

Local Group Dwarf Galaxies and the Star Formation Law at High Redshift

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ABSTRACT

I show how the existing observational data on Local Group dwarf galaxies can be used to estimate the average star formation law during the first 3 Gyr of the history of the universe. I find that the observational data are consistent with the orthodox Schmidt law with a star formation efficiency of about 4 percent if the star formation is continuous (during the first 3 Gyr). The efficiency is proportionally higher if most of the gas in the dwarfs was consumed (and never replenished) in a short time interval well before the universe turned 3 Gyr.

Subject headings: cosmology: theory - galaxies: formation - stars: formation

1. Introduction

Direct observational measurements of the star formation rate in the very first objects in the universe is exceptionally difficult, and even with the recent observational and technological advances, is well beyond reach. Nevertheless, it is possible to reconstruct the general features of the star formation at high redshift in much the same way as paleontologists reconstruct the prehistoric life from fossils.

In the currently widely accepted hierarchical clustering paradigm the characteristic mass scale of cosmological objects increases with time: low mass objects form first, and more massive objects form later. Thus, a considerable fraction of the dwarf galaxies may be very old, and may represent the fossils of the very first star formation in the universe. Although these dwarf galaxies are small and faint, and thus hard to observe, a vast amount of detailed information exists on the Local Group dwarf galaxies, as summarized in several recent reviews (Grebel 1998; Mateo 1998; van den Bergh 1999). The first two reviews are particularly useful for my purpose, as they contain the star formation histories of a large fraction of all Local Group dwarfs. A careful investigation of the available data reveals a striking feature common to the vast majority (more than 90%) of all dwarf galaxies with known star formation histories: a sharp decline in the star formation rate about 10 Gyr ago.

There are at least five possible explanations for such a feature in the star formation history. First, it may be attributed to the tidal effects from the Galaxy or Andromeda. However, in the hierarchically clustering universe neither the Galaxy nor Andromeda existed at that time

as entities, but rather as an interacting collection of proto-galactic clumps (see, for example, Contardo, Steinmetz, & Fritze-von Alvensleben 1998), and thus they were not able to have a large impact on the star formation histories of *almost all* dwarf galaxies.

A second possible explanation is the effect of supernovae, which could have expelled the gas from the low potential wells and quenched the star formation rate. However, it is hard to believe that the supernova activity was so well synchronized in 90% of all dwarf galaxies as to expel the gas almost simultaneously (this is elaborated further in the Conclusions).

Since the drops in the star formation rates in dwarf galaxies are essentially simultaneous, it is plausible that this was triggered by a process that affected the whole universe. One such process is reionization. It is well established that photoheating of the intergalactic medium during cosmological reionization sharply reduces the gas fractions in the low mass objects (Thoul & Weinberg 1996; Quinn, Katz, & Efstathiou 1996; Weinberg, Hernquist, & Katz 1997; Navarro & Steinmetz 1997; Gnedin 2000). This, in turn, will lead to the drop in the star formation rates in dwarf galaxies, including the Local Group dwarfs. This proposal however encounters a difficulty because an age of 10 Gyr corresponds to about $z = 2$ (in a 13 Gyr old universe with $h\Omega_0^{1/2} = 0.4$), which is too late for cosmological reionization. However, if the drop in the star formation rate in dwarf galaxies occurred some twelve billion years ago, the reionization explanation could work. This requires that the measured stellar ages are off by about 2 Gyr, but the question of whether this is plausible or not is outside the scope of this paper.

The fourth explanation is based on the observational evidence (which is admittedly not completely compelling) that the universe experienced a second epoch of reheating at about $z = 3$ (Ricotti, Gnedin, & Shull 2000; Schaye et al. 2000). This second reheating (plausibly attributed to the reionization of helium) has a similar effect on dwarf galaxies as hydrogen reionization at $z \sim 7 - 10$, except that it takes place somewhere between $z = 2$ and $z = 3$.

