

Dwarf Irregular Galaxies and the Intergalactic Medium

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Abstract.

Dwarf galaxies (DGs) are more numerous than large galaxies. Most dwarfs in clusters are dEs, but in the field they belong mostly to late types. The importance of late-type DGs in the context of the intergalactic medium (IGM) lies in the fact that (at least some) are probably “young” galaxies forming stars for the first time. Many DGs have significant amounts of interstellar gas, they may form out of intergalactic gas clouds, and matter ejected from such galaxies as a result of star formation processes may enrich the IGM with metals. The physical mechanism responsible for triggering the star formation process has not yet been identified. The extended halos of DGs may provide (at least some of) the QSO absorption line systems. Recent observations also show that the LSB dwarf galaxies may be good tests of MOND.

Keywords: star formation, dwarf galaxies, irregular galaxies, inter-galactic matter, gravity

1. Introduction: the panoply of galaxies

Taxonomy of phenomena is the first, and most basic, of scientific investigations aimed at understanding nature. Astronomers classified galaxies since the 1920s, from their images on blue-sensitive photographic plates, as belonging to two kinds, ellipticals and spirals. Hubble (1936) refined later the classification to include barred as well as “normal” spirals, and introduced different subclasses of E and S galaxies. This classification, depicted in the well-known fork diagram, is in use even today, albeit with small modifications and with significant additions.

Hubble classified further the elliptical galaxies according to their degree of flattening. A galaxy belongs to sub-type E_n if its apparent semi-axes a and b form the index $n=10(a-b)/a$. No elliptical galaxies flatter than $n=7$ exist; their semi-major axes would be longer by more than 70% than the semi-minor axes and such objects would be classified as edge-on spirals. A spiral is a disk galaxy which can even be fully planar, with no bulge at all, and may belong to sub-types a, b, or c, according to the openness of its (spiral) arms and the relative strength of the central bulge relative to the disk. A galaxy could belong to any of these sub-classes and be either barred [SB] or regular [S]. Finally, another type of disk galaxies can be as flat as the spirals but may lack spiral arms; such galaxies belong to the lenticular category (S0).

Even in Hubble’s original scheme there were outstanding objects which did not fit any of these categories. Such examples, visible with the naked eye in the southern hemisphere, are the Large and Small Magellanic Clouds (LMC & SMC). These satellites of the Milky Way galaxy are irregular galaxies. Both Magellanic Clouds belong to the Irr I type and are perhaps failed or tidally-stripped spirals (it is easier to visualize this for the LMC than for the SMC). The Irr II class contains the genuinely irregular examples, but note that the classification of Irr objects has been revised many times.

A recent classification, in particular of the irregular galaxies, is the result of a seminal work by Binggeli, Sandage, and Tammann and consists of the most comprehensive morphological classification of galaxies in the direction of the Virgo cluster (VC). The Virgo cluster galaxy catalog (VCC: Binggeli *et al.* 1985) contains more than 2,000 objects; most are dwarf ellipticals. These objects have small dimensions but exhibit the general photometric behavior of elliptical galaxies (smooth light distribution, $r^{1/4}$ surface brightness profiles, red colors, lack of interstellar matter [ISM]). Almost 300 objects in the VCC are late-type dwarf galaxies and all have been observed by Hoffman (1987, 1989) with the Arecibo radiotelescope in the 21 cm line. The classification scheme introduced by Sandage *et al.* (1985) for those objects distinguished among five sub-classes of dwarf irregular galaxies (DIGs) separated by luminosity: the most luminous were classified as Irr III and the least luminous as Irr V.

