The Space Density of Galaxies Through $\mu_B(0) = 25.0$ mag arcsec^{-2}

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ABSTRACT

Using the catalog of O'Neil, Bothun, & Schombert (1999), we examine the central surface brightness distribution ($\phi(\mu_B(0))$) of galaxies in the 22.0 $\leq\mu_B(0)$ $\leq$25.0 mag arcsec^{-2} range. Taking advantage of having a catalog in which each galaxy has a known central surface brightness, scale length, and redshift, we apply a bi-variate volume correction to the data and extend the surface brightness distribution function by one magnitude, to 25.0 B mag arcsec^{-2}. The result is a flat (slope = 0) surface brightness distribution function from the Freeman value of 21.65 $\pm$ 0.30 to the survey limit of 25.0 mag arcsec^{-2}, more than 10σ away. This indicates that a significant percentage of the baryonic content of the universe can be contained in potentials only dimly lit by the embedded galaxy.

Subject headings: galaxies: luminosity function – galaxies: statistics – galaxies: low surface brightness

1. Introduction

Using the observed D/H ratio, nuclear cross-sections, and the hot big bang cosmological model, the predicted baryon density of the universe is

$$0.013 < \Omega_B \, h_{100}^2 < 0.019$$

(i.e. Walker, *et.al.* 1991; Weinberg, *et.al.* 1997; Burles & Tytler 1996, Rauch *et.al.* 1997). Estimating the known baryon mass density of the universe using $\Omega_B = \Omega_{E/S0} + \Omega_{Sp} + \Omega_{clusters} + \Omega_{groups}$, Persic and Salucci (1992) found $\Omega_B = 2.2 + 0.6 h_{100}^{-3/2}$ x 10^{-3}, showing that 70% – 80% of the predicted baryon mass does not exist in standard galaxy catalogs. There are three possible locations for these "missing "baryons: 1) a cosmological background (possibly ionized), 2)the hot gas component of galaxy groups/clusters 3) galaxies that are difficult to detect and therefore missing from current catalogs.

At high redshift it appears that most of the baryons are either contained in damped Lyα systems which are neutral (Storrie-Lombardi *et.al.* 1996) or the ionized Lyα forest. Modeling by Rauch *et.al.* (1997) (see also Rauch *et.al.* 1998) is consistent with the general notion that half of the baryons (e.g. hydrogen gas) are in the neutral phase and half are in the ionized phase that forms the Lyα forest. The critical issue now is the evolution of these structures and whether or not the abundance of this gas at high redshift can be reconciled with the abundance of galaxies at low redshift. The calculation of Persic and Salucci, which includes hot gas in galaxy clusters and groups, clearly shows that our baryon census falls well short of the BBNS mark. However, a new census performed by Fukugita *et.al.* (1998) suggests we are far closer to the BBNS estimate than previously thought. They argue that most of the baryons are in the form of a hot, intergalactic gas (see also Cen and Ostriker 1998). The relation of this component to the Lyα forest is unclear, but the implication of the Fukugita *et.al.* study is that most baryons are not contained in galactic potentials. If so, this may leave little room for a large population of uncatalogued galaxies.

In their review, Impey & Bothun (1997) summarize the last 10 years of effort to overcome the selection effects associated with the detectablity of intrinsically diffuse galaxies (e.g. galaxies of low surface brightness - LSB). This effort has established that a) LSB galaxies represent a different evolutionary path available to galaxies, b) that LSB galaxies can be found at all galactic mass scales, c) that some LSB galaxies likely formed relatively recently and d) that the space density of LSB galaxies is approximately 10^6 times higher than the extrapolation of the Freeman (1970) law predicts. The major unresolved issues, difficult to observationally determine are a) how low in central surface brightness do disks galaxies go and b) what's the overall space density of these objects. The latter point bears directly on the missing baryon issue and may tie into the evolution of the Lyα forest clouds if those structures have long cooling and collpase times. Indeed, Linder (1999) shows that its highly plausible that most of the Lyα absorbers are associated with LSB galaxies.

