RevMexAA (Serie de Conferencias), **6**, 36–41 (1997)

EVIDENCE FOR AND AGAINST GALACTIC WIND DOMINATED EVOLUTION OF DWARF IRREGULAR GALAXIES

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RESUMEN

Se revisa, en base a observaciones de galaxias individuales y a modelos numéricos, la idea de que la evolución de las dIs está dominada por vientos galácticos. La evidencia observacional es insuficiente para hacer conclusiones, pero se dan sugerencias para realizar observaciones que puedan mejorar nuestro conocimiento del problema.

ABSTRACT

Here I consider arguments for and against galactic wind dominated evolution of dIs based on observations of individual galaxies, implications from chemical evolution, and numerical modeling experiments. I find that there is insufficient observational evidence to conclude that galactic winds dominate the evolution of present day dIs. I attempt to identify future observations which will improve our understanding of this problem.

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

1. MOTIVATION AND INTRODUCTION

This talk is motivated, in part, by the following statement taken from Marlowe et al. (1995): " ... there is a clear consensus (at least among theorists) that supernova-driven galactic winds are a vital ingredient in the evolution of dwarf galaxies." As an observer, I am vulnerable to an automatic skeptical response to such statements. Perhaps such a response is better ignored, but I thought it would be a worthwhile exercise to weigh the arguments, pro and con, bearing on this consensus. This can be a considered a follow up exercise to the paper which Ralf Bender and I wrote last year, in which we consider the similarities and differences between the two families of dwarfs (Skillman & Bender 1995).

2. DEFINITIONS

First, it is important to define what I mean by "galactic wind dominated evolution," since I think this can mean many different things to many different people. I would like to differentiate two different pictures of galactic wind dominated evolution, a "strong" form and a "moderate form." For completeness, a "weak" form would hold that while galactic winds can occur in dIs, they are not ubiquitous and therefore do not dominate the evolution of dIs. For the strong form, I will take the picture presented by Dekel & Silk (1986; DS86). The main goal of their paper was to present a simple theory to explain the relationships observed in dwarf elliptical galaxies (dEs) in luminosity, surface brightness, size, and metallicity (see Kormendy 1985 and Ferguson & Binggeli 1994). This was done by following the suggestion of Larson (1974) that a galactic wind, caused by the supernovae of an early generation of star formation, could remove a substantial fraction of the mass of a dwarf galaxy. DS86 augmented Larson's suggestion by considering the importance of a dark matter halo, and, after careful consideration of the conditions necessary for gas removal, found very good agreement between their model and the observed properties of dEs. While the main goal of their paper was an evolutionary framework for dEs, they speculated on the nature of dIs as similar in that "... both the dIs and dEs have lost most of their mass in winds after the first burst of star formation, and that this process determined their final structural relations." Thus, the relationships between luminosity, surface brightness, size, and metallicity that the dwarf irregular galaxies (dIs) have in common with the dEs (see Binggeli 1994), are explained by a common mechanism.

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For a moderate form of galactic wind dominated evolution I propose the picture presented by De Young & Gallagher (1990) in which they state that "... the formation of galactic chimneys in low-mass disk galaxies will direct metal-enriched ejecta from SN out of the disk." This idea can also explain the relationship between metallicity and mass (or luminosity, which often serves as a surrogate). Detailed modeling of these winds show that the newly synthesized heavy elements from the current burst of star formation will reside preferentially in the hot phase, and it is this hot gas which is most easily removed from a galaxy. As this process is increasingly more efficient at lower masses, low mass galaxies have more difficulty retaining their heavy elements, and thus, are deficient in metals relative to the more massive galaxies. Thus, the major distinction is that in the strong form one envisions outflows in which all of the ISM is removed, while in the moderate form, only a fraction of the ISM is removed (although a potentially large fraction of the metals). In the parlance of De Young & Heckman (1994), the strong form would hold that "blow-away" is important to the evolution of dIs while the moderate form would imply that "blow-out" is the key process determining the characteristics of dIs.

