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ON THE POSSIBILITY OF GAS-RICH DWARF GALAXIES IN THE LYMAN-ALPHA FOREST

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ABSTRACT

We show that the $N(z)$ for high column density absorbers in the Lyman-α forest is consistent with the increasing luminosity function for dwarf galaxies inferred from the simulations published by Tyson and Scalo in 1988.

Subject headings: galaxies: general — galaxies: intergalactic medium

I. INTRODUCTION

The spectra of QSOs have been known for some time to contain a "forest" of Lyman-α absorption lines blueward of the QSOs' Lyman-α emission. This population of lines is generally considered to be intergalactic in origin (e.g., Sargent *et al.* 1980) and is produced at various redshifts along the lines of sight to the QSOs. Most of the lines in this forest are from low column density absorbers ($N_{\rm H\,I} \approx 10^{14}$ cm^{-2}) while a small fraction of the lines (<1%) come from high column density systems ($N_{\rm H\,I} \geq 10^{20}$ cm^{-2}; Wolfe *et al.* 1986) in which the lines have been broadened by radiation damping.

While the low column density systems have been labeled "clouds," the high column density systems are legitimate galaxy candidates yet they have no numerical correspondence to cataloged objects. Curiously, in spite of their relative paucity, these high column density systems appear 5 times too frequently in the QSO line of sight to be explained by the observed number density and/or H I sizes of "normal" gas-rich galaxies. Scenarios have been proposed (e.g., Wolfe 1986; Schiano, Wolfe, and Chiang 1987) that allow a spherical protogalaxy to collapse and form an extended H I disk at early epochs. This, of course, will increase the likelihood that they will appear in a QSOs' line-of-sight. These large disks subsequently contract in their plane to form the spiral galaxies we see today.

In this *Letter* a rather different view is taken: that these high column density absorbers are low surface brightness, gas-rich, high space density dwarf galaxies that appear in the line of sight thus lending the impression that spiral galaxies must have been enormous in early epochs.

II. THE DWARF GALAXY SPACE DENSITY

If H I–rich dwarf galaxies undergo episodes of star formation bursts, then it is likely that a large fraction of these galaxies remain undetected due to observational selection effects. In a recent attempt to estimate this unobserved fraction, Tyson and Scalo (1988) simulated an episodically bursting population of dwarf galaxies using the stochastic self-propagating star-formation models of Gerola, Seiden, and Schulman (1980) (also Seiden 1983, 1986). Tyson and Scalo found that the observed turnover in the luminosity function for dwarf irregular galaxies is consistent with an increasing luminosity function that has been subjected to a limiting magnitude, surface brightness, and angular size (see Fig. 1). We may obtain a quantitative appreciation for this turnover by noting that for galaxies smaller than $r \approx 0.5$ kpc, the expected duty cycle (Gerola, Seiden, and Schulman 1980) will have star formation (in the form of a burst) that occurs for less than 2% of their life. These galaxies, when farther than about 2 Mpc, will be severely undercounted because their angular size falls below the limits inferred from the cataloged galaxies. The maximum distance of the sample volume used in Tyson and Scalo (1988) extends to 23 Mpc so only about $(2/23)^3 \approx 1/1500$ of the galaxies will be recorded. The product of 2/100 and 1/500 yields a net detection rate of about 1 in 10^5 which is approximately what is found when going from histogram A to histogram D in the low-luminosity side of Figure 1. If it is true that the luminosity function *increases*, then we are likely to detect a subset of these galaxies along the line of sight to QSOs.

In order to verify this possibility, the average space density and the radius distribution of gas-rich dwarf galaxies needs to be known.

Each of these were estimated in Tyson and Scalo (1988) by comparing the luminosity and size distributions of visible dwarf irregulars with a set of simulated observations of a bursting population of galaxies on which selection effects corresponding to the real observations had been imposed. They found a radius frequency function of the form: $f(r) = K(r/{\rm kpc})^{\gamma}$, where $\gamma = -4.2 \pm 0.2$ and $K = 3$ Mpc^{-3}.

Wolfe (1986) finds an average of $N_{\rm abs} \approx 0.25 \pm 0.06$ line of sight high column density ($N_{\rm H\,I} \geq 2 \times 10^{20}$ cm^{-2}) absorbers per unit redshift. His data are also consistent with no redshift evolution. For our calculations we have taken the H I extent of each dwarf to be the radius where $N_{\rm H\,I} \approx 5 \times 10^{20}$ cm^{-2}. Gallagher and Hunter (1984) have suggested this value as a critical column density for star formation. We expect this threshold to coincide roughly with the "$r_{26.5}$" radii of our models (the radius of the 26.5 mag arcsec^{-2} isophotal surface brightness) based on the data given in Huchtmeier, Seiradakis, and Materne (1981) and Skillman and Bothun (1986). We then converted the $r_{26.5}$ to radii that are more appropriate for the high column density absorbers found in Wolfe *et al.* (1986). The work of Wevers (1984) and Skillman, Terlevich, and van Woerden (1985) suggest $r_{\rm abs} \approx \nu r_{26.5}$, where $\nu = 1.2$. In what follows we assume that the systems selected by Wolfe *et al.* (1986) are indeed dwarfs viewed within this radius.