In addition to the dEs and Irr III-V an additional class of DIGs was identified: the blue compact dwarfs (BCDs: see *e.g.*, Loose and Thuan 1986 for a taxonomic study of BCDs). This class is characterized by relatively bright objects of very small dimensions, sometimes undistinguishable from stellar images except by their spectra. A sub-class of BCDs, called “HII galaxies” (*e.g.*, Telles *et al.* 1997), is characterized by strong emission-line spectra. There is considerable cross-over between the BCD and HII galaxy classes, as many BCDs also show strong emission lines, but it is clear that in both cases the galaxies have considerably high surface brightness. In particular, the “type II” less luminous HII galaxies are, in fact, BCDs with a central (nuclear) starburst. Also, there are BCDs devoid of emission lines (Almoznino & Brosch 1998).

de Vaucouleurs (1994) revised the historical Hubble sequence as a three-dimensional distribution. An object could be located in the classification volume along three axes: family, variety, and stage. The “family” variable distinguishes among ordinary [A], barred [B], and transition [AB] types. The second variable can be either spiral-shaped [s], ring-shaped [r], or a transition between the two [rs]. The third is essentially the T-type used, *e.g.*, in RC3; ellipticals and spheroidal galaxies have $T=-6$ to -4 , S0’s have $T=-3$ to -1 , and spirals span the range $T=0$ (S0/a) to $T=9$ (Magellanic Irregulars). The compact late-type galaxies are relegated to $T=10$ and 11.

The different morphological classifications are linked to physical characteristics. From ellipticals to late-type spirals (Sc) the spin of a galaxy and its ISM content increase while the total symmetry decreases. The irregulars stand out by showing a large variety of gas contents. The difference between normal and dwarf galaxies has been set, rather arbitrarily, at $M_B=-18$; dwarfs are fainter than this limit. The dynamical and ISM properties of galaxies translate into observables related to star formation (SF). The more gas-rich a galaxy is the higher its star formation rate (SFR) can be, but not all gas-rich galaxies form stars, at least not at present.

A recently recognized class of galaxies consists of low surface brightness (LSB) objects, with central surface brightness below 23.0 mag./square arcsec. The class has been identified by Bothun and has been studied by him and collaborators (see *e.g.*, Bothun *et al.* 1997 for a review). The best-known member of this class is the giant LSB disk Malin 1, but there are many dwarf galaxies which are LSBs. In fact, the dS class and all Irr IV and V belong to the LSB kind. The LSBs may prove to be an important component of the galaxy population (McGaugh *et al.* 1995), and those objects detected so far may be only the “tip of the iceberg” in their numbers (de Blok 1997). However, Briggs (1997) argued that LSBs may contribute only a small fraction of the total HI content of the Universe.

It is interesting to note that some of the blue galaxies identified in the Hubble Deep Field (HDF) are physically small and have high surface brightness; they would qualify as extremely high surface brightness BCDs, i.e., those with very high SFRs (*e.g.*, Ferguson & Babul 1998). Some compact and faint galaxies, seen with the HST at $z\sim 2.4$, may be sub-galactic entities which will eventually coalesce into a large galaxy (Pascarelle *et al.* . 1996). These messages from the past history of the Universe emphasize that (a) some part of the galaxy evolution may

be similar to what we now witness in local DIGs, and (b) distant DIGs are presumably galactic building blocks of present-day large galaxies.

2. Star formation in DIGs and in other galaxies

The star formation process in large and small galaxies modifies their metal and gas contents. The more massive stars enrich the ISM of a galaxy with heavy elements produced by nucleosynthesis and ejected from a star by radiation pressure during the red (super)giant stage or during a type II supernova (SN) explosion. Additional ISM enrichment, with other types of metals, happens when a white dwarf explodes as a type I SN or during the evolution of close binaries. This metal-enriched ISM may provide an important source of metals for the IGM.

A significant difference in the mode of star formation between DGs and large galaxies (LGs) lies in the number of possible triggers of the SF process. Whereas the large galaxy SF may be triggered by whole-disk processes (*e.g.*, shear forces, spiral density waves), these are probably absent in DGs. Thus, understanding SF should be simpler in DGs than in LGs.

We studied SF in DGs of the Virgo cluster and the results will be discussed here by Almoznino. Briefly, we found that SF takes place in bursts and is present in both high surface brightness (HSB) objects as well as in low surface brightness ones. Other results from this study show that the star-forming regions in DIGs are most often observed at the visible edge of a galaxy, particularly to one side of the galaxy. This result shall be mentioned again, towards the closing of this presentation, in the context of DM and its influence on the star formation.