Since the wind models are called upon to explain relationships between physical parameters that are shared by all dIs, I am not interested in the question if any dwarf galaxies have ever experienced a galactic wind, but whether the majority of all dwarf galaxies have experienced them. I think that this is a very important, and possibly overlooked, point. If the goal is to explain the global relationships, then identifying prototypes of galactic winds is a necessary, but insufficient requirement. In addition, it must be shown that star formation that results in galactic winds is the dominant form of star formation in dIs (i.e., galactic winds must be ubiquitous).

3. A BACKGROUND DISTRACTION?

The observation that clusters of galaxies contain hot intracluster gas (ICM) with masses which are comparable to (or greater than) the mass contained in the galaxies (Henriksen & Mushotzky 1985; David et al. 1995) and comparable in metallicity to the stars in those galaxies (Arnaud et al. 1992) implies that cluster galaxies must efficiently eject metal enriched gas. Thus, it can be reasoned, if galaxies can efficiently eject metal enriched gas, then low mass galaxies, with shallower potentials, must be relatively more efficient at this process. While the reasoning is simple and straightforward, I would like to consider the possibility that this is a distraction. Of course, it is easier to be skeptical than to be right, but I would like to elaborate on the basis for my skepticism. Thorough discussions of the implications of the chemical abundances of the intercluster medium can be found in Arnaud et al. (1992), Renzini et al. (1993), Matteucci & Gibson (1995), Elbaz et al. (1995), and, most recently, Lowenstein & Mushotzky (1996). Since the total mass of iron in the hot ICM scales with the total luminosity of the cluster elliptical galaxies (Arnaud et al. 1992) it seems likely that the iron in the ICM gas is due primarily to large E galaxies. If this is true, then the iron in the ICM comes from a different type of galaxy (large ellipticals) which has evolved in a different environment (dIs avoid the centers of clusters where the large ellipticals are found; Binggeli et al. 1987). Thus, it is not a straightforward argument that the same mechanism leading to gas ejection in elliptical galaxies is important in the dIs. More importantly, the premise is based on a gross simplification. To state that low mass galaxies experience mass loss more easily than high mass galaxies considers only one aspect of the galaxy. For equal mass galaxies, it is the state (and distribution) of the gas in the galaxy which determines how much energy is required for establishing a galactic wind. For example, it is much easier to blow out gas from a galaxy filled with a hot, low density gas than one filled with cold, high density gas (Mathews & Baker 1971).

Before leaving this topic, I would like to point out that some have considered the idea that it is the dwarf galaxies which are responsible for the ICM. Trentham (1994) has argued that for very steep galaxy luminosity functions (i.e., a very large fraction of galaxies are dwarfs), it would be possible for these dwarfs to produce the total mass of the ICM with the appropriate metallicity through galactic winds (although there is no observational support for a very steep luminosity function in clusters). However, Nath & Chiba (1995) found that it is difficult to produce sufficient iron for the high metallicity clusters. They argued that such a model requires the dominance of type II supernovae as the source of the metals. Interestingly, the relative chemical abundances in the ICM as measured by Mushotzky et al. (1996) point to a dominant contribution from type II supernovae (although they argue that this is primarily the result of the stellar initial mass function).

4. ARGUMENTS AGAINST THE STRONG FORM

4.1. Star Formation Histories

As a schematic or working hypothesis, the dE galaxies could be distinguished from the dI galaxies by a dominant burst of star formation at very early times while dIs are better characterized by relatively constant star formation rates over their entire lifetimes (see Hodge 1989, or the discussion in Skillman & Bender 1995).