We do not know, *a priori*, the *true* lower limit for galaxy radii—if one indeed exists. For the Tyson and Scalo (1988) model, a lower radius limit of $r_L = 0.1$ kpc was arbitrarily selected. The simulated observations demonstrated that no galaxy smaller than $r \approx 0.4$ kpc was "detected." This is reflected in luminosity by comparing histogram A with histogram D in Figure 1. For the present analysis, however, we do not pre-

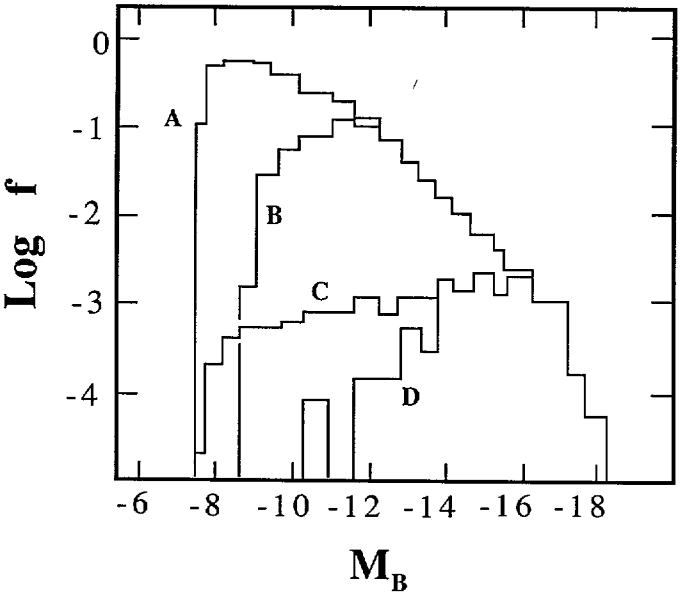

FIG. 1.—The simulated luminosity function for field dwarf galaxies showing the results of various selection effects: (A) No selection effects; (B) only the surface brightness limit imposed; (C) only the angular diameter limit imposed; (D) both surface brightness and angular diameter limit imposed. The cutoff at $M_B \approx -7$ for distribution A is a computing convenience which has no effect on distribution D (from Tyson and Scalo 1988).

suppose a lower limit. Analytically, the number of dwarfs per unit redshift is very sensitive to this lower limit and is only mildly sensitive to the cosmological deceleration parameter, q_0. The expression for the number of line-of-sight absorbers as a function of redshift z, with $\Lambda = 0$, is (cf. Sargent *et al.* 1980)

$$N_{\rm abs}(z) = (\pi c/H_0)n[\textstyle\int (vr)^{\gamma+2}\,dr/\int (vr)^{\gamma}\,dr] \times (1+z)/(1+2q_0 z)^{1/2}\,, \quad (1)$$

where r is the H I radius (out to column density $\approx 5 \times 10^{20}$ cm^{-2}), n is the galaxy number density (computed from the frequency distribution once a lower radius limit is selected), and v is the column density conversion factor for the radius. Following Tytler (1982, 1987) we introduce a coordinate change to remove the redshift dependence in the system density:

$$X = \tfrac{1}{2}[(1+z)^2 - 1]\,; \qquad q_0 = 0\,, \quad (2a)$$

$$X = 1/(3q_0)[(1+2q_0 z)^{3/2} - 1]\,; \quad q_0 > 0\,. \quad (2b)$$

The radial coordinate, X, we define as the "absorption distance." It has been constructed so that systems with constant comoving space density and constant proper sizes have a constant density per unit X along the line of sight. The observed $N_{\rm abs}(z) = 0.25$ (Wolfe *et al.* 1986; Wolfe 1986) now becomes $L_{\rm abs}(X) = 0.11$ for $q_0 = 0$, and $L_{\rm abs}(X) = 0.17$ for $q_0 = \frac{1}{2}$. Equation (1) now takes the form:

$$L_{\rm abs}(X) = (\pi c/H_0)nv^2\left[\int (r)^{\gamma+2}\,dr \Big/ \int (r)^{\gamma}\,dr\right]. \quad (3)$$

Adopting $v = 1.2$, and $H_0 = 100$ km s^{-1} Mpc^{-1}, we find that a value of $r_L = 200$ pc is required to obtain $L_{\rm abs} = 0.17$ with $q_0 = \frac{1}{2}$, while a value of $r_L = 500$ pc is required to obtain $L_{\rm abs} = 0.11$ with $q_0 = 0$. Both these values use $\gamma = -4.2$ from the best-fit simulation in Tyson and Scalo (1988). In Figure 2, $L_{\rm abs}(X)$ is plotted for $v = 1$, 1.2, 2, and 5.