Matter may be ejected from DGs by the SF activity. This was predicted by Dekel & Silk (1986) and was observed in a number of objects (*e.g.*, Papaderos *et al.* 1994, Marlowe *et al.* 1995; Martin 1997). In some cases, the starburst activity heats up the ISM gas to very high temperatures and the gas radiates in the X-ray (*e.g.*, Della Ceca *et al.* 1996, 1997 for ASCA observations; Bomans & Grant 1998 for ROSAT observation). The matter ejection is also observed as major disturbances of the ISM dynamics and as extended HI and ionized gas “ansae” of a galaxy. These may form, in some cases, structures that reach out several kpc from the galaxy (*e.g.*, Hunter & Gallagher 1997; Brosch *et al.* 1998a). Note that while the inflation of gas bubbles in a galaxy is an established observational fact, the question of whether this matter is completely lost by the galaxy or whether it is retained and eventually recycled because of the influence of an extended DM halo has not yet been solved. Recent observations (Meurer 1998) indicate that it is very difficult to completely clean a galaxy of its ISM. NGC 1705, which shows presently a very strong SF burst, may eject eventually $\sim 8\%$ of its ISM during the present event. With the accepted bursting rate of one per Gyr, the full gas content may be released from the galaxy only over one Hubble time.

The metal enrichment of the Universe can be traced from a computation of its star formation history (Madau 1997). Until very recently it was believed that the star formation reached its peak at $z=1-2$ and that both before that time and since $z=1$ to the present the SF was low. New observations with the SCUBA (Submillimetre Common-User Bolometer Array) instrument on the JCMT in Hawaii reveal objects with sub-mm emission which could be high redshift ($z=1.5-3$) galaxies. The emission is indicative of stellar radiation reprocessed by dust in these galaxies. The luminosity corresponds to $\text{SFR} \simeq 140-910 h_{75}^{-2} M_{\odot}$ of gas per year converted into stars (Berger *et al.* 1998); these are extremely high SFRs, \sim one order of magnitude higher than previous maximal estimates. Other IR-bright very distant galaxies were apparently identified in deep NICMOS images of the Hubble Deep Field.

The existence of distant, IR-bright galaxies implies a revision of the Madau (1997) scenario for the history of SF in the Universe; whereas Madau showed that the SF peaks at $z=1-2$, the SCUBA observations indicate that (a) the SFR stays \sim flat at least up to $z=3$ and perhaps up to $z=5$, and (b) many high-redshift galaxies may be hidden from optical detection by dust

extinction. In addition, the new results show also how fast the metal enrichment of a galaxy (understood as the production of dust grains) is proceeding, because when observing galaxies at $z=3-5$ one is probing look-back times which are only about 4-5 Gyr ($H_0=50$, $q_0=0$), or 1-2 Gyr ($H_0=50$, $q_0=0.5$), after the Big Bang.

In this context we may wonder what role can DIGs play in the metal enrichment history of the Universe. Although it is not clear whether matter escapes at all from a DIG, the matter ejection from DIGs should be easier than from larger galaxies. In addition, the reduced (local) gravitational potential ensures that any material levitated into the halo will remain there for a long time indeed, before sinking back into the galactic reservoir of ISM. In other words, “galactic fountains” originating from DIGs should sprout higher, and the material fallback should be longer, than in large galaxies. As the binding energy at high halo locations is much lower than in the visible galaxy, the metal-enriched material levitated there may be separated more easily from its parent galaxy than matter in the optical disk, by *e.g.*, ram pressure effects. In any case, either proto-galactic bodies may exist and the present-day DIGs may form out of these, or matter might escape/be torn off dwarf galaxies, resulting in **some** intergalactic objects (almost) devoid of stars but containing some baryonic non-luminous matter. In both cases, DIGs and their precursors prove to be important IGM components.

3. Intergalactic absorbers and their connection to DGs

The discovery of absorption lines in spectra of high-redshift objects (Bahcall 1968), and in particular the existence of lines at a redshift very different from that of the object whose spectrum was analyzed, emphasized the presence of gas in the intervening space up to the highest redshift QSOs. Many of these systems, perhaps most of them, may be produced in DIGs and/or in their immediate precursors.