It is also possible that photoionization associated with the burst of star formation that made the bulges of the Galaxy and Andromeda (“local reionization”) inhibited the star formation in the surrounding dwarfs (van den Bergh 1994). While possible in principle, it is not clear whether this explanation is plausible within the hierarchical clustering paradigm, or whether it agrees with the observed metallicity distribution of the Galactic bulge (McWilliam & Rich 1994).

Whatever the explanation of the observed simultaneous drop in the star formation rate in 90% of Local Group dwarfs is, it is not essential to the measurement described in this paper. The only thing that matters is that there exists a subset of the Local Group dwarfs that had little star formation in the last 10 Gyr, so that their stellar content provides a fossil record of the early universe.

Table 1. Local Group Dwarfs Used in this Analysis

Galaxy	R_{10}^a	$\log(L_V/(I_c r_c^3))^b$	$\log(I_c \text{pc}^3/L_\odot)^{b,c}$	$f_{>10}^d$
NGC 3109	0.2-0.5 ^e	1.55 ± 0.23	$-1.75 \pm 0.20(0.33)$	0.7-0.5 ^e
NGC 205	0.2	1.69 ± 0.27	$-0.37 \pm 0.20(0.25)$	0.8
NGC 147	0.3	1.84 ± 0.15	$-0.41 \pm 0.12(0.17)$	0.7
Ursa Minor	0-0.2 ^e	0.78 ± 0.26	$-2.22 \pm 0.21(0.23)$	0.9
Sextans	0.1	0.82 ± 0.24	$-2.70 \pm 0.21(0.28)$	0.8-0.7 ^e
Antlia	0-0.2 ^e	0.95 ± 0.12	$-1.80 \pm 0.10(0.12)$	0.9
Sculptor	0.1	1.47 ± 0.20	$-1.26 \pm 0.17(0.19)$	0.9
And I	0-0.1 ^e	1.00 ± 0.12	$-2.05 \pm 0.10(0.11)$	0.9
And II	0.2	1.21 ± 0.12	$-1.77 \pm 0.23(0.25)$	0.9
And III	0-0.1 ^e	1.03 ± 0.14	$-1.75 \pm 0.10(0.11)$	0.9

^aThe ratio of the star formation rate just after the drop at 10 ± 1 Gyr ago to the star formation rate just before the drop. Estimated from Fig. 8 of Mateo (1998) or Fig. 5-6 of Grebel (1998). This column is shown for illustration only, and is not used in the analysis.

^bThe data are taken from Tables 2-4 of Mateo (1998).

^cThe errors in parenthesis are corrected by a factor of and outside of parenthesis are uncorrected.

^dThe fraction of all stars formed more than 10 Gyr ago. Estimated from Fig. 8 of Mateo (1998) or Fig. 5-6 of Grebel (1998).

^eThe first number is from Mateo (1998) and the second one is from Grebel (1998); for $f_{>10}$ the arithmetic mean is used in the analysis.

2. Results

Because the star formation histories of the Local Group dwarfs are quite diverse, only a subset of all galaxies can be used, namely those that have a large fraction of their stars formed more than 10 Gyr ago. This limits the available sample to seventeen out of thirty two shown in Fig. 8 of Mateo (1998) and Fig. 5-6 of Grebel (1998). Out of a total of seventeen, seven (Fornax, Sextans B, NGC 185, Phoenix, GR 8, Draco, and Tucana) either have some of the essential data missing or Mateo (1998), Grebel (1998) and Hernandez, Gilmore, & Valls-Gabaud (2000) strongly disagree on their star formation histories, so only the ten listed in Table 1 are used in the present analysis. The other seven can be added to this analysis when the missing or disagreed upon data become available.