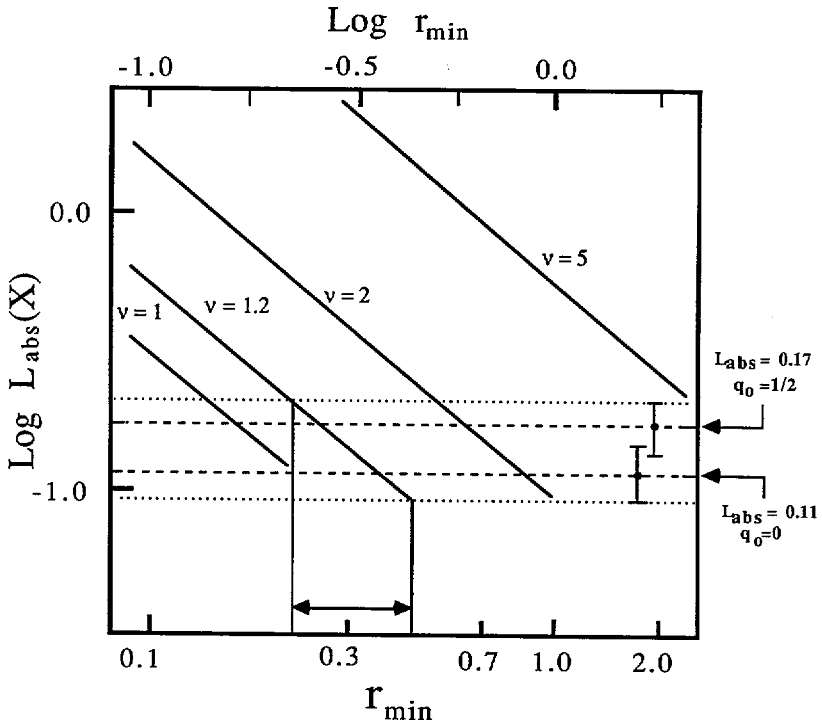

FIG. 2.—The number of dwarf galaxies per unit "absorption distance" (see text) is plotted as a function of minimum radius cutoff (kpc) in the radius distribution. If we convert the observed value of $N_{\rm abs}(z)$ as given by Wolfe (1986) to $L_{\rm abs}(X)$, we get $L_{\rm abs} = 0.11$ for $q_0 = 0$, and $L_{\rm abs} = 0.17$ for $q_0 = \frac{1}{2}$. These values, along with their errors, are indicated. For $v = 1.2$ the lower radius cutoff lands in the range $0.2 < r_{\rm min} < 0.5$ kpc. Some of the smallest known dwarf galaxies also lie in this range such as II Zw 40 and DDO 155.

There is evidence that some gas-rich galaxies have H I envelopes that extend 5–10 optical radii (see, e.g., Hunter and Gallagher 1981 and references therein). Many of these envelopes, however, were measured out to $n_{\rm H\,I} \approx 10^{19}$ cm^{-2}, while the Wolfe *et al.* (1986) data do not include $n_{\rm H\,I} < 2 \times 10^{20}$ cm^{-2}. If we have underestimated the H I extent of these dwarf galaxies, then in the context of the model it cannot be by very much. For example, if $v = 5$ then $r_{\rm min} \approx 2$ kpc (see Fig. 2). These galaxies (now with an H I diameter ≈ 20 kpc) would have been detected easily in the Lo and Sargent (1979) H I cloud search of the M81 group.

If $v = 2$ then, quite reasonably, the limits of the acceptable range for the lower radius limit are: $0.5 < r_{\rm min} < 1.0$ kpc. The radius limits for $v = 1.2$, however, are consistent with the smallest known low surface brightness galaxies in the Local Group (Longmore *et al.* 1978), and the sizes of some high surface brightness dwarfs, such as II Zw 40: $r \approx 0.5$ kpc; Haro 4: $r \approx 0.4$ kpc; and DDO 155: $r \approx 0.3$ kpc (Thuan and Martin 1981 and references therein). While there are likely to be galaxies that are even smaller, we do not expect the radius distribution to continue increasing below $r \approx 0.2$ kpc unless "galaxies" smaller than this have lower H I column densities.

The typical simulated absorbing dwarf has a surface brightness between 24 and 28 mag arcsec^{-2} which is consistent with the upper limit of 23.5 mag arcsec^{-2} quoted for the high column density Lyman-α absorbers in Foltz, Chaffee, and Weymann (1986) and in Smith, Cohen, and Burns (1987).

III. CONCLUSION

We find that the frequency distribution of dwarf galaxy radii inferred by Tyson and Scalo (1988) quite naturally accounts for the observed number of high column density absorbers in the Lyman-α forest without invoking extremely large H I diameters at early epochs and without interfering with the more securely established bright end of the luminosity function.

This problem was initially called to my attention by Greg Shields. I have benefited from discussions with John Scalo, James Felten, and Michael Disney. An anonymous referee provided comments that helped to clarify the presentation of several points in the *Letter*.

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