Previous studies (e.g. McGaugh Bothun, & Schombert 1995, Schwartzenberg *et.al.* 1995, McGaugh 1996, Dalcanton *et.al.* 1997) have shown that the space density of galaxies as a function of central surface brightness ($\mu_B(0)$) is either flat or slightly rising out to a limit of $\mu_B(0) \sim 23.5$ mag arcsec^{-2}. These results hold for disk galaxies (not dwarfs) of scale length larger than 1 kpc. Thus, there appears to be as many Freeman disks ($\mu_B(0) \sim 21.5$ mag arcsec^{-2}) as there are disks with $\mu_B(0)$ 2 mag fainter. Given this, Impey and Bothun (1997) speculate that if the M/L of LSB galaxies is higher than in HSB galaxies, as is indicated in most LSB galaxy studies (i.e. McGaugh & de Blok 1997) and if the faint end of the luminosity function has a slope of -1.6 – -1.8 (i.e. de Propris, *et.al.* 1995; Bothun, Impey, & Malin 1991) then the total contribution to the baryonic mass from galaxies is $\Omega_B\, h_{100}^2 = 0.014 - 0.020$, well within the above bounds. This assumes that the space density of LSB galaxies remains flat through $\mu_B(0) \sim 29$ mag arcsec^{-2}. The point of this letter is to use new survey data to extend the previous limits by ~ 1.5 magnitude in $\mu_B(0)$ to further probe whether or not the space density of LSB galaxies remains flat.

2. A New LSB Galaxy Sample

2.1. The Detectability of LSB Galaxies

Our ability to detect objects in the Universe has been likened to standing in a well-lit room in the middle of the night, and trying to look through the window to describe the garden 100 yards away. Although it may be possible to definitively say that the garden exists, and even describe some of the large, well-defined plants, coming up with a quantitative description of the fainter, or smaller, or more distant plants is an extremely difficult task. Moreover, of primary scientific interest is not the garden itself, but rather the evolutionary history of the plants that occupy it. With only this one view of the garden available to us, it would be extremely unlikely that our derived evolutionary history would be very accurate. The parallel between the garden and galaxy detection should be clear. In 1965 Arp attempted to quantify this limited view of the universe by defining a "band of visibility," outside of which we are unable to discern galaxies, due to either the galaxies small apparent size or optically diffuse nature. Arp's argument was later quantified by Disney (1976), showing that the visibility bias was rather severe.

Since Arp's work was published, the "band of visibility" has been significantly broadened through improvements in both instruments and detection techniques. As an example, the superb angular resolution of HST has allowed for the distinction between true stars and galaxies which appear star-like in lower resolution surveys (*e. g.* Lilly, *et.al.* 1995; Ellis, *et.al.* 1996; Cowie, *et.al.* 1996; Steidel, *et.al.* 1996; Abraham, *et.al.* 1996; Morris, *et.al.* 1999; O'Neil, Bothun, & Impey 1999). The fact that most of these newly resolved galaxies are very far away means that the local Universe is not filled up with little, dinky, high surface brightness (HSB) galaxies. On the other end of the spectrum, both improvements in detection techniques (i.e. Malin 1978; Schwartzenberg, *et.al.* 1995) and the advent of

CCD cameras as a tool in observing has allowed for the detection of increasingly diffuse (low signal-to-noise) stellar systems (*e. g.* Impey, Bothun, & Malin 1988; Davies, Phillipps, & Disney 1988; Dalcanton, *et.al.* 1997; Schombert & Bothun 1988; O'Neil, Bothun, & Cornell 1997; Matthews & Gallagher 1997). Indeed the recent detection of extremely low surface brightness (LSB) dwarf spheroidal galaxies around Andromeda by Armandroff, Davies, & Jacoby (1998) is consistent with the local Universe having a large population of low mass, nearly invisible galaxies. The Andromeda discovery underscores the severity of surface brightness selection effects. Where once the Milky Way stood alone in the Local Group as a unique host of 7 LSB dwarf spheroidals, we now have detected an apparently equivalent population around M31.

To establish the true space density of these newly discovered galaxies, we must make accurate corrections for the decreased probability of detecting a galaxy the closer it lies to the survey limits. The mathematical formalism of this correction has been extensively discussed in the literature (i.e. Disney 1976; Disney & Phillipps 1983; McGaugh 1996; de Jong 1996). When applied to the available data (i.e. McGaugh, Bothun, & Schombert 1995; de Jong 1996, Dalcanton *et.al.* 1997) these corrections yield the flat space density distribution discussed in Section I. We emphasize again that this distribution refers exclusively to *non-dwarf* galaxies; i.e. those objects with scale lengths larger than $\sim$ 1 kpc.