The absorption-line systems have been classified into three categories: the Lyman- α systems which show only absorption from this line, the Lyman-limit or damped Lyman- α systems (the Ly- α absorption line in these systems is saturated at the line center), and the metal-line systems where additional absorption lines, produced by neutral or ionized elements heavier than H and He, are observed (*e.g.*, Wolfe *et al.* 1986). All the metal-line systems belong also to the damped Ly- α class. The main difference between these systems lies in the hydrogen column density [$\log N(\text{HI})$]: this is 12-15 cm^{-2} for the Ly- α systems, 16-19 cm^{-2} for the damped Ly- α systems, and $\geq 20 \text{ cm}^{-2}$ for the metal line systems, which can reach up to 22-23 cm^{-2} .

The absorption line systems have diverse clustering properties, but mostly they tend to follow the large-scale distribution of galaxies. A claim that the Ly- α absorbers “avoid the voids” has not been confirmed by new HST observations (Shull *et al.* 1996). Ly- α systems with $\log N(\text{HI}) > 12.7 \text{ cm}^{-2}$ are found every $\sim 3,400 \text{ km/s}$. If the entities producing the Ly- α absorption are spherical bodies with 100 kpc radii, their masses are $10^9 M_\odot$ and their space density would be comparable to that of the dwarf galaxies. This is not the case for the damped Ly- α systems; the distribution of their metal abundances with redshift can be reproduced with evolutionary models of large spiral galaxies (Ferrini *et al.* 1997).

In addition to matter which reveals itself through the optical-UV (rest frame) absorption lines one can also hope to detect neutral matter through its HI 21 cm line. Many such attempts were made as “blind searches” for HI signatures (*e.g.*, Brosch & Krumm 1984 with the Green Bank 300’ radiotelescope [search for emission features], Brosch 1989 with the Arecibo radiotelescope [search for 21 cm absorption features against radio QSOs]), but were unsuccessful. A positive result was obtained by Szomoru *et al.* (1996) in a VLA survey for HI emission from the Bootes void, where 18 HI objects not previously known were found.

Apart from (mostly negative) attempts to detect isolated HI emission, searches were conducted for HI features associated with galaxies. These were successful in detecting a giant HI

ring around the small group of galaxies in Leo centered on M96 (Schneider *et al.* 1983), extended HI emission in the M81 group (Lo & Sargent 1979), HI companions to dwarf galaxies (for $\sim 25\%$ of the cases: Taylor *et al.* 1996), a large neutral hydrogen cloud in the southern outskirts of the Virgo cluster (HI 1225+01: Giovanelli & Haynes 1989), and the Malin-1 galaxy.

The case of Malin-1 is particularly interesting. The object was detected originally as an LSB through photographic amplification (“Malinization”) of optical images taken by a Schmidt telescope in the direction of the Virgo cluster (Bothun *et al.* 1987). The location of the object, which appeared as a faint “smudge” on the original plate, showed a large galaxy after the photographic amplification. The nuclear region showed a faint [OII] emission line at $z=0.083$, indicating that the galaxy was in the far background of the VC. The redshift was confirmed later by a 21 cm observation, which showed that the giant LSB galaxy is very hydrogen-rich. Malin-1 is so large that if it would be located in the VC its amplified optical angular size would be \sim one degree !

Additional searches for LSB galaxies were done by Schombert (1997) on the PSS II plates, by photographic amplification of plates of the nearby Fornax cluster (Morshidi *et al.* 1997), by automatic scanning of plates (APM survey, Loveday 1997), and by a wide-field CCD survey (O’Neil *et al.* 1997). Until now, only three giant LSB galaxies have been identified: Malin 1 (Bothun *et al.* 1987), F568-6 (Bothun *et al.* 1990), and 1226+0105 (Sprayberry *et al.* 1993). The latter is outstanding in that it is located very close (in projected sky position) to the HI 1225+01 feature mentioned above. Note though that its redshift is $23,660 \text{ km s}^{-1}$, well in the background of the VC. These searches also yielded many tens of “normal”-sized LSBs

