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Spheroidal Dwarfs and Early Chemical Evolution of Galaxies

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Abstract

We consider the evolution of dwarf spheroidal galaxies (dSphs) within the context dwarf galaxy populations. The stellar and chemical properties of dSphs reflect a combination of internal and environmental factors that yield superficially similar low density, gas-free "stellar fossil" galaxies as evolutionary end products. An important development is the recognition that even the oldest dSphs likely experienced extended periods of star formation with the associated evolutionary complications. We suggest that rapid early astration provides a common thread among dSphs that may account for their higher stellar abundances than those of dwarf irregular galaxies.

1.1 Introduction

Following the discovery of dwarf spheroidal galaxies in the late 1930s, W. Baade recognized that stellar populations in these systems differ from those near the Sun, but resemble the Milky Way's stellar halo (Baade 1951). The potential connection between dwarf galaxies and halo stars in the Milky Way thus dates from the foundation of Baade's stellar populations concept. This work was largely carried out at Mt. Wilson, and the prominence of dwarf galaxies in this centennial meeting at The Observatories is highly appropriate.

While the existence of low luminosity galaxies was recognized early-on, their elevation to the status of a galaxy class was delayed until G. Reaves' 1953 Ph.D. thesis study of faint Virgo cluster members. This is the first reference to "dwarf galaxies" that I know of. Zwicky recognized that such objects, which he called "pygmy galaxies" in *Morphological Astronomy*, are the most common type of galaxy. Dwarf galaxy studies, with further impetus from the DDO survey (van den Bergh 1959), were active by the early 1960s (e.g., see Hodge 1971 for a review of early research).

The modern era of dwarf galaxy studies emerged about a decade ago. This was fueled by new data, beginning with stellar population studies from the ground with CCDs and with the *Hubble Space Telescope*. For example, the Carina dSph revealed that, despite its narrow, globular cluster-like red giant branch (RGB), episodic star formation occurred in the recent past (see Smecker-Hane 1997). Han et al. (1997) used WFPC2 photometry to show that NGC 147, a dE with lower luminosity than that of the Milky Way's stellar spheroid, has a relatively metal rich intermediate age stellar population. Dwarfs no longer could be viewed as simple, star cluster-like systems, where stars formed rapidly and with a narrow range of metals (see reviews by Hodge 1989, Gallagher & Wyse 1994, Grebel 1997, Da Costa 1998).

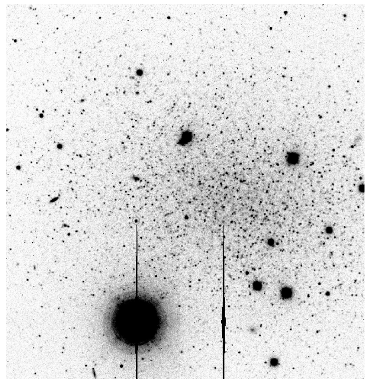

Fig. 1.1. V-band image of And VI illustrates the diffuse nature of a typical dSph system (JSG with WIYN; see also Armandroff et al. 1996). The seeing was 0.7 arcsec, the field of view corresponds to approximately 1 kpc^2. Orientation is north on the right and east at the top.

Table 1.1. *Summary of Dwarf Galaxy Properties*

Observed Parameter	Implications
Low baryon surface density	Low dissipation & mass loss
Low V_{escape}	Tidal & internally powered mass loss
Low metals	Wind metal loss; dilution by infall
Bimodal HI/L	Inefficent star formation + gas removal
Minimum $\sigma_* \geq 5$ km/s	"Magic" 10^4 K sound speed
Range in M_*/L_V	Large dark matter content in some cases

A second impetus for work on dwarf galaxies came from cold dark matter (CDM) cosmologies. In CDM models, small masses collapse first and it is tempting to identify these objects with present-day dwarf galaxies (Faber & Lin 1983). While such models successfully reproduce many features of dSphs (Dekel & Silk 1986), the simple versions of CDM dwarf models predict ∼10 times more low mass dark halos than are seen as dwarf galaxies (cf. Moore et al. 1999, Bullock et al. 2000, Chiu et al. 2001). This and other issues relating to connections between dwarfs and dark matter are areas of active research.

