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The Parameter Space Occupied by Galaxies: The optical window

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Abstract. We discuss the optical parameter space (luminosity and surface brightness) over which galaxies are known to exist and report on the results from three recent datasets: the Two-degree Field Galaxy Redshift Survey, the Hubble Deep Field north, and the Local Group. These data are combined to provide a unique and comprehensive insight into the luminosity distribution of galaxies over the range $-24 < M_B < -8$ mags, and the surface brightness distribution over the range $18 < \mu_e < 28$ mags/$\square''$. The main conclusions are: (1) luminous low surface brightness galaxies are rare; (2) there exists a universal luminosity-surface brightness relation; (3) the most numerous galaxies are low luminosity low surface brightness dwarfs.

1. Introduction

The study of galaxy formation and evolution cannot commence in earnest until we have a full and complete description of the local galaxy population - our benchmark if you will. Until we've fully defined the local "zoo of galaxies" and their relative abundances we can never be sure that any trend in redshift cannot be interpreted as "selection bias" rather than "evolution". So how close are we getting to a complete description ? Typically the galaxy population is quantified via the following observable parameters: luminosity, surface brightness, morphology and colour. These are in turn loosely associated with the fundamental properties of: mass, angular momentum, evolutionary history and age, respectively. In this article we review our current insight into the parameter space occupied by galaxies in terms of their luminosity and surface brightness distributions. We argue that in order to unambiguously remove the spectre of selection bias, the luminosity and surface brightness distributions must be considered simultaneously. This is borne out by three recent datasets: the Two-degree Field Galaxy Redshift Survey (2dFGRS), the Hubble Deep Field (HDF), and the latest Local Group (LG) census. Combining these datasets provides the current state-of-the art insight into the low redshift galaxy population.

2. The current state-of-play

2.1. The Luminosity Distribution

The number density of galaxies as a function of luminosity is conveniently described by a Schechter function (Schechter 1976), i.e.:

$$\phi(L)dL = \phi_*(\frac{L}{L_*})^{\alpha}e^{-(\frac{L}{L_*})}dL,$$

this effectively reduces the entire galaxy population to three crucial defining parameters: ϕ_*, L_* and α. These represent the density and luminosity calibration points, and the faint-end slope respectively. The main asset of the Schechter function is its simplicity, and the ability to thereafter calculate the galaxian luminosity-density (j) and mass-density (ρ):

$$j = \phi_* L_* \Gamma(\alpha + 2), \qquad \text{and} \qquad \rho = (\frac{M}{L})j,$$

The ease with which these fundamentally important cosmological parameters can be extracted from a galaxy catalogue is however beguiling. Table 1 and Figure 1 show a compendium of recent measurements of these three key parameters and the implied luminosity- and mass- densities (expressed in terms of the critical density assuming $\frac{M}{L} \sim 250$). The variation in these parameters is a cause for alarm.

Table 1. Summary of key values derived from redshift surveys

Survey	Reference	M_* (mags)	ϕ_* (Mpc^{-3})	α	j_B ($10^8 h L_\odot \mathrm{Mpc}^{-3}$)	Ω_M
SSRS2	Marzke et al. (1998)	-19.43	0.013	-1.12	1.28	0.12
UKST	Ratcliffe et al (1998)	-19.63	0.017	-1.04	2.02	0.19
ESP	Zucca et al (1997)	-19.61	0.020	-1.22	2.58	0.23
LCRS*	Lin et al (1996)	-20.29	0.019	-0.70	0.87	0.08
EEP	Efstathiou et al (1988)	-19.68	0.016	-1.07	1.89	0.17
APM	Loveday et al (1995)	-19.50	0.014	-0.97	1.35	0.12
Afib	Ellis et al (1996)	-19.20	0.026	-1.09	2.05	0.19
CfA	Marzke et al (1994)	-18.8	0.040	-1.00	2.06	0.19

*: A mean $(b - r) = 1.5$ has been assumed.

So what's going on ? There are two prime candidates for the large variations seen in Table 1: (1) our galaxy catalogues are plagued by selection biases; (2) clustering in the universe is much more severe than previously thought. The most lamented selection bias is that of surface brightness incompleteness (i.e. galaxies are either missing from the original imaging survey, their magnitudes are severely underestimated or their redshifts were unobtainable). Similarly although clustering has been known since the pioneering work of de Lapparent, Geller & Huchra (1986) no survey has so far been sufficiently large as to establish the scale at which large-scale structure averages out. Of these problems only the latter will be solved by the new generation surveys currently underway (i.e the 2dFGRS and the SDSS).

