RevMexAA (Serie de Conferencias), **3**, 25–30 (1995)

THE DWARF GALAXY STAR FORMATION CRISIS

Evan D. Skillman
Astronomy Department, University of Minnesota
116 Church St. SE, Minneapolis, MN 55455, USA
and
Ralf Bender
Universitäts – Sternewarte München
Scheinerstrasse 1, 81679 München, Germany

RESUMEN

Revisamos las ideas de la literatura relativas a los procesos que podrían remover el gas de las galaxias enanas y su relación con los problemas concernientes a la formación y evolución de éstas. Encontramos que muchos de los estudios tienen una falla en común al aplicar argumentos válidos solo para un subconjunto de galaxias enanas a la variedad total de objetos, insistiendo en escenarios de evolución unificada. Intentamos aclarar estos argumentos y determinar las preguntas y conflictos críticos. Entonces señalamos las observaciones claves y los proyectos teóricos que creemos que son necesarios para un progreso futuro en el entendimiento de la formación y evolución de las galaxias enanas.

ABSTRACT

We review ideas from the literature concerning the process of gas removal from dwarf galaxies and its relationship to problems concerning the formation and evolution of dwarf galaxies. We find that many studies suffer from the common failure of applying arguments applicable to a subset of the dwarf galaxies to the entire spectrum of dwarfs by insisting on unifying evolutionary scenarios. We attempt to clarify these arguments and determine the critical conflicts and questions. We then outline the key observational and theoretical projects which we feel are necessary for future progress on understanding the formation and evolution of dwarf galaxies.

Key words: **GALAXIES: EVOLUTION — GALAXIES: ABUNDANCES**

1. HOW DOES A DWARF ELLIPTICAL LOSE ITS ISM?

We start with this very simple question. If one conducts a poll of astronomers, the overwhelmingly favorite response is that the gas is blown out of the dE by the energetic events associated with star formation (stellar winds and supernovae). This community consensus represents an acceptance of models first proposed by Larson (1974) and later applied specifically to dwarfs by Vader (1986) and Dekel & Silk (1986, DS86). The simple basis for this idea is that these processes can accelerate the ISM above the escape velocity of the relatively shallow potential of a dwarf galaxy.

This model has many appealing characteristics. The first, of course, is its simplicity. The energy requirements are easy to match in any model of clustered star formation (Heiles 1990). Additionally, this model explains two empirical relationships found in dwarf galaxies. The strong correlation between mass and metallicity found for both the dEs and dIs (Aaronson 1986; Skillman, Kennicutt, & Hodge 1989) is a natural result of the successively less massive galaxies inability to retain the heavy elements produced in each generation of star formation. This model has been worked out in detail in the chemo-dynamical models of Clayton & Pantelaki (1993) and Burkert & Hensler (1991).

Another natural by-product of the outflow model is the luminosity–surface brightness relationship for dwarf galaxies. Kormendy (1985) showed that dEs and dIs follow nearly identical relationships in velocity dispersion, core radius, central surface brightness, and absolute magnitude. As a galaxy loses an increasing fraction of its mass to stellar winds, the gravitational potential is further decreased, and the stellar surface mass density decreases in response. DS86 hypothesized that both dEs and dIs have lost the majority of their original gas, and thus follow the same relationships, regardless of current gas mass fraction.

While this model is clearly attractive, observations of galaxies from the present epoch pose problems. The first problem lies in the details of the mass loss mechanism. Today we know of many dwarf irregular galaxies where we can observe blow-outs associated with star formation events (Meurer et al. 1992; Marlowe et al. 1995). None of these events appear to be nearly efficient enough to completely remove the ISM from the parent galaxy. Instead, fountains are formed which carry away gas in the vertical direction, but there is little evidence of horizontal gas transport. A related problem is posed by the recent color-magnitude diagram (CMD) of the Carina dwarf (Smecker-Hane et al. 1994a,b). Here a complex history of star formation with four distinct generations of star formation is observed. This prompts the question of how it was possible for the last burst of star formation to clear the galaxy of its ISM where the first bursts failed?