If this schematic difference were to be taken seriously, then dIs would lack a dominant burst of star formation early on, and thus, would not fit into the picture given by DS86. However, obtaining observational constraints on this schematic picture is not trivial. What we do know about the star formation histories of dIs neither points to nor excludes a dominant burst of star formation in their early histories. The best observational studies of isolated dIs, which construct star formation histories from deep color-magnitude diagrams, are *consistent* with relatively constant star formation rates (averaged over $\sim$ 0.1 Gyr; Tosi 1994; Greggio 1994; Tolstoy 1995) in agreement with the early discussion by Gallagher et al. (1984). Unfortunately, these studies can only really cover the last billion years or so, and it is very difficult to exclude the possibility of a dominant early burst of star formation. *HST* observations of the nearest dIs will strengthen this argument; by assembling deep color-magnitude diagrams it will be possible to obtain detailed star formation histories back several billion years. The *HST* should be able to do as well for the Local Group dIs as can be done from the ground on the Magellanic Clouds. Note that Butcher (1977) first identified a burst of star formation 3 to 5 Gyr ago in the LMC from its field star main sequence luminosity function, which was later confirmed by Bertelli et al. (1992), based on the distribution of stars in the upper parts of the color-magnitude diagram. Recently this feature has been revealed spectacularly in the *HST* photometry of Gallagher et al. (1996).

Note that we might expect some real surprises in the next few years. Recent studies of dEs have shown that they are not all well characterized by a single early burst of star formation (e.g., the study of the Carina dwarf by Smecker-Hane et al. 1994) and Hodge (1994) emphasizes that the boundary between dIs and dEs is becoming quite blurred with several candidates for a "transition" class. It remains to be seen whether the early star formation histories of dIs and dEs are significantly different.

4.2. DDO 154: The Dark Galaxy

One can find dIs which do not fit easily into the DS86 scenario. These would be dIs in which the gas mass dominates stellar mass and both are dominated by dark matter. In such cases, it is unlikely that most of the gas mass has been lost from the galaxy in an early burst of star formation.

The prototype for this class is DDO 154, first discovered to have very extended H I by Krumm & Burstein (1984). Carignan & Freeman (1988) and Carignan & Beaulieu (1989) reported VLA observations which detected H I out to a radius in excess of 15 optical scale lengths (6.5′). This extended H I is in a simple, flattened, and slightly warped rotating disk. Using the greater sensitivity of Arecibo, Hoffman et al. (1993) extended the detectable H I out almost twice as far. Carignan & Beaulieu found that the stars accounted for a significant fraction of the mass surface density in only the inner 1 kpc. At only 2 kpc, the H I mass fraction begins to dominate the stellar mass fraction. The dark matter halo is the dominant mass component from the first kpc on outward. Given the small size of the stellar distribution relative to the gas distribution, it is highly unlikely that a burst of star formation has swept away a large fraction of the original mass of gas.

Of course, one galaxy alone cannot nullify a theory. However, I see DDO 154 as fitting in well with the continuum of properties shared by dIs. Côté (1995) has shown that the dark mass to luminous mass ratio for DDO 154 is comparable to other low luminosity dIs (see also the study of NGC 2915 by Meurer et al. 1996) and Kennicutt & Skillman (in prep.) find the oxygen abundance in DDO 154 to be in good agreement with the metallicity-luminosity relationship in Local Group galaxies (see Skillman et al. 1989 and Richer & McCall 1995).

5. ARGUMENTS FOR THE MODERATE FORM

While I do not find very much observational evidence in favor of the strong form of galactic wind dominated evolution of dIs, there is plenty of support for the moderate form.

5.1. Examples of Galactic Winds in dIs

There are now numerous examples of individual dIs with outflows. NGC 1569 is perhaps the best case, as evidence of high velocity gas is found both in Hα (Marlowe et al. 1995) and in H I (Israel & van Driel 1990). Meurer et al. (1992) have found high velocity gas in Hα in NGC 1705, but not in H I (Meurer 1994). Marlowe et al. (1995) have shown numerous examples of outflows of ionized gas in dIs, and Martin (1996) has found a remarkable example of a Doppler ellipse in I Zw 18. Thus, there is no question that an individual dI can produce an outflow. The question is what fraction of star formation in dIs results in such phenomena.