At this point it is also worth noting that, accepting the discrepancies in the existing surveys, they also only probe over a narrow range of luminosity ($-21 < M_B < -17$). However galaxies are known with absolute magnitudes of $M_B = -6$ (Mateo 1998). Hence we have only charted, and poorly at that, one quarter of the luminosity range over which galaxies are known to exist. **Our assessment of the local galaxy population is both inaccurate and incomplete.**

2.2. The Surface Brightness Distribution

The surface brightness distribution of galaxies is really a by-product or outcome of the raging debate over the impact of surface brightness selection biases on galaxy catalogues (as introduced in §2). The debate originates from the observation by Ken Freeman that most spiral galaxies appeared to have a central disk surface brightness close to 21.7 B mags/$\square''$ (Freeman 1970). This led to the conjecture (Disney 1976) and formulation (Disney & Phillipps 1987) that there exists an optimal surface brightness window through which galaxies are readily observable. This selection window was shown to be dependent on the isophotal depth of the survey and redshift (for a full description of visibility theory see Phillipps, Davies & Disney 1990, or the summary in Cross et al 2000). Outside of this narrow window galaxies are either too compact to be distinguished from stars or too diffuse to be detectable. More recently the cause has been taken up by others (see review by Impey & Bothun 1996) and recent surveys, which push to faint limiting isophotes, have indeed uncovered populations of low surface brightness galaxies - for example, Sprayberry et al (1996), Dalcanton et al (1997), and O'Neil & Bothun (2000) and references therein.

One claim from the low surface brightness community is that a substantial amount of luminosity and mass may reside in very luminous very low surface brightness galaxies, hitherto overlooked in the spectroscopic surveys listed in Table 1. This is indeed plausible as the source material for all local spectroscopic surveys are photographic plates scanned with bright isophotal limits ($\sim$ 24.5 B mags/sq arcsec). This conjecture is fueled from the serendipitous discovery of Malin 1 (see Bothun et al 1987) - the most luminous and HI massive field galaxy known. This "crouching giant", was originally thought to be a dwarf elliptical in the Virgo cluster. Spectroscopic follow-up revealed that it lay well beyond the cluster and subsequent deep imaging revealed a spectacular low surface brightness spiral disk with a central surface brightness of $\sim$ 25.5 V mags/sq arcsec and an unprecedented scale length of 55 kpcs. Malin 1 itself is easily detectable, because of its active AGN core, however its extensive disk is invisible to photographic surveys. This raises two concerns; firstly that Malin 1's without cores may exist, and secondly that many of the systems we currently accept as dwarfs might actually represent just the cores of other crouching giants. The blind HI surveys are the most promising method for searching for these