According to the Schmidt law, on sufficiently large scales the star formation rate can be

parametrized as a power-law of the gas density,

$$\frac{d\rho_*}{dt} \propto \rho_g^n, \quad (1)$$

where ρ_* is the mass density of stars, and ρ_g is the mass density of gas. Integrating equation (1) over the total volume of a galaxy and time, and assuming that the mass-to-light ratio is independent of radius, I can obtain the following equation connecting the total luminosity of a galaxy at some moment t_f with the total baryon core density $\rho_{b,c}$ at the same time,

$$L_* \propto \Delta t_{\text{eff}} \rho_{b,c}^n r_c^3 4\pi \int_0^\infty \left(\frac{\rho_b}{\rho_{b,c}} \right)^n \left(\frac{r}{r_c} \right)^2 \frac{dr}{r_c}, \quad (2)$$

where L_* is the luminosity of a dwarf galaxy, r_c is the core radius, and Δt_{eff} is the effective time interval, $\Delta t_{\text{eff}} \equiv \int_0^{t_f} \int \rho_g^n dV dt / \int \rho_b^n(t_f) dV$, which incorporates all the details of the increase (due to infall) and decrease (due to consumption by star formation) of the gas.

It is important that I use the core baryon density rather than core gas density. The gas in the center can be almost entirely consumed, whereas the baryon density will likely stay the same (unless there is diffusion of stars from the center outward).

If all dwarf galaxies are structurally similar (which means that the integral in eq. [2] is the same for all dwarfs), and in the core almost all the gas is transformed into stars ($\rho_{b,c} \approx \rho_{*,c}$, this assumption is addressed below), then equation (2) reduces to the power-law dependence between the total luminosity of a galaxy and its central luminosity density I_c ,

$$L_*/r_c^3 \propto I_c^n \quad (3)$$

at $t = t_f$. However, this equation also holds at the present time if the star formation at later times ($t > t_f$) is negligible or can be corrected for.

It is important to point out here, that it is the luminosity density (i.e. the stellar mass density) and not the total mass density that matters. The dark matter density in the Local Group dwarfs varies enormously and is not correlated to the stellar density, as can be easily seen from the total mass-to-light ratios (Table 4 of Mateo 1998). Since the galaxies included in Table 1 formed most of their stars more than 10 Gyr ago, it can be presumed that the observed core luminosity densities of the dwarfs are representative of the core luminosity densities at $t_f \approx 3$ Gyr. This cannot be said about the dark matter, however. In the last 5 Gyr or so the Local Group dwarfs inhabited a region with the mean density about hundred times higher than the mean density of the universe, and therefore they had enough opportunities to accrete large quantities of dark matter. Thus, their dark matter contents is representative of their whole evolutionary history, and not of only the first 3 Gyr of their life.

The data from Table 1 can be used to investigate the relationship (3) in the Local Group dwarfs. It is natural to take t_f as the time 10 Gyr ago, corresponding to the sharp drop in the star formation rate in all galaxies in Table 1. For a 13 Gyr old universe this would imply $t_f = 3$ Gyr.