5.2. Chemical Evolution Arguments

Matteucci & Chiosi (1983) pointed out that simple closed box evolution models were inadequate in order to understand the abundances and gas mass fractions of many dIs. They proposed that the dIs with relatively low gas mass fractions ($\leq$ 20%) and yet low metallicities (oxygen abundances less than 10% of solar) could be explained by metal enhanced winds which would allow galaxies to evolve to their current state. Peimbert et al. (1994) have additionally pointed out that metal-enhanced winds result in a steeper relationship between He/H and O/H which resolves the long standing disagreement between the observationally derived and theoretically predicted values of $\Delta Y/\Delta Z$ (Pagel et al. 1992; Maeder 1992).

5.3. Hydrodynamical Arguments

De Young & Gallagher (1990) have used hydrodynamical models to simulate metal enhanced winds in dIs. Although these models neglected the presence of a dark matter halo, they found that roughly two-thirds of the metals produced in a burst of star formation would be lost to the galaxy by the construction of a chimney of host gas. De Young & Heckman (1994) further investigated the possibility that a burst of star formation could denude the galaxy entirely of its gas. They found that the border between "blow-away" and the more frequently considered "blow-out" (e.g., as discussed by Tomisaka & Ikeuchi 1986; Tenorio-Tagle et al. 1987; Mac Low et al. 1989) was not impossible to overcome for dwarf galaxies (although, again, no dark matter haloes were considered).

6. ARGUMENTS AGAINST THE MODERATE FORM

6.1. A Statistical Argument

Hunter et al. (1993) surveyed 51 galaxies, searching for ionized gas which could extend beyond the size of the parent galaxy. Limiting the survey to galaxies with inclinations larger than 60°, only 2 of 15 galaxies were found to have structures extending outside of their disks (although two galaxies are discounted as "clearly in an abnormal state"). From this they conclude that blow-outs are not a frequent phenomenon, and, by implication, galactic winds are not frequently present.

6.2. Chemical Evolution Arguments

Theories which predict a metallicity – luminosity relationship based on metal enhanced winds all predict a threshold mass, above which, the galaxy retains all of its metal. Thus, above a particular luminosity, galaxies with similar gas mass fractions should have similar metallicities. Various calculations of this threshold arrive at characteristic values of the mass corresponding to velocities of order 100 km s^{-1} (Larson 1974, DS86). In fact, the predicted flattening in the metallicity – luminosity relationship is not seen (e.g., Zaritsky et al. 1994). Perhaps it is just that the normalization of the theory is off, but the fact that several theorists approach this independently and arrive at the same value is puzzling. Carigi et al. (1995) have pointed out that while metal enhanced winds help to explain the He/H vs. O/H relationship, they cause problems in understanding the C/O abundance ratios in dIs. The basic problem is that as a galactic wind becomes more efficient at removing O from the galaxy, it results in C/O ratios which are too high (because a large fraction of the C is produced in intermediate mass stars which release the newly formed C at times much later than the galactic wind is maintained) compared to what is observed (Garnett et al. 1995).

6.3. Hydrodynamical Arguments

While the initial models indicated that large fractions of the newly synthesized materials could be lost in a galactic wind, later results have been mixed. There are two main questions: What fraction of star formation events result in a blow-out, and What fraction of the metals is lost in an individual blow-out?

H I observations of dIs may be able to answer the first question. For example, H I observations of Holmberg II (Puche et al. 1992) indicate that only a small fraction ($\leq$ 20%) of the holes are large enough to have experienced break-out. This small fraction may be at odds with the calculations which show that even modest OB associations should be able to produce blow-outs (De Young & Gallagher 1990). The additional consideration of the effects of the presence of a warm gas layer, a dark matter halo, magnetic fields, and a clumpy ISM could lead to considerably higher energy requirements for blow-out (see Heiles 1990; Tomisaka 1990,1992; Ferrière et al. 1991; Silich et al. 1996). Concerning the fraction of metals that are lost in an individual blow-out, I think that this is still an open question. The initial modeling by De Young & Gallagher was, by design, quite simplistic. As this problem is addressed with more sophisticated codes, the loss fraction may change. Regardless, if only a small fraction of the star formation occurs in events which lead to blow-out, then the loss of metals due to galactic winds can only be a second-order effect, and cannot be responsible for the global patterns, like the metallicity-luminosity relationship, that are observed.