As a result of extensive surveys of the Local and nearby galaxy groups (e.g., Binggeli et al. 1990, van den Bergh 2000), the field in the Local Supercluster (e.g., Karachentsev & Karachentseva 1998) and galaxy clusters (e.g., Conselice et al. 2003), we now have a fairly complete description of the various structural families of dwarf galaxies and their intrinsic properties. Table 1.1 summarizes some of the defining characteristics of dwarf galaxies (see Mateo 1998), and Figure 1.1 illustrates an example of a dSph system as seen in optical light.

The variety of dSph star formation histories complicates theoretical modeling of their formation and evolution (e.g., Armandroff et al. 1999, Gallart et al. 1999, Grebel& Guhathakurta 1999, Tolstoy et al. 2001). The diversity of dSph stellar population properties possibly can

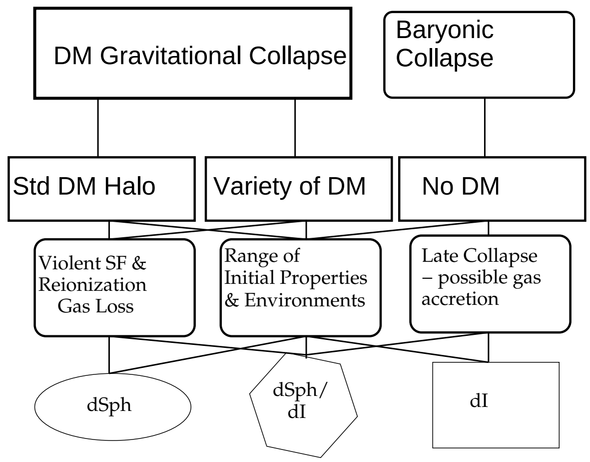

Fig. 1.2. Simplified flow chart illustrating multiple evolutionary paths leading to present day dwarfs. The top shows the gravitational instability leading to collapse and yielding the gravitational potentials in the second row. Various star formation histories depend on internal and/or external factors, which lead to the range of observed dwarfs. Most galaxies, especially in dense regions, are dSphs, followed by the dI irregular dwarfs, while the transition types are least frequent.

be accommodated in CDM models if the initial perturbations cover a range in density contrast (Mori et al. 1999, Carraro et al. 2001).

Alternatively, some dwarfs may be tidally stripped remnants of larger systems, or debris left over from galaxy mergers (Gerola et al. 1983, Mayer et al. 2001), in which case they are products of galaxy *devolution*. Figure 2 sketches some of the evolutionary pathways of dwarf galaxies (see also Grebel 1999). We also bear in mind the correlation of dwarf galaxy characteristics with environment, even in the Local Group (Bellazzini et al. 1996, Tamura & Hirashita 1999, Grebel et al. 2003; hereafter GGH), which suggests that environment also plays a substantial role in producing diversity in dwarf galaxies.

1.2 Dwarf Galaxy Evolution Time Scales

If dwarf galaxies formed via coherent collapse and feedback from star formation were not a factor, then we would expect their births to produce violent bursts of star formation. In this case the star formation time scale would be a few internal dynamical times, $t_{dyn} \approx 10^8$ yr, and the star formation rates, *SFRs* $\sim 0.01 - 0.1$ $M_\odot$/yr. These estimates lead to predictions of bursting dwarfs among high redshift faint blue galaxies (Babul & Ferguson 1996). By way of contrast, violent starbursts in nearby dwarfs can achieve peaks of $SFR \sim 1\ M_\odot$/yr, but only for $\sim 10^6$ yr when super star clusters are forming. This is the situation, for example, in the NGC 1705 blue compact dwarf galaxy that is considerably more massive than a small dSph galaxy. These effects illustrate one of the major difficulties in modeling dwarf galaxies: the mismatch of the various internal and external time scales (see Table 1.2).

Modern numerical models include the effects of feedback from energy supplied by massive stars (Fukunaga-Nakamura & Tosa 1989, Hirashita et al. 1998, Carraro et al. 2001, Tamura et al. 2001). A second concern is the effect of delayed gas infall (Silk et al. 1987,

Table 1.2. *Time Scales for Dwarf Galaxy in 100 kpc Orbit around a Giant System*

Gravitational	Stellar Evolution	Other
$t_{intern\ cross} \sim 10^8$ yr	$t_{SN\ II} \sim 10^7$ yr	$t_{star\ form} \geq t_{cross}$
$t_{orbit} \geq 10^9$ yr	$t_{AGB} \geq 4 \times 10^7$ yr	$t_{chem\ mix} \geq t_{star\ form}$
$t_{dyn\ friction} \gg 10^{10}$ yr	$t_{SNI} \geq 0.1 - 1 \times 10^9$ yr	$t_{gas\ loss} > 10^9$ yr?