2.2. The OBS Sample

In this paper we use the sample of LSB galaxies in the O'Neil, Bothun and Schombert (1999) (OBS) catalog to determine the surface brightness distribution function from a $\mu_B(0)$ of 22.0 B mag arcsec^{-2} through 25.0 B mag arcsec^{-2} (the catalog limits). This sample has well defined survey limits and known $\mu_B(0)$, scale lengths, and redshifts, allowing for the use of a bi-variate correction for the survey selection. The OBS sample is comprised of 43 galaxies with 21-cm measured redshifts with 22.0 $\leq \mu_B(0) < 25.0$ mag arcsec^{-2} and with scale lengths ranging from 0.5 – 6.0 kpc (see Figure 1). The galaxies are located in the direction of the Pegasus Cluster, Cancer Cluster, and near various known galaxies lying in the region of the 'Great Wall' (i.e. Dell'Antonio, Geller, & Bothun 1996). As detailed in OBS the galaxies span a large range in color, size and circular velocity majority having characteristics similar to those of L* spirals. Thus this sample will allow for an accurate determination of the space density of galaxies with $\mu_B(0)$ in the range of 23.0 – 25.0 B mag arcsec^{-2} ; substantially fainter than previous studies.

3. The Volume Correction

As has often been discussed, detecting HSB galaxies within a survey is considerably easier than detecting low surface brightness (LSB) galaxies (i.e. Freeman 1970; Disney 1976; Disney & Phillipps 1983; McGaugh, Bothun, & Schombert 1995; Davies 1990; de Jong 1996; Bothun, Impey, & McGaugh 1997; Dalcanton *et.al.* 1997). Thus determining the true (underlying) surface brightness distribution of a sample of galaxies requires accounting for the probability of a galaxy being detected by a survey of a given design. For a field galaxy survey, the probability of detection is determined simply by the available volume which can be sampled for a galaxy of a given size and luminosity (e.g. its surface brightness). The volume corrected surface brightness distribution is thus

$$\phi(\mu_0) = \sum_{i=1}^{N} \frac{S^i}{V^i_{max}} \tag{1}$$

where i is summed over all N galaxies in the sample, S^i is 0 or 1 depending on whether a galaxy lies within the described volume, and $V_{max} = \frac{4\pi}{3} d^3_{max}$, the maximum volume in which a galaxy could be detected.

For a surface brightness limited sample (i.e. OBS) d_{max} can be found by requiring that the diameter of the galaxy be equal to, or greater than, the minimum detectable diameter ($\theta = 2r \geq \theta_l$). For a galaxy with an exponential surface brightness profile this gives:

$$\mu(r) = \mu_0 + 1.086\frac{r}{\alpha} \tag{2}$$

$$\theta = 2r = 1.84\,\alpha\,(\mu_l - \mu_0) \propto \frac{h}{d}(\mu_l - \mu_0) \tag{3}$$

$$d_{max}(\mu_0) \propto \frac{h}{\theta_l}(\mu_l - \mu_0)\,. \tag{4}$$

where $\mu(0)$ is the central surface brightness of the galaxy, α is its scale length in arcsecs, and h is its scale length in kilo-parsecs. Thus, for a surface brightness limited sample,

$$V_{max}(\mu_0) \propto \left(\frac{h}{\theta_l}\right)^3 (\mu_l - \mu_0)^3 \propto \left(\frac{\alpha\, d}{\theta_l}\right)^3 (\mu_l - \mu_0)^3\,. \tag{5}$$

4. The Surface Brightness Distribution, $\phi(\mu_0)$

Figure 2 shows the results of applying the correction given in equation 5 to the O'Neil, Bothun and Cornell (1997) data using the redshifts available in OBS. The limiting diameter was set to 25", and $\mu_l = 25.0$ mag arcsec^{-2}. This corresponds to an approximate minimum physical diameter of 3 kpc (so again, these are *non-dwarf* galaxies). For the OBS survey, the limiting central surface brightness was found through an extensive series of computer models, in which Monte-Carlo-type simulations of the images were created and searched for galaxies (O'Neil, Bothun, & Cornell 1997). As the true underlying galaxy distribution of the computer-generated images was known, the detection cut-off could be well determined. Thus, μ_l, and V$_{max}$ for the OBS catalog are also well determined.