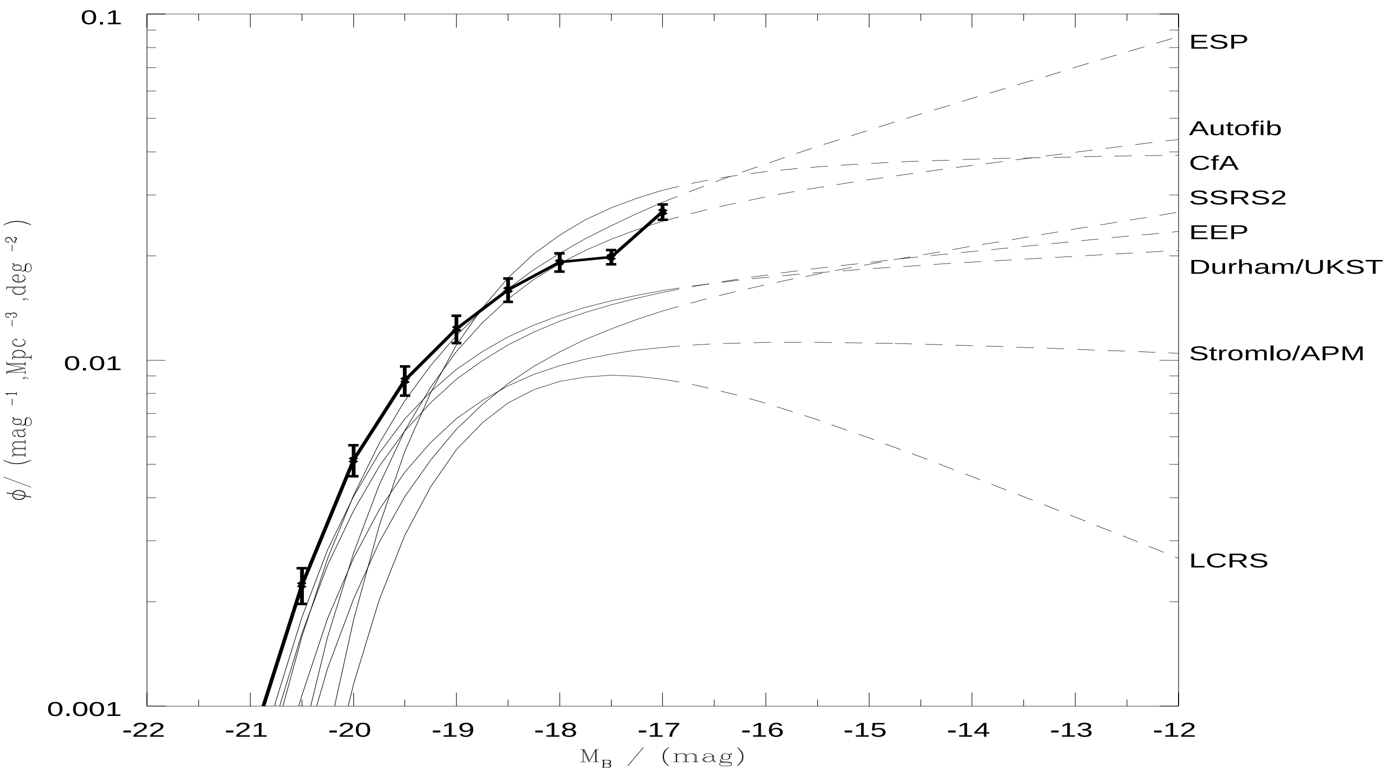

Figure 1. A comparison of recent luminosity function measures (see Table 1 for references). The solid line shows the luminosity range over which data was obtained and the dashed lines are extrapolations. The thick line shows the latest results from the 2dFGRS corrected for surface brightness selection effects and clustering

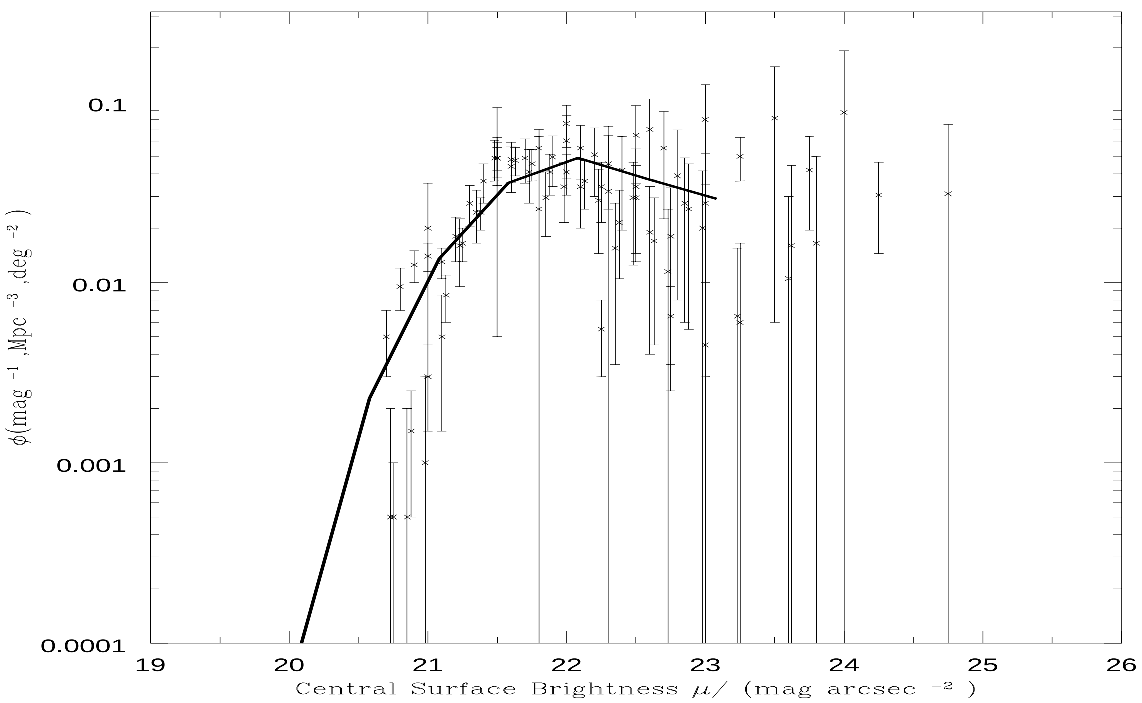

Figure 2. The surface brightness distribution of galaxies adapted from O'Neil & Bothun (2000). The solid line shows the latest result from the Two-degree Field Redshift Survey for galaxies with $M_B < -17$ mags (Cross et al 2000).

systems and fortuitously the papers presented at this meeting have, in my mind, gone a long way towards demonstrating that core-less Malin 1 type objects are very rare (see articles in this proceedings by Webster, Schneider and Tully).