GGH). Both processes are difficult to model, but for the stars we have the advantage of starting from a basic physical description of the relevant astrophysics. Feedback or infall also lengthen star formation time scales and influence abundance levels, and patterns of chemical elements (Wyse & Silk 1985, Recchi et al. 2001).

Observationally the difficulty lies in determining how feedback affected the various families of dwarf galaxies. The present approach to dwarf galaxy evolution therefore emphasizes determination of evolutionary trends among stellar populations in an effort to constrain basic families of models. For example, dSph stellar populations covering a wide range in metallicity, in combination with the emerging evidence for modest α/Fe enrichments even in old dSphs, suggest that starburst models, where stars form in a stellar orbital crossing time, $t_{intern\ cross}$, are unlikely to generally apply (Smith 1985, Shetrone et al. 2001).

An additional complication lies in modeling star formation. This commonly is parameterized in disk galaxies in terms of gas (or mass) surface densities. Unfortunately dwarf galaxies are 3-dimensional bodies, so surface densities are not necessarily physically significant. We therefore do not have particularly sound descriptions of star formation in low density galaxies, even at a phenomological level (cf. Hunter et al. 2001).

1.3 Fossil Records: the Oldest Stars

Investigations of the old stellar populations in dwarfs, while ongoing for several decades, recently made rapid progress with new results from HST and large ground-based telescopes. In particular, deep photometry with WFPC2 shows that the main sequence turnoffs in the Draco (Grillmair et al. 1998), Sculptor (Monkiewicz et al. 1999), and Ursa Minor (Wyse et al. 2002) dwarf spheroidals are indistinguishable from those of Galactic globular star clusters, even though these galaxies contain a range in metals (Bellazzini et al. 2003). Some of the Galactic family of dSphs on average are about as old as the Milky Way's halo, to within our current age dating precision of about 1-2 Gyr.

Unfortunately, no comparable data have been obtained on main sequence turnoffs for the M31 dSphs, whose evolved stars show old stellar population characteristics, such as well-defined horizontal branches. Harbeck et al. (2001) analyzed the horizontal branch structures of these galaxies. If second parameter effects are not important, the old dSphs could be a few Gyr younger than the Milky Way globular clusters, but this issue is not yet settled (Hurley-Keller et al. 1999, Majewski et al. 1999). Further comparisons of ages derived from main sequence turnoffs and horizontal branches would be worthwhile (c.f. Wyse et al. 2002).

Of course, many dSphs have strongly composite stellar populations with ranges in abundances and therefore also ages (Ikuta & Arimoto 2002). Their detailed chemical abundance patterns potentially offer finer resolution clocks, that reveal early evolutionary phases, even in the older dSphs where small age differences are difficult to resolve in color-magnitude diagrams (Tsujimoto & Shigeyama 2002). This approach is being exploited with by several groups (e.g., Shetrone et al. 2001, Smith et al. 2002, Tolstoy et al. 2003, Smecker-Hane & McWilliam 2003) using high resolution optical and infrared spectrographs at the Gemini, Keck, and VLT observatories. The initial results are somewhat surprising in that they suggest slow chemical evolution and a scaled version of the G-dwarf problem in some dSphs. In contrast, simple models rapid formation models for dSphs predict excesses of low abundance stars with strong SN II enrichment signatures, so a possible conundrum exists. The extent of this problem should become clear when additional abundance data become available for the RGB and more numerous main sequence stars, which is possible with existing and planned (e.g., LBT, GranTeCan, SALT) large telescopes.

Also noteworthy is the comparison between old stellar populations in dSphs and in dwarf irregulars (dIs; GGH). Photometric data for Local Group galaxies from HST suggest that dI galaxies generally have lower central surface densities of old horizontal branch stars than are found in dSphs (compare Harbeck et al. 2001 with, e.g., Cole et al. 1999). Most dwarfs seem to be coeval, but dI systems evidently began with more leisurely SFRs than the dSphs, although ages of dI systems are less well-constrained than those of the dSphs.