Because the OBS sample is not uniformly distributed in space, but instead follows the same large scale structure as the HSB galaxies in the region (i.e. Figure 2 of OBS), performing a V/V_{max} test on the galaxies, and normalizing the distribution function to that (i.e. de Jong 1996) would be extremely difficult and possibly misleading at best. In practice, the OBS sample lies in a shell bounded by radial velocities of 4000 and 12000 km sec^{-1} . The data for this sample, as well as for the comparison samples, have therefore been normalized to one (Figure 2). Additionally, to insure against bias due to under sampling within a bin, the data from OBS was binned to 0.5 mag $arcsec^{-2}$. The errors bars for this data are simply $\sqrt{N}/N$. The low values for the surface brightness distribution between 22 – 23 mag $arcsec^{-2}$ are artificial, caused by the 22.0 B mag $arcsec^{-2}$ cut-off in the survey sample imposed in the OBS catalog. This was not corrected for. The total number of galaxies in each bin, then, is: $22.25 \leq \mu_B(0) < 22.75$, 6 galaxies; $22.75 \leq \mu_B(0)$ 23.25, 7 galaxies; $23.25 \leq \mu_B(0) < 23.75$, 18 galaxies; $23.75 \leq \mu_B(0) < 24.25$, 5 galaxies; $24.35 \leq \mu_B(0) < 24.75$, 5 galaxies; $24.75 \leq \mu_B(0)$, 1 galaxy. Although there is only one galaxy in the last bin ($24.75 \leq \mu_B(0)$), the fact that any galaxies were found so close to the survey cut-off is highly significant, as the probability of its detection is extremely low.

The data from this survey extends the faint end of the surface brightness distribution function in a horizontal line from 23.0 mag $arcsec^{-2}$ through 25.0 mag $arcsec^{-2}$, the survey cut-off, matching the predictions made by, *i. e.* McGaugh (1996) and Impey & Bothun (1997). A flat distribution here, however, does not imply that most of the luminosity density in the Universe is contained in LSB galaxies for the simple reason that at a given scale length, LSB galaxies are less luminous compared to HSB galaxies. Arguments given in McGaugh (1998) show that even for a flat space density of LSB disks, $\leq 30\%$ of the total extragalactic light is contained in that population.

Our flat space distribution does contradicts some of the data points of both de Jong (1996) and Davies (1990) in the 23.0 – 24.0 mag $arcsec^{-2}$ range, where their counts appear to dip downwards. The first, and most obvious, explanation for the discrepancy is that the volumetric corrections for one or more of these samples was done incorrectly, either due to mis-identifying the selection limits of the survey or through poor statistical sampling. The OBS sample is designed to look for galaxies above the 22.0 mag arcsec^{-2} range, and is therefore complete through 24.0 mag arcsec^{-2}, with the uncorrected data having a flat surface brightness distribution from 22.5 through 25.0 mag arcsec^{-2} (*i. e.* Figure 8 of O'Neil 1998) . Additionally, the surface brightness and diameter cut-off for the OBS sample was determined through computer modeling (O'Neil, Bothun, & Cornell 1997) and therefore is well determined. In contrast, the de Jong sample ranges in central surface brightness from approximately 20.0 mag arcsec^{-2} through 24.1 mag arcsec^{-2}, with the majority of the galaxies lying in the 21.0 – 22.0 mag arcsec^{-2} range. The volumetric corrections for the de Jong sample are concerned only with the diameter limit (θ_l) imposed on the survey and do not account for potential surface brightness selection effects, an omission which de Jong states could cause his survey to be undersampled at the faint $\mu(0)$, large scale length and/or small scale length, bright $\mu(0)$ ends of the spectrum. Combined with the survey's under-sampling in the $\mu(0) > 22.5$ mag arcsec^{-2} range, this could result in an artificial drop in the de Jong surface brightness distribution.

Like the de Jong (1996) sample, the Davies (1990) sample is concerned with the entire range of central surface brightnesses, but in this case the total number of galaxies involved in the survey should preclude any difficulties with under-sampling. The Davies sample was corrected for surface brightness selection effects, with a limiting central surface brightness $\mu_{lim}(0) = 25.6$ mag arcsec^{-2}, and θ_l=7". This low value for θ_l potentially mixed dwarfs and non-dwarfs together which could greatly confuse the situation. More importantly, no galaxies were actually detected near the defined survey limits. Thus it is entirely possible that the chosen sample limits simply do not accurately reflect the nature of the survey and thus are inappropriate in determining the volumetric correction. This could account for the apparent under-sampling in the 23.25 mag arcsec^{-2} bin compared to our data. Figure 3 show the results of changing the binning for the OBS sample, from bins of 1.0 mag arcsec^{-2} through bins of 0.3 mag arcsec^{-2}. The behavior of the surface brightness distribution as the data becomes undersampled imitates the behavior of the de Jong and Davies samples. It is therefore possible that, as both the de Jong and Davies samples are primarily HSB galaxy samples, they are relatively undersampled in LSB galaxies.