A success of the gas outflow model also presents a short-coming. The mass–metallicity relationship for dwarf galaxies is the same for both dEs and dIs (although there are several caveats as outlined in Skillman et al. 1989). This is true for dI galaxies with dominant gas mass fractions (e.g., DDO 154 has a ratio of H I mass to stellar mass of 5.4; Carignan & Beaulieu 1989). How is it possible that these galaxies can conform to the relationship while gas loss has not yet played an important role in their evolution? Additionally, the mass–metallicity relationship is known to continue on up to the most massive elliptical, spiral, and S0 galaxies (Pagel & Edmunds 1981; Garnett & Shields 1987; Bender, Burstein, & Faber 1993; Zaritsky, Kennicutt, & Huchra 1994). The outflow model predicts that the relationship should have a "turnover", and yet none is observed. As an aside, it is interesting that a turnover may be seen in Fe, where it is not predicted (Faber, Worthey, & González 1992)!

Finally, the outflow model cannot properly explain the distribution of the morphological types of dwarf galaxies. In the Local Group, dEs are only found as companions to more massive galaxies. In the Virgo cluster, the dEs are strongly concentrated in the core of the cluster, while the dIs are absent from the cluster core (Binggeli, Tammann, & Sandage 1987). From a survey of 179 dwarf galaxies, Binggeli, Tarenghi, & Sandage (1990) concluded that there are virtually no isolated dEs. This prompts the very troubling question: *How can it be that gas rich dwarf galaxies in low density environments are unable to blow out their ISM while dwarf galaxies in high density environments are able to do so very efficiently?*

2. STRIPPING AS AN ALTERNATIVE EXPLANATION?

These problems are sufficient that it might cause one to consider alternative theories. The most popular alternative is that of stripping. This theory also has an appealing and simple basis. In clusters of galaxies, the IGM can strip away the outer parts of spiral galaxies, and the observations agree well with the simple model of ram pressure stripping of Gunn & Gott (1972) (see Warmels 1986; Kenney & Young 1989; Cayette et al. 1994). The surface mass densities for dwarf galaxies are lower than the outer parts of the stripped spirals, so the ram-pressure stripping model predicts complete removal of the ISM from cluster dwarfs. In fact, one case has been found where a dwarf galaxy appears to be located beside its stripped ISM (Sancisi, Thonnard, & Eckers 1987). Lin & Faber (1983) suggested ram pressure stripping of dIs as a possible origin for the dEs associated with the Milky Way.

The stripping model would appear to explain the distribution of dEs and dIs in clusters, but what about the mass–metallicity relationship? If all galaxies lie on a single mass–metallicity track, then the gas mass fraction must be unimportant in determining the present metallicity of the galaxy. In this case, the position of the galaxy will be virtually unaffected by the gas removal process, so stripped and un-stripped galaxies should overlap. However, the real appeal of the outflow model is its perceived ability to explain the origin of the mass–metallicity relationship. If one abandons the outflow model, a substitute explanation must be sought. This may not be a fatal flaw, since the mass–metallicity relationship could well be a natural product of a star formation threshold related to surface mass density (Kennicutt 1989).

While stripping appears to be a credible alternative at first glance, it also has many problems. At the distances of the Milky Way spheroidals, there would appear to be insufficient halo gas to strip them (although a class of models for the origin of the Magellanic Stream favor a strong interaction of the Magellanic Clouds with Milky Way halo gas; see Heller & Rohlfs 1994, and references therein). The dEs in the Virgo cluster are

MORE strongly clustered than the giant galaxies. This is impossible to explain with an infalling population that is later stripped (Vader & Sandage 1991). Stripping also fails to produce the luminosity–surface brightness relationship.

3. ASKING THE WRONG QUESTION

The above arguments have all been stated with the implicit assumption that the gas-rich dwarf galaxy progenitors of today's dEs had similar characteristics to today's gas-rich dIs. This assumption is most likely in error. To paraphrase Binggeli (1994), present day dEs and dIs may share a common ancestor, just as humans and apes do, but dEs do not evolve from dIs, just as humans do not evolve from apes.

Binggeli has collected four arguments in support of this. These are: (1) the surface brightnesses of gas-rich dwarfs are too low; (2) the metallicities of dwarf ellipticals are too high; (3) dwarf irregulars have no central nuclei; and (4) the flattenings of dEs and dIs are different.

While all of these statements are true when considering constructing the entire spectrum of present day dEs from dIs, they really only apply to the high luminosity dEs. For example, Binggeli points out that point (1) applies only to the bright dEs and that constructing faint dEs from dIs is not ruled out. Point (2) is based on the infrared photometry of Zinnecker & Cannon (1986), but the existence of identical metallicity – luminosity relationships for the dEs and dIs would argue just the opposite. In fact, metallicities cannot be derived unambiguously from infrared photometry (as discussed by Zinnecker & Cannon), and the metallicities for the nearby dEs (which show the metallicity – luminosity relationship) are now reliably derived from individual stellar spectra and the position of the giant branch in a CMD (see Armandroff et al. 1993 and references therein). This would appear to undermine point (2). Regarding point (3), in the past few years, there have been several suggestions that the Blue Compact Galaxies (or H II galaxies) can evolve into nucleated dEs. Binggeli also points out that the flattenings are not that much different, and that point (4) is not a particular problem for any evolutionary scenario. Thus, it is entirely possible that at least *some* of the present day dEs *could* be constructed from present day dIs.