1.4 Gas Supplies

Most dwarf galaxies either have nearly constant SFRs (dIs; Hunter 1997) or are old, gas free spheroidal systems, as emphasized a quarter century ago by van den Bergh (1977). It is only recently that the indications for objects filling the gaps, the "transition-type" dI/dSph systems, received much attention (see GGH). Similarly, there is increasing evidence for underlying dSph-like structures in some dI galaxies, most notably the SMC (Gardiner & Hatzidimitriou 1992, Zaritsky et al, 2000).

Despite these similarities, dSphs still are the sole galaxies where *no* interstellar matter normally can be found. The sensitive HI limits of Young (2000) and our new upper limits on ionized gas in the Draco and UMi dSphs (Gallagher et al. 2003), in combination with a few UV and X-ray observations fail to reveal any ISM. As we discuss in GGH, some process must have acted to clean the dSphs of gas and then keep them in this state, even as gas was fed back by dying stars, such that the present day ISM mass is $<$10% of that of the stars (and probably $<$1%). Theoretical models imply that this condition is difficult for any but the smallest galaxies to achieve through stellar powered galactic winds (see Ferrara & Tolstoy 2000).

GGH revisit the idea that gas was removed from dSphs via ram pressure from an external medium (van den Bergh 1994). The difficult phase of stripping a dense initial gas supply probably occurred at early times, when denser intra-group matter and vigorous galactic winds from giant systems existed. Once a dSph is mostly cleared of gas, even a low density atmosphere in the Local Group, consistent with observations of highly ionized low velocity oxygen with *FUSE* and *Chandra*, could prevent regrowth of an interstellar medium.

In this picture the evolution of some dSphs was rapidly truncated by externally induced gas loss that also would bring the chemical evolution of the system to an abrupt halt. The recent measurement of the stellar metallicity distribution in Leo I by Smecker-Hane et al. (2003) supports a sudden cessation of star formation and metal enrichment. Even though metals produced by dSphs may have been lost to galactic winds, some remained to enhance internal abundances. Yet, as Shetrone et al. (2001) emphasize, the metal-poor Galactic

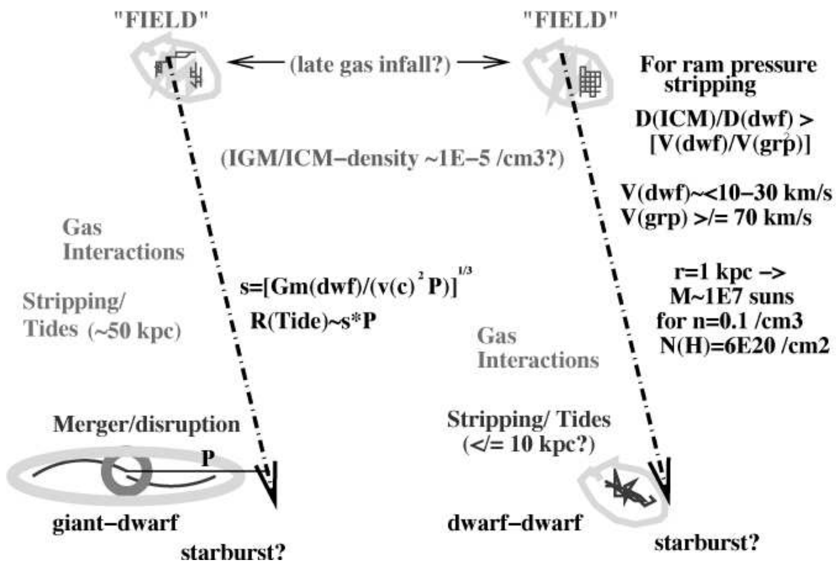

Fig. 1.3. A schematic view of environmental influences on a dwarf system located in a small galaxy group. Interactions with other systems include ram pressure stripping and tidal effects, while the intragroup medium can either remove or add gas, depending on the circumstances.

displays different chemical signatures than are seen in the old Galactic satellite dSphs. The Galactic halo cannot be a simple conglomeration of typical Draco-like dSphs, but instead has enhanced $\alpha/$Fe, an indicator of high SFRs at an early stage. Perhaps this hints at a key role for the gas in young dwarfs, which could have greatly exceeded their stellar masses, and could contribute raw materials to an early Galactic starbursts?