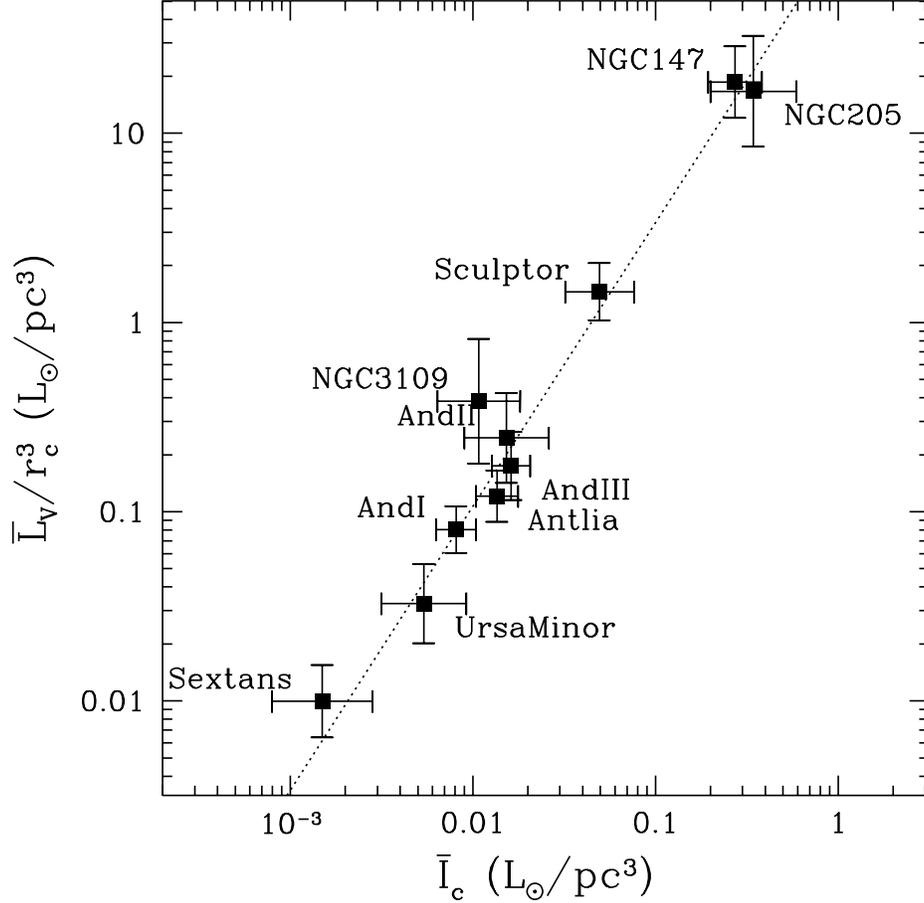


Fig. 1.— The corrected V-band luminosity per cube of the core radius versus the central luminosity density for the Local Group dwarfs from Table 1. The dotted line shows the power-law fit with the slope fixed to 3/2.

However, even if the galaxies in Table 1 formed most of their stars more than 10 Gyr ago, they still had additional star formation at later times. These “recent” stars need to be excluded from the analysis. It is straightforward to estimate the fraction $f_{>10}$ of all stars formed more than 10 Gyr ago, from Fig. 8 of Mateo (1998) and Fig. 5-6 of Grebel (1998). The quantity $f_{>10}$ is listed in the last column of Table 1. Thus, instead of L_* and I_c from equation 3, I use $\bar{L}_* = L_* f_{>10}$ and $\bar{I}_c = I_c f_{>10}$ instead. Figure 1 shows the relationship (3) for the data from Table 1 together with a power-law fit with the slope $n = 3/2$.

However, Fig. 1 is a bad way to represent the data because the errors along the two axes are not independent - both quantities include the large errors due to uncertainties in the distances and the core radii. It is better to represent the relationship (3) as

$$y \equiv \frac{L_*}{I_c r_c^3} \propto I_c^{n-1}. \quad (4)$$

In this form the left hand side is dimensionless, and thus independent of the distance, whereas the errors on I_c are dominated by the error in the distance, because the central luminosity density is inversely proportional to the distance cubed. In this form the errors on y and I_c are not strongly correlated, and I can measure the statistical significance of the correlation between the two quantities in equation (4).

Given the the errors on the observed quantities: the relative photometric error δV in the total luminosity, the relative error in the measured angular core radius δr_c , the relative distance error δD , and the relative photometric error in the observed central surface brightness $\delta \Sigma_c$, the errors on y and I_c are calculated as $\delta y^2 = \delta V^2 + 4\delta r_c^2 + \delta \Sigma_c^2$, and $\delta I_c^2 = \delta \Sigma_c^2 + \delta r_c^2 + 9\delta D^2$.

However, my correction to the total luminosity and the central luminosity density is, admittedly, uncertain, because the star formation histories are not known too accurately, and thus the quantity $f_{>10}$ is somewhat uncertain as well. To account for this uncertainty, I increase the errors on \bar{I}_c a factor of $1/f_{>10}$, in which case the contribution of dwarfs with a large correction to the total χ^2 is reduced by a factor of $f_{>10}^2$.