Figure 2 shows the latest compendium of the surface brightness distribution of galaxies (adapted from O'Neil & Bothun 2000). This is directly analogous to Fig. 1 except central surface brightness rather than luminosity is plotted. This figure has moved on a lot since the initial Freeman result and it demonstrates that surveys with bright isophotal cutoffs will incompletely sample the galaxy population. This problem is exacerbated as one probes towards higher redshift. The combination of $(1+z)^4$-dimming and K-corrections combine to radically shift the selection windows through which we sample the underlying galaxy population. **Low surface brightness galaxies are missing in large numbers from our local galaxy catalogues**.

2.3. Galaxy Morphology

The Hubble tuning fork and its revision to include Magellanic type irregulars has been the bread-and-butter of galaxy morphology with the majority of all nearby galaxies being classified onto this system. However in recent years there has been a quiet revolution with the discovery of many galaxies which fall outside of the revised tuning fork (Ferguson & Binggeli 1994). As we have probed deeper into the local universe, numerous varieties of dwarf galaxies have emerged. Figure 3 shows the absurdly confusing picture when the Hubble tuning fork is further revised to include the full zoo of commonly used morphological nomenclature. Of further concern is the evidence from the Hubble Deep Field which indicates that the Hubble sequence is a recent phenomena representing only the luminous-minority of possible types (Driver et al 1998). **The Hubble tuning fork is an incomplete description of the galaxy population**.

2.4. Recap'

To recap the luminosity function of galaxies varies in amplitude at the L_* point by a factor of 2 with a faint end that flaps around from -0.8 (Lin et al 1996) to -1.25 (Zucca et al 1997) and runs out of steam at $M_B \sim -17$. The surface brightness distribution of galaxies shows equal variation with the champions of surface brightness arguing that we may be missing up to 50% of the local galaxy population at all luminosities (although this is not borne out by the HI surveys). Together these lead to an uncertainty in the local luminosity density of a factor of ~ 6. The impact on the mass-density is potentially worse given the high mass-to-light ratios of both low luminosity (Mateo 1998) and low surface brightness (Zwaan et al 1995; de Blok et al 1996) galaxies yielding a potential order of magnitude uncertainty in Ω_M (as derived from existing luminosity functions, e.g. Carlberg et al 1996; Persic & Salluci 1992; Fukugita, Hogan & Peebles 1998). In addition the simple elegance of the original Hubble tuning-fork has been severely compromised by the discovery that the majority of galaxies, in terms of numbers, lie outside of the Hubble tuning fork (Driver 1999).

Given this degree of uncertainty the study of galaxy evolution via statistical methods (e.g. galaxy counts, redshift distributions and comparisons between high and low redshift samples) is fundamentally flawed.

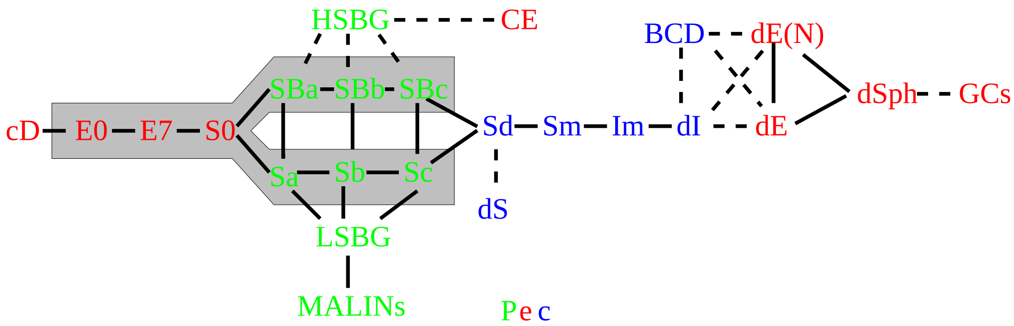

Figure 3. The breakdown of the once elegant Hubble tuning fork system of galaxy classification. Solid and dashed lines denoted suggested or speculative evolutionary links respectively.