7. SUMMARY

As one might infer from the title of this talk, I do not think that either case, for or against galactic wind dominated evolution of dIs, is very strong. There appear to be some obvious places that will benefit from immediate work. As an observer, I think that following up on the statistical argument made by Hunter et al. is of primary importance. If we can quantify the fraction of star formation in dIs that is associated with bursts which are sufficiently large to develop a galactic wind, then we can determine the degree to which this mechanism dominates the evolution of dIs. This will require a complete census of both high surface brightness and low surface brightness dIs, a non-trivial task (see Shade & Ferguson 1994). Additionally, more X-ray observations of dIs (both active and quiescent) of the type shown by Heckman at this conference will be useful in pinning down the statistical argument. Obviously, spectral information of the X-ray gas would provide invaluable chemical abundance determinations of the hot halo gas. I also think that more detailed modeling of the evolution of starbursts within dIs is required, using more realistic parameters for the parent galaxies. These models may also be useful in helping us to identify important signatures of the blow-out phenomenon.

I have benefited from conversations from several colleagues, but I would especially like to thank Tim Heckman and Serge Silich for discussions held during the conference and Mordecai-Mark Mac Low for sharing his insights. I thank Don Garnett and Bob Benjamin for careful readings of drafts and helpful comments. I also gratefully acknowledge the hospitality of the Max-Planck-Institute for Astrophysics, my home during my sabbatical year, and the libraries and computing resources of the European Southern Observatory and the Munich University Observatory. This work was supported, in part, by NASA-LTSARP grant NAGW-3189 and a Bush Sabbatical Fellowship from the graduate school of the University of Minnesota.

REFERENCES

Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L., & Vangioni-Flam, E. 1992, A&A, 254, 49
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
Butcher, H. 1977, ApJ, 216, 372
Carigi, L., Colín, P., Peimbert, M., & Sarmiento, A. 1995, ApJ, 445, 98
Carignan, C., & Beaulieu, S. 1989, ApJ, 347, 760
Carignan, C., & Freeman, K. C. 1988, ApJ, 332, L33
Côté, S. 1995, Ph.D. thesis, Australia National University
David, L. P., Forman, W., & Jones, C. 1990, ApJ, 359, 29
Dekel, A., & Silk, J. 1986, ApJ, 303, 39 (DS86)
De Young, D. S., & Gallagher, J. S. 1990, ApJ, 356, L15
De Young, D. S., & Heckman, T. M. 1994, ApJ, 431, 598
Elbaz, D., Arnaud, M., & Vangioni-Flam, E. 1995, A&A, 303, 345
Ferriére, K. M., Mac Low, M.-M., & Zweibel, E. G. 1991, ApJ, 375, 239
Ferguson, H., & Binggeli, B. 1994, A&AR, 6, 67
Gallagher, J. S., Hunter, D. A., & Tutukov, A. V. 1984, ApJ, 284, 544
Gallagher, J. S., et al. 1996, ApJ, 466, 732
Garnett, D. R., Skillman, E. D., Dufour, R. J., Peimbert, M., Torres-Peimbert, S., Terlevich, R., Terlevich, E., & Shields, G. A. 1995, ApJ, 443, 64
Greggio, L. 1994, in The Local Group: Comparative and Global Properties, ed. A. Layden, R. C. Smith, & J. Storm (ESO: Garching), 72
Heiles, C. 1990, ApJ, 354, 483
Henriksen, M., & Mushotzky, R. 1985, ApJ, 292, 441
Hodge, P. W. 1989, ARAA, 27, 139
———. 1994, in The Local Group: Comparative and Global Properties, ed. A. Layden, R. C. Smith, & J. Storm (ESO: Garching), 57
Hoffman, G. L., Lu, N. Y., Salpeter, E. E., Farhat, B., Lamphier, C. & Roos, T. 1993, AJ, 106, 39
Hunter, D. A., Hawley, W. N., & Gallagher, J. S. 1993, AJ, 106, 1797
Israel, F. P., & van Driel, W. 1990, A&A, 236, 323
Kormendy, J. 1985, ApJ, 295, 73
Krumm, N., & Burstein, D. 1984, AJ, 89, 1319