The best power-law fit to the data listed in Table 1 is given by the following formula:

$$\frac{\bar{L}_V}{r_c^3} = 10^{1.19 \pm 0.06} \bar{I}_c \left(\frac{\bar{I}_c}{0.02 L_\odot / \text{pc}^3} \right)^{0.54 \pm 0.11}. \quad (5)$$

In this form the errors on the amplitude and the slope are uncorrelated. If, instead, I use uncorrected errors, the reduction of the fit error is minor: the power-law index is 0.52 ± 0.10 , and the logarithm of the amplitude is 1.20 ± 0.06 , which demonstrates that my correction procedure is not too important. I can also fit the original data, without correcting the total luminosity and the central luminosity density by a factor $f_{>10}$. In the latter case I obtain an equally good fit: the power-law index is 0.51 ± 0.10 , and the logarithm of the amplitude is 1.16 ± 0.06 . The reason why the original data work equally well is that the fit is dominated by the data points with the smallest error-bars, and those also have the smallest correction. Whether this is a mere coincidence, or has a physical meaning, can only be speculated at the moment.

All three fits are highly significant statistically, which indicates that the error bars are not underestimated.

The result (5) is non-trivial. It shows that the *average* luminosity density of dwarf galaxies was proportional to the 3/2 power of their *central* luminosity density in the first 3 Gyr. The central luminosity density, as I argue below, is representative of their original gas density, since the star formation at the center is efficient enough to be able to convert all their gas into stars. The average luminosity density (i.e. the total luminosity) of the dwarfs is however dominated by the outer regions (as can be seen from Table 1 since $y \gg 1$). In the outer regions the star formation is inefficient, and thus the total luminosity is proportional to the gas density (and thus the central luminosity density) to the 3/2 power (or about that), and not to the central luminosity density to the first power, which would be the case if the star formation was efficient everywhere and all the

gas in the dwarfs was converted into stars.

It is remarkable that the observed slope is so close to the orthodox Schmidt law power-law index of 3/2. Therefore, it is worthwhile to investigate this special case in more detail. The star formation rate in this case can be rewritten in the following form, fixing the coefficient of proportionality in the Schmidt law:

$$\frac{d\rho_*}{dt} = \epsilon \frac{\rho_g}{t_{\text{dyn}}}, \quad (6)$$

where a dimensionless quantity ϵ measures the efficiency of star formation, and the dynamical time t_{dyn} is defined as in Binney & Tremaine (1987), $t_{\text{dyn}} \equiv (3\pi/[16G\rho_g])^{1/2}$. Note, that I *define* the dynamical time as depending on the gas density, and not on the total density. If one desires to define the dynamical time in terms of the total density, ϵ simply needs to be decreased by a factor of $(\Omega_0/\Omega_b)^{1/2}$.

Integrating equation (6) over time and space, and again invoking Δt_{eff} to hide the consumption or infall of gas, I obtain the following relationship between the total luminosity of a galaxy and the core baryon density:

$$L_* = 3.37 \times 10^{-4} \text{ cm}^{3/2} \text{ g}^{-1/2} \text{ s}^{-1} 4\pi \Upsilon^{-1} \Delta t_{\text{eff}} \epsilon \rho_{b,c}^{3/2} r_c^3 C_{3/2}, \quad (7)$$

where Υ is the mass-to-light ratio, and $C_n \equiv \int_0^\infty (\rho_b/\rho_{b,c})^n r^2 dr/r_c^3$. For the King model with the concentration parameter 2.5, $C_{3/2} = 0.6$. Since, as I argue below, the central luminosity density in the dwarfs is representative of the central baryon density (i.e. almost all of the gas is consumed at the center), the King profile is a good approximation to the total baryon density profile near the center. The Navarro, Frenk, & White (1997) density profile, motivated by cosmological simulations, also gives $C_{3/2} = 0.6$, which indicates that this number is not very sensitive to the details of the density profile.

Finally, I can relate the core baryon density to the core luminosity density by $\rho_{b,c} = \Upsilon I_c/f_*$, where f_* is the fraction of baryons turned into stars at the center.

Comparing equation (5) taken with the power-law index 3/2 with equation (7), I obtain the expression for the value of the star formation efficiency ϵ :

$$\epsilon = 0.040 \times 10^{\pm 0.06} \Delta t_2^{-1} \Upsilon_4^{-1/2} f_*^{3/2}, \quad (8)$$

where $\Delta t_2 = \Delta t_{\text{eff}}/2 \text{ Gyr}$, and $\Upsilon_4 = \Upsilon/(4M_\odot/L_\odot)$.