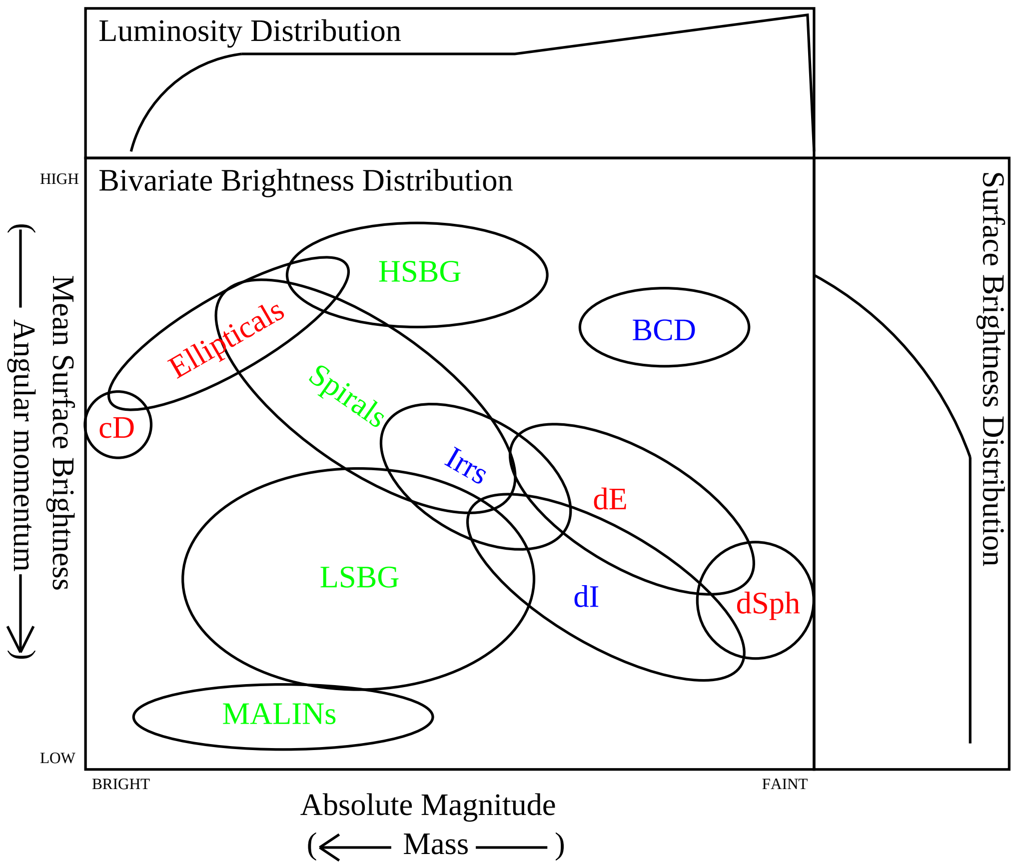

Figure 4. The Galaxy Population Plot: a new way of looking at the galaxy population ?

3. Combining Luminosity, Surface Brightness and Morphology

The conclusion from Figs 1 & 2 is that galaxies occupy a range in both luminosity and surface brightness. But the figures, as well as containing unsatisfactory scatter, do not indicate whether the surface brightness distribution of Figure 2 exists at all luminosity intervals (and vice versa). For example although Fig. 2 indicates that low surface brightness galaxies exist, do they really exist at bright luminosities ? To address this we require a representation which couples these two properties together. In 1994 at a dwarf galaxy meeting Bruno Binggeli showed a schematic bivariate-brightness distribution (BBD) for the Virgo cluster. In this rather inspirational diagram, galaxies from the Virgo cluster were shown on a plot of surface brightness versus luminosity. The Virgo population was seen to lie along a luminosity-surface brightness relation with some degree of natural morphological segregation (Binggeli 1994). Can we construct a similar plot, from existing galaxy catalogues for the general field population ? The concept is illustrated in Figure 4 which attempts to convey the usefulness of Binggeli's plot to simultaneously reconcile luminosity, surface brightness and morphology. Figure 4 is divided into three distinct panels the central BBD or Galaxy Population (GP)-plot, an upper panel representing the luminosity distribution (obtained from summing across the surface brightness axis in intervals of luminosity) and a side panel representing the surface brightness distribution. Currently there exist three datasets for which a BBD or GP-plot can be derived, these are: the Two-degree Field Galaxy Redshift Survey; the Hubble Deep Fields; and the Local Group. These three datasets are shown as Fig. 5(top), 2dFGRS; Fig. 5(middle), HDF; and Fig 5(bottom), LG and discussed independently below.

3.1. The Two-degree Field Galaxy Redshift Survey: Cross et al 2000

The 2dFGRS is an Anglo-Australian collaboration which will eventually obtain 250,000 redshifts for galaxies with $b_j < 19.45$ mags selected from UK Schmidt plates ($\mu_{lim} = 24.67$ mags/$\Box''$). The survey will cover 2000 sq degrees in two continuous regions (north and south Galactic caps) plus a number of randomly located fields. Currently $\geq 100,000$ redshifts have been obtained and the expectation is that the survey will be completed by the time these proceedings are published. The prime goal of the survey is to study large scale clustering and to derive the power spectrum of high surface brightness luminous galaxies over large ~ 100 Mpc scales. Figure 5 (upper) shows the range in surface brightness and luminosity over which 2dFGRS galaxies are seen. Note the data is the observed distribution uncorrected for the volume bias. The galaxy magnitudes and surface brightnesses have been corrected for light lost below the isophote assuming perfect face-on exponential profiles (see Cross et al 2000 for details). Also shown is the selection line derived from visibility theory which defines the window through which galaxies are seen with volumes $> 10^4$Mpc^3.