A final possibility is that the difference in the samples is a reflection of some true variance in surface brightness distributions, caused by environmental factors, within the local universe. That is, as only a (relatively) small spatial volume was examined for each survey we may be viewing local differences in the surface brightness distribution. If this is the case, the true surface brightness distribution of the local universe may lie somewhere between our sample and the de Jong and Davies samples. An all sky survey is needed to rectify this but it remains unclear, at this point, if the automatic image detection software of the Sloan Digital Sky Survey will in fact detect LSB galaxies on the first pass (Strauss 1998). While not an all sky survey, O'Neil, Bothun and Cornell (1997) did take care to sample a range of environments in order to minimize any possible variances caused by environmental factors.

At this point the importance of the chosen value for μ_{lim} should also be noted. Choosing a value which is fainter (or brighter) than the true survey limits will result in an artificial lowering (raising) of the surface brightness distribution slope at faint μ_0. This is not surprising as it simply is a statement that if a survey is believed to extend to, say, 26.0 mag arcsec^{-2} and yet detects no objects with $\mu_0 \geq 25.0$ mag arcsec^{-2}, it would be accurate to assume that a fall-off in galaxy number density at faint ($\mu_0 \geq 25.0$) surface brightness is occurring. The OBS sample is no exception to this rule. Were μ_{lim} reduced to 26.0, a slight decline in the slope of the surface brightness distribution function, beginning at 24.0 mag arcsec^{-2} would be evident. As μ_{lim} was carefully determined for the OBS sample, though, it should be an accurate representation of the survey's true limitations. With this, and the above, considerations in mind, it is likely the flat surface brightness distribution given by the OBS sample through 23.5 – 25.0 mag arcsec^{-2} is an accurate representation of the surface brightness distribution in the local (z<0.03) universe. The implication of such a flat distribution remains profound in terms of whether or not most of the baryons are located within a galaxy potential or are distributed in some cosmological background.

5. Conclusion

Using a bi-variate volume correction, we extend the surface brightness distribution function in a horizontal line from the Freeman value of 21.65 B mag arcsec^{-2} through 25.0 B mag arcsec^{-2}, the limit of the OBS catalog. This result is consistent with previous studies (e.g. McGaugh, Bothun, & Schombert 1995; Dalcanton *et.al.* 1997) but extends them to fainter surface brightness levels. Our result is somewhat inconsistent with the findings of two previous surveys in the 23.0 – 24.0 B mag arcsec^{-2} range (Davies 1990; de Jong 1996). However, our survey was designed specifically to detect galaxies in this surface brightness range and we have quite well defined survey limits (θ_l, mu_l). This leads us to have considerable confidence in our principle result that the space density of disk galaxies as a function of $\mu_B(0)$ remains flat out to values of $\mu_B(0)$ = 25.0 mag arcsec^{-2}.

The surface brightness distribution as predicted by Freeman's Law is $\mu_B(0) = 21.65 \pm 0.35$ mag arcsec^{-2}. We are thus 10σ fainter than this mean value and our data indicates an equal space density of galaxies at this level. For every galaxy with $\mu_B(0) = 21.65$ there is one with $\mu_B(0)$ = 22.0,23.5, and 25.0 mag arcsec^{-2} and each of these galaxies has similar circular velocities. Hence, the LSB galaxies are not preferentially less massive than their higher surface brightness counterparts (e.g. OBS, McGaugh and de Blok 1997, Schombert *et.al.* 1992). As a result, our data is highly consistent with the proposition put forth in

Impey and Bothun (1997) that much of the apparent missing baryon problem is resolved with a flat distribution of the space density of galaxies as a function of $\mu_B(0)$. That is, a lot of baryons are contained in potentials that host very diffuse and hard to detect galaxies. Whether the space density of LSB galaxies remains flat through $\mu_B(0) = 28.0$ mag arcsec^{-2} or falls off after $\mu_B(0)$ =26.0 mag arcsec^{-2} awaits deeper data to determine. Given the extant data, we would not venture a prediction on this important matter.

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FIGURES

Fig. 1.— The distribution of scale lengths (in kpc) for the galaxy sample in this paper.

Fig. 2.— The volume corrected surface brightness distribution function for all the galaxies in this and other surveys.

Fig. 3.— The effects of under-sampling the data in this survey. The circles, crosses, Xs, and squares result from binning the galaxies in 1.0, 0.5, 0.4, & 0.3 mag arcsec^{-2} bins, respectively.