We think that there may be a more important difference than the structural differences listed by Binggeli. Perusing the "population box" representations of dwarf galaxies sketched by Hodge (1989), one is struck by the fact that all well observed dEs have a dominant early burst of star formation, while the dIs lack evidence for such an event. Here, the key word is dominant, i.e., that the bulk of the star formation occurred during a single period early in the history of the galaxy. While this is only an impression, and needs to be put on firmer grounds, it provides an interesting vantage point from which to view the dE/dI dichotomy.

Under this assumption, the correct question is: what drives some low mass galaxies to dominant early bursts of star formation, while others start out on a path of nearly constant star formation rates? We call this deciding question the dwarf galaxy star formation crisis.

Unfortunately, the early star formation histories of the Local Group dIs are not well determined. This may come as a surprise considering the number of observational studies of the stellar populations of the Local Group dIs. Indeed, there have been many observational programs that have been very successful at modeling the *recent* star formation histories of dIs (e.g., Hodge 1980; Aparicio et al. 1987). However, constraining the *early* star formation histories of galaxies is a very difficult problem. Two-point star formation histories, like those determined from Hα equivalent widths (Kennicutt, Tamblyn, & Congdon 1994) are unable to answer the pertinent question concerning the existence of an early dominant burst of star formation. Gallagher, Hunter, & Tutukov (1984) proposed a three-point scheme based on the dynamical mass, the blue luminosity, and the Hα luminosity, and found that these measures were consistent with roughly constant star formation histories for the irregular galaxies in their sample. Unfortunately, the uncertainties in the conversion of these observables into a star formation history allow consistency with a large range of star formation histories.

Resolved measures of stars offer another avenue. As an example of what can be done from the ground, one can consider the impressive studies of Sextans B (Tosi et al. 1991) and NGC 3109 (Greggio et al. 1993). These galaxies have distance moduli of about 26.6, so with a V-band limit of roughly 23, stars with absolute magnitudes brighter than -3.5 can be reliably recorded. Their method of comparing synthetic color magnitude diagrams to the observations is successful in re-creating the distribution of the stars, but the comparisons are not very sensitive to the star formation histories (i.e., the CMDs for constant star formation models look very similar to models of exponentially decreasing star formation and models of two distinct bursts).

4. INITIAL CONDITIONS

Accepting, for the moment, the star formation crisis hypothesis (that the true distinction between dIs and dEs can be traced to an event very early in their history), the arguments concerning the evolution of dwarf galaxies that have taken place in the last decade mirror the arguments concerning the origin of the Hubble sequence which took place 30 years ago. Both are resolved with the conclusion that it is the initial conditions which determine how a dwarf galaxy resolves its star formation crisis. It may be the environment which plays a role in this resolution, but it is the dwarf galaxy's early environment, and not present environment that is important. Another relevant parameter for the star formation history of dwarfs and the distinction between dEs and dIs may be the density of the dark matter halos.

What clues are available from today's theoretical models of galaxy formation? The logical starting point is the model of DS86 since it addresses the formation of dwarf galaxies directly. DS86 assume a cold dark matter cosmology with biasing, and associate the formation of dwarf galaxies with the small statistical density fluctuations. The predictor of whether a small fluctuation grows into a dE or a dI is not an outcome of their model; however, they do offer speculation concerning the dE/dI distinction.

DS86 suggest that both dEs and dIs lose most of their mass in winds after an early burst of star formation, i.e., they are not distinguished by their early star formation histories as we have postulated. This idea was based, in part, on the chemical abundance pattern of a constant N/S ratio with luminosity. Under the assumption that N is produced as a secondary nucleosynthesis product (and that S is a primary), Wyse & Silk (1985) argued that blowing out the ISM does not allow successive generations of star formation to build-up the metallicity in the gas, and thus, evidence of secondary nitrogen is not seen in the dIs. In the DS86 model, the true distinguishing characteristic of the dwarf galaxies is the ability of the dIs to hold on to some small fraction of their original gas mass, while the dEs loss their entire gas contents. DS86 also note that extended halos of dwarfs could be tidally truncated in the cluster environment, leading to field dwarfs preferentially retaining some fraction of their ISM.