3.2. The Hubble Deep Field: Driver 1999

The superb image quality and depth of the HDF provides an insight into both the distant luminous universe *AND* the local intrinsically faint universe. Supplementing the spectroscopic redshifts with photometric redshifts where necessary allows us to extract a *volume-limited* sample over a well defined range of luminosity and surface brightness yielding Figure 5 (middle). The full details of how this sample and the selection lines were derived are in Driver (1999).

3.3. The Local Group: Mateo 1998

Finally the local group, albeit an ad hoc sample, was recently summarised by Mateo (1998). While further members of the local group are likely to be found this sample represents the *ONLY* current insight into the ultra low luminosity and low surface brightness regimes. Figure 5 (bottom) shows the derived GP plot from this sample with approximate selection lines shown (these selection lines are based on the depths to which recent surveys have probed; e.g. Armandroff et al 1999).

3.4. An $L-\Sigma$ relation and the paucity of luminous LSBGs

So what can we derive from these plots ? The main impression is that each dataset probes a very distinct region of the possible parameter space over which galaxies can exist. Together they arguably define the full extent of the low redshift population.

The 2dFGRS sample, while containing the most galaxies ($\sim 20,000$ shown here), spans the smallest although possibly the most important region. This is because the sample is *magnitude-limited* and therefore strongly biased towards sampling high luminosity systems (this is perfectly adequate, if not ideal, for the purposes of mapping out large scale structure). The upper and side panels show the volume-adjusted luminosity and surface brightness distributions respectively. We see that the bright end of both distributions are well defined (as also seen in Figs. 1 and 2.). The 2dFGRS shows a clear luminosity-surface brightness trend, indicating that lower surface brightness systems are of lower luminosity. This may well explain part or all of the variation seen in Fig. 1, for example a survey with a bright isophotal limit will preferentially select against dwarf systems and return a falling faint end slope. The 2dFGRS data also shows clear space between the bulk of the luminous galaxies and the selection boundary. This suggests that luminous core-less low surface brightness galaxies are either rare or form an entirely separable population at ultra-low surface brightnesses.

The HDF provides an intermediate window overlapping in parameter space with both the 2dFGRS and LG samples and includes morphological information (circles, squares and triangles denoting ellipticals, spirals and irregulars respectively). The HDF and LG data are both *volume-limited* and the data shown directly reflects the relative abundance of each galaxy type (within the optical window defined by the selection limits). The HDF confirms the paucity of luminous low surface brightness galaxies and the trend of the luminosity-surface brightness relation, albeit with a slightly steeper slope. The LG data shows that this luminosity-surface brightness relation continues to the faintest limits.

The luminosity and surface brightness distributions of the HDF and LG data are relatively flat showing that over the previously unexplored range of $-17 < M_B < -8$ and $21 < \mu_e < 28$, galaxies exist in equal numbers up to the selection limits.