It is useful, at this point, to summarize the observed properties of LSBs. These galaxies lack bulges, bars, and nuclear activity, as well as CO or IR emission (i.e., no molecules or dust). Their typical SFRs are $\sim 0.1 M_{\odot}/\text{yr}$ and the metallicities are $\sim 1/3$ solar. Their colors are generally blue, though some red LSBs have been detected (O’Neil *et al.* 1997). The HI rotation curves, measured by de Block *et al.* (1997) and by Pickering *et al.* (1997), indicate that their gaseous component is dynamically significant at all radii and that the galaxies are dark-matter (DM)-dominated at all radii; the baryonic component is less than 4% of the total mass. Mass models for the LSBs indicate that their DM halos are less dense and more extended than DM halos of HSBs. One may extrapolate from this to the LSB dwarfs in the VC studied by Heller *et al.* (1998), in particular so as to explain the asymmetry of SF (Brosch *et al.* 1998b). This could be produced if the galaxy orbited on an off-center track within the DM halo with a retrograde spin in respect to the sense of its orbital motion (Levine & Sparke 1998), or if the halo itself had some intrinsic anisotropy (Jog 1997).

The question one can ask at this point is whether there is a clear connection between Ly- α absorption systems, HI emission/absorption features, and dwarf or LSB galaxies. The best test case is offered by Ly- α absorption lines produced by nearby material and discovered in the UV spectrum of 3C273. This high luminosity QSO is at a redshift of 0.158 and its HST UV spectrum (Bahcall *et al.* 1991) shows two Ly- α absorptions produced by material at the redshift of the VC. This is clearer from the high-resolution UV spectroscopy (Weymann *et al.* 1995), where the two lines appear at $1,012.4 \pm 2 \text{ km/s}$ and $1,582.0 \pm 2 \text{ km/s}$. Both Ly- α lines have approximately the same column density: $\log(\text{HI})=14.19 \pm 0.04$ and 14.22 ± 0.07 respectively. The hydrogen could be associated with the large isolated HI cloud mentioned above (HI 1225+01), at $1,298 \pm 20 \text{ km s}^{-1}$ and which has two concentrations, where the highest HI column density peak harbors a dwarf irregular galaxy (Salzer *et al.* 1991), but its dynamics may make this explanation problematic.

While it is clear that the Ly- α absorptions are produced by hydrogen atoms in the VC, very deep searches for luminous material close to the line of sight to 3C273 and which may be associated with this intergalactic hydrogen body have been so far unsuccessful. One of the more promising explanations (Hoffman *et al.* 1998) associated one of the Ly- α lines with a dwarf irregular galaxy (MCG+00-32-16) rather distant from the line of sight to 3C273 ($\sim 200 \text{ kpc}$, for a VC distance of 18 Mpc); if this is a typical DIG, then the HI envelopes of such galaxies may

extend to a large fraction of a Mpc. One should then wonder about the mere existence and long-term stability of such extended halos in the gravitational environment of the VC.

It is not clear what role, if any, do the HI companions play in the development of a DIG. In a number of cases, notably the two galaxies with the lowest known metal abundance I Zw 18 (Dufour *et al.* 1996) and SBS0335-052 (Melnick *et al.* 1992), two optical entities are distinguished which may be two separate and interacting galaxies, or may be understood as two parts of the same system. In the case of I Zw 18 the different stellar concentrations of the galaxy have somewhat different stellar histories (Hunter & Thronson 1995). In SBS0335-052 two small galaxies share the same surrounding HI cloud (Pustilnik *et al.* 1997). It is interesting that the major axis of this cloud points in the same direction as the major axes of the two dwarf galaxies, and all three axes point back to a large spiral, which is ~ 150 kpc away and has a similar redshift. A similar double structure is seen in HI1225+01, where one lobe harbors a star-forming DIG. The three objects, although not forming a statistically significant sample, indicate that some sort of interaction may be triggering the SF process in DIGs.

4. Puzzling questions

The consideration of DIGs in the context of their contribution to the IGM leaves a number of puzzling questions. We shall not discuss all, but will single out three, related to the nature of the DM, the mechanism triggering the SF, and their connection with an alternate theory of gravity.