Using equations (6) and (8), I can obtain the following expression for the star formation time $\tau_{*,c} \equiv \rho_{*,c}/(d\rho_{*,c}/dt)$ at the center of a dwarf galaxy:

$$\tau_{*,c} = 1.5 \times 10^9 \text{ Gyr} \Delta t_2 I_2^{-1/2} (1 - f_*)^{-3/2},$$

where $I_2 \equiv I_c/(0.01L_\odot/\text{pc}^3)$. Thus, for all dwarfs with $I_c \gtrsim 2 \times 10^{-2} L_\odot/\text{pc}^3$ (which are all galaxies listed in Table 1 with the exception of the Sextans and Ursa Minor dwarf spheroidals)

$\tau_{*,c} \lesssim t_f$ until most of the gas is consumed and f_* becomes close to unity (an average 1σ error on I_c corresponds to about 40% error on f_* , so $f_* = 0.6$ and $f_* = 1$ cannot be distinguished on the basis of the current data). Thus, assuming $f_* = 1$ (which is certainly true for the most dense dwarfs with $I_c \gg 2 \times 10^{-2} L_\odot / \text{pc}^3$), I obtain the final expression for the average efficiency of star formation in the first 3 Gyr:

$$\epsilon \Delta t_2 = 0.040 \times 10^{\pm 0.06} \Upsilon_4^{-1/2}. \quad (9)$$

While Υ_4 is unlikely to be different from unity, the last remaining factor Δt_2 is less certain. It cannot be larger than 1.5, since the gas density cannot exceed the total baryon density. In particular, $\epsilon > 0.022 \Upsilon_4^{-1/2}$ at 3σ . However, Δt_2 can be much smaller than 1 (giving $\epsilon \gg 0.04$) if most of the gas in the dwarfs was consumed (and never replenished) in a short time interval well before the universe turned 3 Gyr (it is not clear whether the existing data rule out such a scenario).

3. Conclusions

I use a sample of Local Group dwarf galaxies selected by the criterion that they form most of their stars more than about 10 Gyr ago to measure the star formation law in the first 3 Gyr of the life of the universe (assuming the age of the universe is 13 Gyr). I find that the star formation rate on scales comparable to the sizes of dwarf galaxies (100 – 600 pc) is a power-law function of the gas density, with the power-law index 1.54 ± 0.11 . If the index is fixed at $n = 3/2$, the star formation rate is given by equations(6) with an efficiency of about 4% if the gas is consumed continuously. The efficiency cannot be smaller than 2.2% but can be higher if the gas was consumed well before the universe turned 3 Gyr.

The efficiency is not a strong function of scale for scales in the range from about 100 to 600 parsecs (if it were, the straight power-law would not be a good fit in Fig. 1).

Admittedly, the time of the drop in the star formation rate in the Local Group dwarfs is not very well determined, and is, perhaps, uncertain to about one or two billion years. Thus, the “simultaneous” drop in star formation rates in the majority of the dwarfs is perhaps not sufficiently simultaneous to preclude the possibility that it was supernova driven winds rather than reheating of the universe (or local reionization), which was responsible for the observed drop. However, in this case it would be difficult to explain the observed correlation, since the central regions of the dwarfs galaxies can be expected to be affected most by the supernova activity, thus spoiling the beautiful correlation shown in Fig. 1. Therefore, the present result indicates that the supernova driven winds play only a modest role in the early evolution of low-mass galaxies.

Curiously, equation 4) can be used, in principle, as a novel distance indicator, since only the x -axis depends on the distance. However, it is likely to not be competitive with other indicators given the amount of information needed to measure \bar{L}_V and \bar{I}_c .

The result presented here can be incorrect if the structural form of the Local Group dwarfs changes monotonically with their luminosity as to mimic the observed relationship (5). I would like to emphasize that, while this possibility cannot be completely excluded, there is currently no observational evidence that supports it, and this assumption also contradicts the modern theoretical view on the structure of galaxies.

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