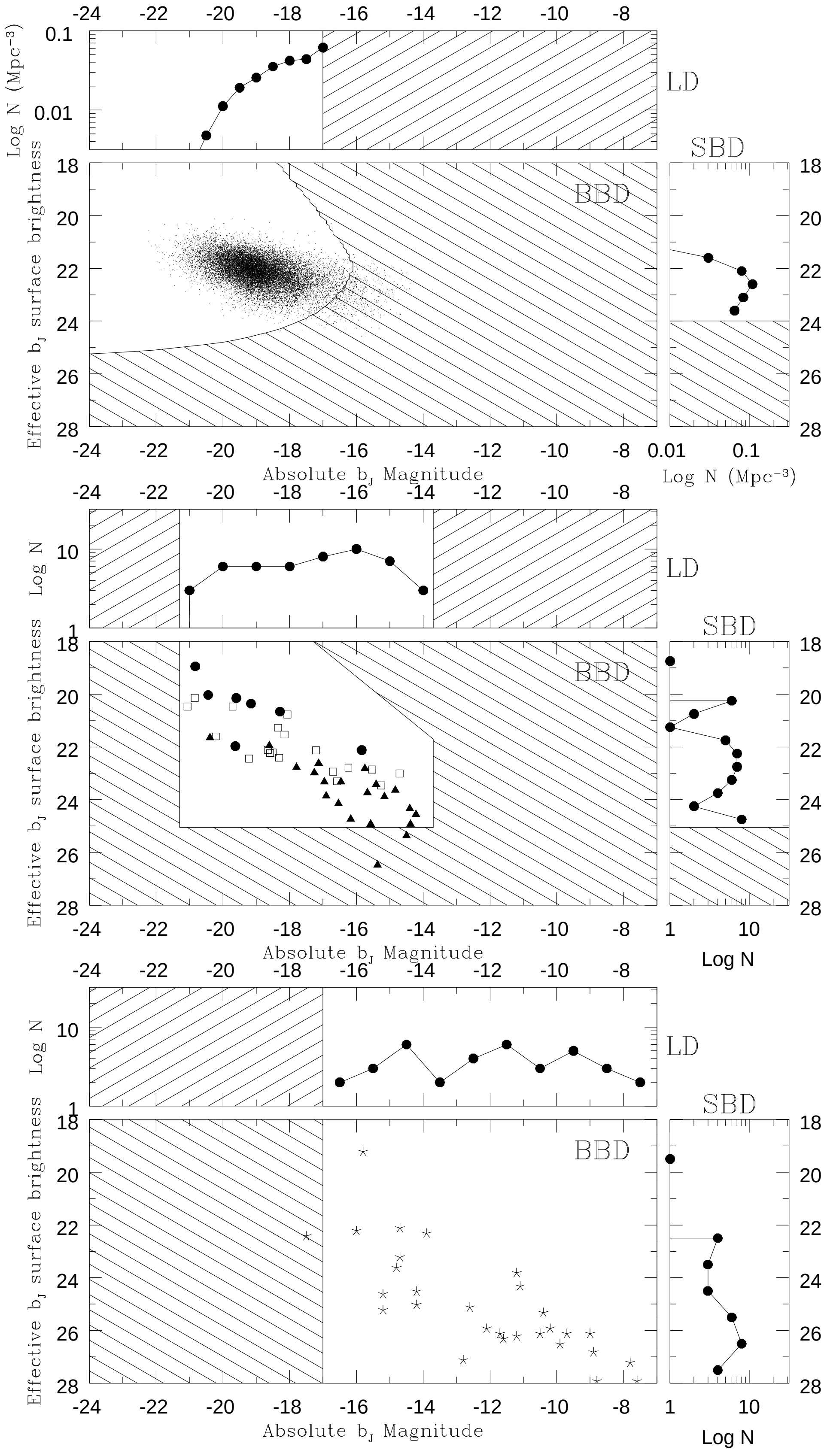

Figure 5. The bivariate brightness distributions recovered from: (top) the two degree field; (middle) the Hubble deep field; and (bottom) the local galaxy group

4. The combined Optical Window

Figure 6 shows the combination of these three datasets along with a low surface brightness galaxy sample of de Blok et al (1996), Malin 1 and a smattering of globular clusters. The densely shaded area illustrates the optical parameter space which has *NOT* been explored by any survey. The lightly shaded area is the region that has *ONLY* been explored within the local group (radius < 1 Mpc). This region should be taken with caution as we are unaware as to how representative the local group may be of the low luminosity universe at large - for example the recent results from Virgo paint a dramatically different, and deeply alarming (divergent), picture of the low luminosity population (see Phillipps et al 1998). As before the upper and side panels of Fig. 6 represent the luminosity and surface brightness distributions derived from the combination of our three datasets. These have been crudely derived by scaling the Hubble Deep Field (covering ~ 300 Mpc^3) and the local group (covering $\sim \pi$ Mpc^3 until they overlap with the faint end of the 2dFGRS data (covering $> 10^4$ Mpc^3). Both distributions are relatively flat suggesting equal numbers of galaxies at all luminosity and surface brightness intervals up until some bright luminosity or surface brightness cutoff. The central plot shows the luminosity-surface brightness relation seen in each of the individual datasets. The low surface brightness galaxy sample of de Blok occupies a fairly unique region reflecting their unique selection criterion (see Figure 4). Malin 1 lies in the totally unexplored region. **Fig. 6 represents our combined optical window into the low redshift galaxy population, it represents the parameter space over which galaxies are known to exist coupled within carefully defined selection boundaries.**

5. Conclusions

Here we have summarised the current understanding of the field galaxy luminosity function and the surface brightness distribution. Because of the clear luminosity-surface brightness relation we conclude that treating these key parameters as separable can lead to confusion and error. We advocate a bivariate brightness distribution which allows us to construct a window into the galaxy population. Using three distinct independent datasets to explore this region we map out the locations in luminosity and surface brightness over which galaxies are known to exist. The three datasets considered here are the Two-degree Field Galaxy Redshift Survey (spanning the high surface brightness luminous regime), the Hubble Deep Field (spanning the medium surface brightness medium luminosity regime), and the Local Group (spanning the low luminosity regime). Combining these three surveys reveals a consistent picture in which *BOTH* the luminosity and surface brightness distribution are flat to the detection boundaries. Across the full optical window over which galaxies are known to exist we have only censured a quarter-panel of this parameter space. Much work remains to be done before we can confidently state that we have a comprehensive and complete understanding of the low redshift universe and all that lies within.

