyr it would seem possible to produce galaxies with both the colors and mean surface brightness of dwarf spheroidals in this way. But crucial to this theory is the existence of *gas-rich* quiescent systems. There is some evidence that, in the Local Group, DDO 210 (Fisher and Tully 1979), LGS 3 (Schild 1980) and the Pegasus dwarf (Hoessel and Mould 1982) may be in such a state, but in general gas-rich dwarf galaxies are blue and active. It is hard to argue that a significant number of gas-rich red galaxies remain undetected in the Local Group.

It is also possible, of course, that this transition from late to early type occurs only once, when a dwarf irregular exhausts its gas through star formation. The rapid rates of star formation in dwarf irregulars (Gallagher, Hunter and Knapp 1981) permit late type galaxies (viewed as closed systems) to run out of gas on short timescales, provided that low mass stars form together with their brighter massive counterparts (Humphries and Sandage 1980, c.f. Hoessel and Mould 1982). However, in this regard it is noteworthy that the only dead galaxies known in the Local Group are found in the halos of massive spirals. Dwarf ellipticals are found in abundance in the Virgo cluster (Reaves 1971, Sandage 1982), but it is not clear whether they are as prolific in the gas-rich groups of galaxies adjacent to the Local Group.

This leads us to a fourth possibility for an evolutionary connection between early and late type dwarf systems. That is the notion that the dwarf spheroidal galaxies and some other entities in the outer halo might have been formed in a close polar passage of the Magellanic Clouds or some other dwarf irregular about the Milky Way (Lynden-Bell 1976, Kunkel 1979). Gerola (1982) has suggested that the 'unbinding' or 'heating' of the parent dwarf irregular would permit the very low observed surface brightnesses to be attained. Star formation occuring in the parent galaxy up to this time would provide the observed intermediate age population. One could imagine that the existing dwarf spheroidal satellites of the Galaxy are the prominent remnants of a merging process which was much more frequent in the past and might be largely responsible for the formation of the outer halo.

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