In the last decade, new observations have shown that at least parts of the DS86 scenario are no longer tenable. It is often noted that the large-scale distribution of dwarfs does not agree with that predicted by DS86 (dwarfs are not found preferentially in the voids; Binggeli, Tarenghi, & Sandage 1990). Additionally, there have not been any detections of large halos of expelled gas surrounding dwarf galaxies. This probably indicates that more detailed modeling of dwarf galaxy evolution would be a profitable pursuit.

Specifically, we find the work of Kauffmann, White, & Guiderdoni (1993) intriguing. Within their model, a dwarf galaxy losses its gas as the result of a merger (of the dark matter halos) with a more massive galaxy. This could be viewed as a stripping mechanism, but different from the ram-pressure stripping discussed earlier. The merging of dark matter halos happens early on, and thus we have the elements of the processes which we have required. Unfortunately, we do not see an immediate solution to the problem of the production of high surface brightness dEs emerging from this work. While it is, admittedly, very early in the development of theories of this type, perhaps the ability to produce gas-poor dwarfs is evidence in favor of more work along these lines. Piatek & Pryor (1995) and Oh, Lin, & Aarseth (1995) have modeled the encounters of dEs with the Galaxy, but the model dEs did not have dark matter halos. Similar work, adding in the dark matter halos, would be of great interest.

5. WHAT WE NEED TO KNOW

If we are correct that the star formation history of a dwarf galaxy is the distinguishing factor in the dE/dI dichotomy, then future observational and theoretical work should concentrate on determining the physical parameters which control the early star formation histories of dwarf galaxies. Specifically, we suggest focusing on the following:

(1) The early star formation histories of dIs from photometry of resolved stars.

Here there is potential for progress in the near future. Studies of the field stellar populations in the Magellanic Clouds have revealed very detailed star formation histories (Mateo 1992; Bertelli et al. 1992). If the photometry is deep enough to inventory the "red clump" of helium core burning stars (absolute magnitudes in the range $0 - 1$) good constraints can be put on the age of the older stellar population. This population is just at the limits of what the *HST* can observe in the Local Group dIs.

(2) Infrared Imaging of dIs.

This is a second method to measure the older stellar populations in dIs. Primarily, this allows us to "weigh" the stellar component more reliably. This will be very useful in determining the true driver in the metallicity–mass–luminosity relationship. *K*-band imaging of galaxies will provide the ability to distinguish between the regions of recent star formation, where the infrared luminosity can be dominated by a few supergiants, and the underlying old stellar population. The latest generation of infrared arrays allow reliable surface photometry of low surface brightness objects. While past infrared observations of dwarfs have concentrated on the higher surface brightness Blue Compact Dwarfs (with notable success in identifying older stellar population, see Salzer & Elston 1992) we feel that infrared observations of normal dwarf irregulars will be of great use.

(3) Testable galaxy formation models for dwarfs.

Of course this is easy to ask for, but we would like to add an additional incentive. To date, much work on chemical evolution has been based on the fact that the relative abundances of the elements fall into patterns as a function of metallicity. This is a very important observation since it is possible to imagine chemical evolution scenarios where the abundance patterns observed in one galaxy are completely different from those observed in another (e.g., see the models by Gilmore & Wyse 1991). Thus, whole classes of models are ruled out by the present data. However, the next level of interpretation (which has become the standard) of sequencing relative abundances from different galaxies as a function of metallicity, is not justified from the point of view of galaxy evolution. Clearly, low mass, metal-poor galaxies are not going to evolve into high mass, metal-rich galaxies. A future goal of all chemical evolution models will be to incorporate models of galaxy formation which will evolve naturally to produce the abundance patterns we see today.

We have benefited from conversations from several colleagues including T. Armandroff, J. Gallagher, D. Garnett, M. Mateo, E. Olzewski, T. Pryor, and J. Salzer. We acknowledge support from NASA-LTSARP grant NAGW-3189 (EDS). EDS also gratefully acknowledges the hospitality of the Universitäts – Sternwarte during a visit in February/March 1995.