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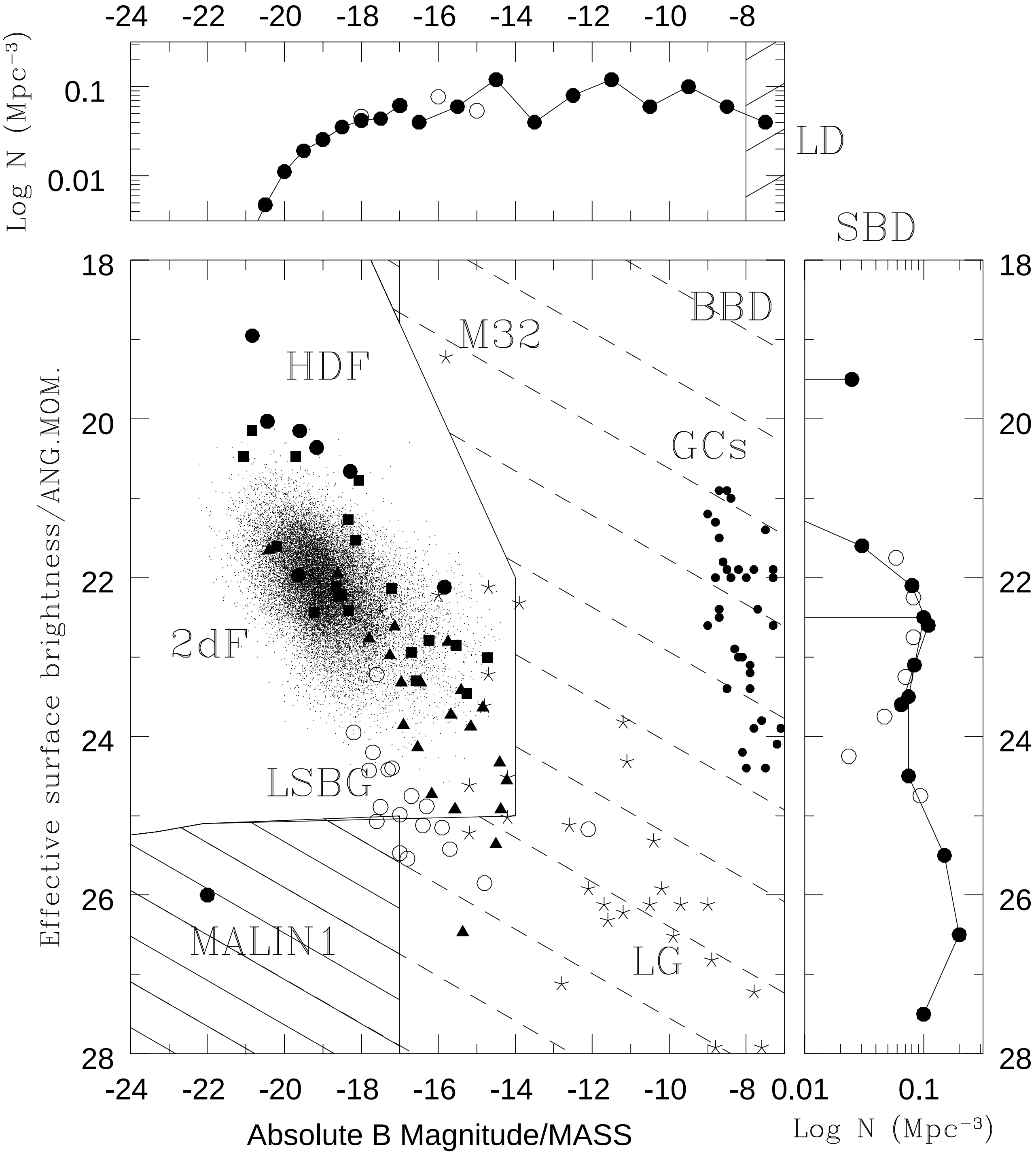

Figure 6. The optical window of galaxy existence. The principle data shown are: the Two-degree Field Galaxy Redshift Survey (Cross et al 2000), the Hubble Deep Field (Driver 1999), the Local Group (Mateo 1998), a low surface brightness galaxy sample (de Blok et al 1996) and Malin1 (Bothun et al 198?). The heavily shaded region denotes areas in which none of the surveys can probe. The lightly shaded region is that surveyed by the local group only.

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