Figure 1.3 outlines some of the environmental processes that are likely to have acted on dwarf galaxies. These include both gas inflows and outflows, circumstances that can lead to complicated variations in stellar chemical abundances with age. As a result, the record of early galaxy evolution dSphs probably is largely obscured by stars that formed either from internally or externally supplied, chemically enriched gas at later times.

1.5 Trends in Mean Metallicities

The RGBs of galaxies are useful for probing chemical abundances. Since the lifetimes of red giants change only slowly for stars with ages of 2-12 Gyr, the number of red giants arising from any stellar population age group is set approximately by the SFR weighted by the IMF. For a constant SFR, as in typical dI galaxies, the oldest red giants come from stars with about half the mass of those responsible for the youngest ones. Due to the IMF the old red giants in a constant SFR system then are $\geq$4 times more common than the younger ones. We therefore see that the RGBs of star-forming galaxies, such as dI systems, still tell us about properties of older stars.

In GGH we compared mean RGB metallicities determined by a variety of techniques for Local Group galaxies. A subset of the results are shown in Figure 2. Here we see an offset exists between the metallicities of red giants in dIs as compared with the dSphs. We used

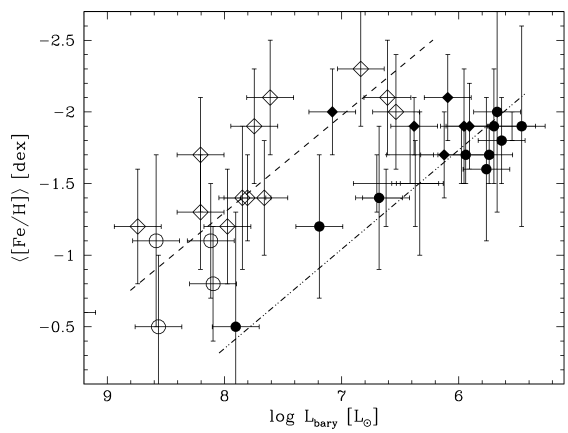

Fig. 1.4. This figure adapted from Grebel et al. (2003) shows the mean RGB metallicity as a function of L_{baryon} (see text). The lines are hand fits to illustrate the offset in RGB abundances between Local Group dSph/dE (filled circle) and dI (open diamond) galaxies. Transition type dwarfs (filled diamonds) tend to bridge the gap between dSphs and dIs.

"baryonic luminosity," L_{bary} as a metric. L_{bary} is an artifical luminosity derived by assuming gas would produce light at the mean M/L of each galaxy. In this way we can take the total baryonic content of the galaxy into account when comparing systems.

The dI-dSph metallicity offset is well-established (Thuan 1985, Skillman & Bender 1995, Mateo 1998). This could be an effect of metal dilution in the large dI gas reservoirs along with metal loss in winds. It also can be interpreted as a result of dIs being slow starters in an evolutionary sense. It therefore is consistent with what we see from the horizontal branch stars; dSphs evidently formed stars more vigorously than typical dIs about 10 Gyr ago. This result suggests that present-day environment is not be the sole factor in differentiating the dI and dSph families. Apparently the transition dwarfs are the evolutionary bridge between the two main dwarf families. This observation led GGH to speculate whether transition dwarfs could be genetically dSph-like galaxies that retained their gas into the present epoch due to their generally isolated locations with the Local Group.

The dSph-dI metal offset also has implications for metal loss via galactic winds. While our understanding of the mixing and loss of metals in dwarfs remains imperfect, some general themes are emerging (see Gallagher 2003). Numerical models and observations agree that metals are readily ejected from a disk or other locally dense region where young stars are likely to be concentrated (e.g., De Young & Gallagher 1990, De Young & Heckman 1994, Mac Low & Ferrara 1999). The amount of metal lost from the fraction of hot ejecta escaping the galaxy depends on details, and the rate of mixing of metals into the remaining cool gas probably is relatively slow (Silich & Tenorio-Tagle 1998, Ferrara & Tolstoy 2000). As the gas reservoir of a galaxy is lost, the amount of material into which new metals will be mixed must be reduced. In galaxies where the gas loss process is slow compared to the time scale to form stars and mix in new metals (Table 1.2), we expect the final phases of star formation to produce increasingly metal-rich stars. This phenomenon apparently is observed in the Sagittarius dSph by Smecker-Hane & McWilliam (2003). Even though this galaxy has been tidally disrupted by the Milky Way, its abundances suggest star formation ended slowly, such that near solar metallicity levels were achieved in some stars.