REFERENCES

Aaronson, M. 1986, in Star Forming Dwarf Galaxies and Related Objects, ed. D. Kunth, T. X. Thuan, & J. Tran Than Van (Paris: Editions Frontières), 125
Aparicio, A., García-Pelayo, J. M., Moles, M., & Melnick, J. 1987, A&AS, 71, 297
Armandroff, T. E., Da Costa, G. S., Caldwell, N., & Seitzer, P. 1993, AJ, 106, 986
Bender, R., Burstein, D., & Faber, S. M. 1993, ApJ, 411, 153
Bertelli, G., Mateo, M., Chiosi, C., & Bressan, A. 1992, ApJ, 388, 400
Binggeli, B. 1994, in Panchromatic View of Galaxies, ed. G. Hensler, Ch. Theis, & J. Gallagher, 173
Binggeli, B., Tammann, G. A., & Sandage, A. 1987, AJ, 94, 251
Binggeli, B., Tarenghi, M., & Sandage, A. 1990, A&A, 228, 42
Burkert, A. & Hensler, G. 1991, in Evolutionary Phenomena in Galaxies, ed. J. E. Beckman & B. E. J. Pagel (Cambridge: Cambridge University Press), 230
Carignan, C., & Beaulieu, S. 1989, ApJ, 347, 760
Cayette, V., Kotanyi, C., Balkowski, C., & van Gorkom, J. H. 1994, AJ, 107, 1003
Clayton, D. D., & Pantelaki, I. 1993, Phys. Rep., 227, 293
Dekel, A., & Silk, J. 1986, ApJ, 303, 39 (DS86)
Faber, S. M., Worthey, G. & González, J. J. 1992, in IAU Symp. No. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Reidel), 255
Gallagher, J. S., Hunter, D. A., & Tutukov, A. V. 1984, ApJ, 284, 544
Garnett, D. R., & Shields, G. A. 1987, ApJ, 317, 82
Gilmore, G., & Wyse, R. F. G. 1991, ApJ, 367, L55
Greggio, L., Marconi, G., Tosi, M., & Focardi, P., 1993, AJ, 105, 894
Gunn, J. E., & Gott, J. R. 1972, ApJ, 176, 1
Heiles, C. 1990, ApJ, 354, 483
Heller, P., & Rohlfs, K. 1994, A&A, 291, 743
Hodge, P. W. 1980, ApJ, 241, 125
———. 1989, ARA&A, 27, 139
Kauffmann, G., White, S., & Guiderdoni, B. 1993, MNRAS, 264, 201
Kenney, J. D. P., & Young, J. S. 1989, ApJ, 344, 171
Kennicutt, R. C. Jr. 1989, ApJ, 344, 685
Kennicutt, R. C. Jr., Tamblyn, P., & Congdon, C. W. 1994, ApJ, 435, 22
Kormendy, J. 1985, ApJ, 295, 73
Larson, R. B. 1974, MNRAS, 169, 229

Lin, D. N. C., & Faber, S. M. 1983, ApJ, 266, L21
Marlowe, A. T., Heckman, T. M., Wyse, R. F. G., & Schommer, R. 1995, ApJ, 438, 563
Mateo, M. 1992, in IAU Symp. No. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Reidel), 147
Meurer, G., Freeman, K., Dopita, M., & Cacciari, C. 1992, AJ, 103, 60
Oh, K. S., Lin, D. N. C., & Aarseth, S. J. 1995, ApJ, 442, 142
Pagel, B. E. J., & Edmunds, M. G. 1981, ARA&A, 19, 77
Piatek, S., & Pryor, C. 1995, AJ, 109, 1071
Salzer, J. J., & Elston, R. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Reidel), 482
Sancisi, R., Thonnard, N., & Ekers, R. 1987, ApJ, 315, L39
Skillman, E. D., Kennicutt, R. C., & Hodge, P. W. 1989, ApJ, 347, 875
Smecker-Hane, T. A., Stetson, P. B., Hesser, J. E., & Lehnert, M. D. 1994a, AJ, 108, 507
———. 1994b, BAAS, 26, 1396
Tosi, M., Greggio, L., Marconi, G., & Focardi, P. 1991, AJ, 102, 951
Vader, J. P. 1986, ApJ, 305, 669
Vader, J. P., & Sandage, A. 1991, ApJ, 379, L1
Warmels, R. H. 1986, Ph.D. thesis, University of Groningen
Wyse, R. F., G. & Silk, J. 1985, ApJ, 296, L1
Zaritsky, D., Kennicutt, R. C., & Huchra, J. P. 1994, ApJ, 420, 87
Zinnecker, H., & Cannon, R. D. 1986, in Star Forming Dwarf Galaxies and Related Objects, ed. D. Kunth, T. X. Thuan, & J. Tran Than Van (Paris: Editions Frontières), 155