Searches for HI not associated with luminous material have, so far, been rather unsuccessful, except in the neighborhoods of luminous galaxies. On the other hand, there are indications that the Universe contains more matter than it is actually observed; this is the dark matter which provides part of the binding force of galaxies and clusters of galaxies. Until now, no fully suitable explanation of the nature of dark matter has been proposed. As mentioned above, LSBs, and in particular dwarf LSBs, may be DM-dominated at all radii. They may, therefore, be the best case studies for establishing the nature of the DM. One question which may be posed from a study of galaxies, in particular those of low surface brightness, is whether there are dark matter halos without (neutral) gas and devoid of stars. Such halos may provide seeds for the formation of future DGs. This question is linked to and may be constrained by lensing arguments; such DM halos would make ideal gravitational lenses, being \sim massive and \sim transparent.

O’Neil *et al.* (1998) proposed that SF is triggered by distant (soft) tidal encounters. This is similar to the mechanism of Icke (1985), and moreover the scenario proposed by O’Neil *et al.* (1998) seems to produce mainly spiral arms and inner ring density enhancements, not one-sided SF at the edge of a galaxy as shown in Brosch *et al.* (1998b). The morphology of SF can, therefore, constrain the evolution of galaxies. It is also possible to test the hypothesis of tidal triggers of SF with galaxies from Zaritsky *et al.* (1997). Their sample contains 115 satellite galaxies in 69 systems, where the primaries are large isolated spiral galaxies. Zaritsky *et al.* list for each satellite the (projected) distance from its primary and the presence or absence of emission lines in its spectrum. The presence of emission lines implies a recent SF event (because of the need for ionizing photons to produce these lines); we check this against the distance of the satellite from its primary. The expectation is that the closer a satellite is to its primary galaxy, the stronger the tidal force must be and the stronger should be its SF.

One should be careful in such comparisons because (a) strong and recurrent SF may deplete a nearby satellite of its ISM preventing further SF, although tides could still be strong, (b) the listed distances are only projections and an object which seems nearby may actually be more distant, and (c) there are significant numbers of satellites with no spectral indications. With all these caveats, we remark that the sample of Zaritsky *et al.* does not seem to show a link of the distance of a satellite from its primary. In particular, the fraction of satellites with emission lines among those within 200 kpc of their primaries (85%) is exactly the same as for the satellites

more distant than 200 kpc. I conclude that distant tidal interactions are not likely triggers of SF in DIGs.

Finally, LSB galaxies are apparently an excellent laboratory for testing gravity. An interesting proposal by Milgrom (1983) to explain the flat rotation curves of disks without invoking DM required a modification of the law of gravity. Briefly, the Modified Newtonian Dynamics (MOND) of Milgrom invokes a change in the long-range behavior of gravity: at accelerations much smaller than $10^{-11}g$ the force behaves as the inverse distance, not as the inverse distance squared. MOND remained a theoretical possibility until early this year McGaugh & de Blok (1998) showed that the best fit to the observable properties of LSB disks was with MOND, not with Newtonian gravity. Until now, no similar studies have been performed specifically for LSB DIGs. It is possible that in the MOND regime, which may be best tested in LSB DIGs, the SF may proceed in a different manner than in the Newtonian regime.

If there is truth in the assumption that there is some kind of link between gravity, mass, and light, and that galaxies form in the deeper potential wells of the Universe, then the intergalactic space, where gravity is weak, should be dominated by a MOND-like behavior of the gravity. Therefore, learning more about this theory, and in particular attempting to falsify it, should be high on the agenda of present-day astrophysics.

5. Conclusions

Dwarf galaxies form a natural link between “normal” large galaxies and the intergalactic matter. They are probably the building blocks out of which large galaxies, such as the Milky Way, are formed by numerous mergers and bursts of star formation. They form from material in the IG space and evolve independently, if not “harrassed” by interactions with other objects in a dense cluster of galaxies. Their evolution is probably providing the IGM with the metals now observed in the X-ray emission of rich clusters, but may also provide (part of) the Ly- α blanket of lines seen against background QSOs. Finally, the LSB dwarfs may prove observational tests of MOND.

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