1.6 Discussion and Conclusions

We conclude by considering some of the open issues that currently limit our ability to use spheroidal dwarfs as nearby tracers of the earliest phases of galaxy formation. In other words we ask what additional information is required for us to make use of these remarkable objects for "near field" cosmology in the spirit of Freeman and Bland-Hawthorn (2002)?

Models of Stellar Populations: If we had nearly perfect stellar isochrones, then we could learn more from the readily observed RGB and horizontal branch stars within and beyond the Local Group dwarfs. Unfortunately, this is not yet the case. Star formation histories based only on the more luminous evolved stars, which have substantial uncertainties. In some cases (e.g., Skillman et al.) such models yield reasonable results, but in others evolved stars do not readily reveal evolutionary complexities (e.g., in Carina).

Similar difficulties confront efforts to derive the ages of the first epochs of star formation in dwarfs beyond the Milky Way's satellites. In our Galactic neighborhood all galaxies appear to be about as old as globular star clusters, but have star formation lifetimes that considerably exceed the internal crossing times. These seem to be required to produce the relatively normal chemical abundance patterns, abundance spreads, and radial spatial gradients in HB structures found by Harbeck et al. (2001) and in A. Maxham's Wisconsin senior thesis. If dSphs avoided prompt astration, then they cannot make spiral galaxy spheroids through accretion of their dynamically collisionless stellar components. However, they possibly contributed to this process if their dissolution into giant galaxies was accompanied by gas injection and subsequent intense star formation.

An additional factor is our lack of knowledge of observable signatures of presumably massive Population III stars. If the dSphs are remnants of the "first galaxies" which may have formed stars $\leq$0.3 Gyr after the big bang to provide for the earliest reionization estimates of WMAP, then they might contain a record of the first phases of star formation. Even if Pop III stars were born in dSphs, their remnants might be gone (e.g. even a modest kick will eject compact objects from dSphs that have escape velocities of $\leq$50 km s^{-1}), but their nucleosynthetic imprints should remain.

Impact of Reionization on dSph Evolution:

Reionization heats gas and should have a profound effect on the evolution of low mass galaxies. However, any connection between properties of dSphs and reionization remain unclear. Better quantitative comparisons between theory and the observed properties of dwarfs are essential for understanding the critical links between the formation of dwarf galaxies and the reionization of the IGM (e.g., Riciotti & Shull 2000, Bromm & Clarke 2002 from the pre-WMAP era).

Evolution of the ISM: Spheroidal dwarfs are low metallicity systems. This circumstance arises in standard chemical evolution models through two types of processes: preferential metal loss through galactic winds or the dilution of metal production in relatively pristine gas reservoir. Possibly both processes work in tandem (e.g., Pilyugen & Ferrini 2001). However, if gas is lost slowly, it becomes difficult to avoid making some stars with metallicities near the average nucleosynthetic yield, as seen in the Sgr dSph. On the other hand, such stars are not seen in the Dra and UMi dSphs, which also are gas-free systems. Evidently dSphs can become gas-free by different routes. Sometimes this happens slowly, with a small gas reservoir retaining metals and producing moderate metallicity stars. In other cases rapid gas removal, presumably aided by an external process such as ram pressure stripping, abruptly halts the evolution, and prevents metal-rich stars from forming, but leaves a metallicity spread.

The dSph ISM retention/loss issue also connects to the dark matter question. For the simplest model, one might expect dwarfs with more dark matter to better retain gas and metals, yet such patterns are not obvious in the data. For example, the Dra dSph has all of the characteristics of a dark matter dominated galaxy (Odenkirchen et al. 2001, Kleyna et al. 2002), but has normal chemical abundances. Possibly effects associated with the environment of the dwarf or structures of the dark matter halos obscure any simple evolutionary correlations. Optical morphologies alone do not tell the whole story in dwarf galaxies.

The dSphs have yet to reveal their evolutionary secrets. Chemical abundances are one key to the history stored in these extraordinary stellar fossils, and much remains to be learned from its application.

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