Larson, R. B. 1974, MNRAS, 169, 229
Loewenstein, M., & Mushotzky, R. F. 1996, ApJ, 466, 695
Mac Low, M.-M., McCray, R., & Norman, M. L. 1989, ApJ, 337, 141
Maeder, A. 1992, A&A, 264, 105
Marlowe, A. T., Heckman, T. M., Wyse, R. F. G., & Schommer, R. 1995, ApJ, 438, 563
Martin, C. 1996, ApJ, 465, 680
Mathews, W. G., & Baker, J. C. 1971, ApJ, 170, 241
Matteucci, F., & Chiosi, C. 1983, A&A, 123, 121
Matteucci, F., & Gibson, B. K. 1995, A&A, 304, 11
Meurer, G. 1994, in Dwarf Galaxies, ed. G. Meylan & P. Prugniel, ESO, 351
Meurer, G., Carignan, C., Beaulieu, S. F., & Freeman, K. C. 1996, AJ, 111, 1551
Meurer, G. H., Freeman, K. C., Dopita, M. A., & Cacciari, C. 1992, AJ, 103, 60
Mushotzky, R., Loewenstein, M., Arnaud, K. A., Tamura, T., Fukazawa, Y., Matsushita, K., Kikuchi, K., & Hatsukade, I. 1996, ApJ, 466, 686
Nath, B. M., & Chiba, M. 1995, ApJ, 454, 604
Pagel, B.E.J., Simonson, E.A., Terlevich, R.J., & Edmunds, M.G. 1992, MNRAS, 255, 325
Peimbert, M., Colín, P., & Sarmiento, A. 1994, in Violent Star Formation, ed. G. Tenorio-Tagle (Cambridge: Cambridge Univ. Press), 79
Puche, D., Westpfahl, D., Brinks, E., & Roy, J.-R. 1992, AJ, 103, 1841
Renzini, A., Ciotti, L., D'Ercole, A., & Pellegrini, S. 1993, ApJ, 419, 52
Richer, M. G., & McCall, M. L. 1995, ApJ, 445, 642
Shade, D. J., & Ferguson, H. C. 1994, MNRAS, 267, 889
Skillman, E. D., & Bender, R. 1995, in the Fifth Mexico-Texas Conference on Astrophysics: Gaseous Nebulae and Star Formation, ed. M. Peña & S. Kurtz, RevMexAASC, 3, 25
Skillman, E. D., Kennicutt, R. C., & Hodge, P. W. 1989, ApJ, 347, 875
Silich, S. A., Franco, J., Palouŝ, J., & Tenorio-Tagle, G. 1996, ApJ, 468, 722
Smecker-Hane, T. A., Stetson, P. B., Hesser, J. E., & Lehnert, M. D. 1994, AJ, 108, 507
Tenorio-Tagle, G., Bodenheimer, P., & Rozyczka, M. 1987, A&A, 182, 120
Tolstoy, E. 1995, Ph.D. thesis, Groningen University
Tomisaka, K. 1990, ApJ, 361, L5
____________. 1992, PASJ, 45, 513
Tomisaka, K., & Ikeuchi, S. 1996, Pub. Astr. Soc. Japan, 38, 697
Tosi, M. 1994, in Dwarf Galaxies, ed. G. Meylan & P. Prugniel (ESO: Garching), 465
Trentham, N. 1994, Nature, 372, 157
Zaritsky, D., Kennicutt, R. C., & Huchra, J. P. 1994, ApJ, 420, 87