The Number Density of Low Surface Brightness Galaxies

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I present the distribution of the numbers of disk galaxies as a function of central surface brightness that can be derived from extant data. This cuts off sharply brighter than a certain value, but falls slowly faintwards, indicating a substantial number of low surface brightness galaxies. I discuss the implications of this for the galaxy luminosity function and galaxy counts predicted therefrom.

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1 Morphology and Surface Brightness

Quantitative galaxy classification is an oxymoron. Morphological typing is an inherently qualitative personal judgement of the appearance of a galaxy. While it may be possible to automate this process (see Lahav, this workshop), there is no guarantee that it provides physically meaningful information.

A basic, quantifiable property of galaxies is their luminosity profiles. These generally fall into two categories; $r^{1/4}$ profiles for spheroidals and exponential profiles for disks. Here we will only be concerned with the latter.

The exponential profile, in magnitude units, has the form

$$\mu(r) = \mu_0 + 1.086\frac{r}{h}.$$

The two parameters central surface brightness μ_0 and scale length h are obtained by fitting the observed luminosity profile and provide a way of characterizing the global luminosity density and size of a galactic disk. These are the most fundamental observable properties of a galaxy.

These basic parameters may or may not be related to morphological class, depending on the classification scheme used. Generally, there does seem to be a trend of type with surface brightness in the sense that later types tend to be of lower surface brightness. It is thus interesting to try to understand the numbers of low surface brightness galaxies both in general and in the context of the high incidence of late and irregular types ($\sim 30\%$) observed in deep HST images (see Ellis, this workshop).

2 The Distribution of Central Surface Brightness

The number density of low surface brightness galaxies has long been a contentious issue. Before this question can be addressed, it is necessary to quantify what is meant by low surface brightness. I usually take it to mean disk galaxies which are fainter than the night sky even at the peak, so $\mu_0 > 23$ in B. Some seem to use the term to mean things which are nearly or totally invisible, so $\mu_0 > 26$. Others use the term to mean anything that deviates from "Freeman's law" that all spiral disks have $\mu_0 = 21.65 \pm 0.35$.

Note that $\mu_0 = 23$ is 4σ away from the Freeman value. This predicts that the number of disks with $\mu_0 \geq 23$ is $< 10^{-4}$ that of disks obeying Freeman's law, i.e. they do not exist. Yet we know of many examples of such objects, ranging in size from true dwarfs to enormous giants. A crude estimate of their density from recent surveys indicates a number comparable to Freeman disks. Even with order of magnitude error bars, this is inconsistent with a Freeman law at the 4σ level.

What we really wish to know is the distribution as a continuous function of surface brightness. Obtaining this requires clear understanding of the selection function of a galaxy survey. Since galaxies are resolved, two dimensional objects as observed projected on the sky, it is necessary to specify two parameters to describe their selection for inclusion in a catalog. As well as a flux or a diameter, one needs to know the isophotal level at which these are measured. For example, a diameter selected sample would require the apparent size θ to exceed some limit θ_ℓ when measured at isophotal level μ_ℓ. The volume probed by such a survey goes as the cube of the distance to which an object could be included; from the form of the exponential profile it follows that

$$V \propto h^3(\mu_\ell - \mu_0)^3.$$

A similar expression can be derived for magnitude selected samples. In both cases, V is a very strong function of surface brightness. Finding even a few low surface brightness galaxies

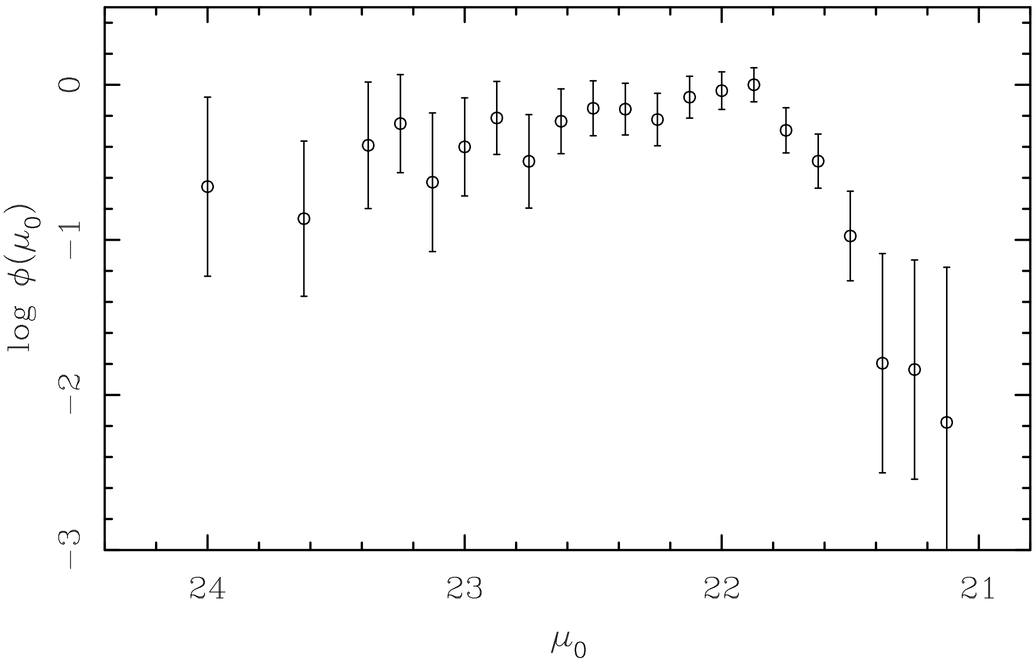

Figure 1: The relative number density of disk galaxies as a function of central surface brightness μ_0 in the field. The distribution falls off sharply brightwards of the peak at the Freeman value, but very slowly faintwards. There exist a large number of galaxies with surface brightnesses considerably fainter than the Freeman value.

in a complete sample immediately implies a substantial space density, since $1/V$ blows up as $\mu_0 \rightarrow \mu_\ell$. This volume correction, analogous to the original Malmquist bias, has generally not been considered but *must* be applied. Ignoring it is similar to concluding that K giants are the most common kinds of stars because they are readily apparent to the naked eye.

If we assume that scale length is not correlated with surface brightness, which is consistent with but not demanded by extant data, then we can obtain the surface brightness distribution without redshifts since surface brightness is distance independent. We require a sample with well defined completeness limits in both θ_ℓ and μ_ℓ and with surface photometry for all objects. Very few samples satisfy these requirements, but one is provided by Davies (1990) [MNRAS, 244, 8]. Applying the volume correction (arbitrarily normalized to the peak) to his field data gives the surface brightness distribution shown in figure 1.

This distribution function now allows us to directly assess the numbers of low surface brightness galaxies. Choose your definition of low surface brightness and integrate $\phi(\mu_0)$! The ratio of the number of Freeman disks to those with $\mu_0 = 23$ is about 3:1, though the uncertainties are still large, and both 1:1 and 10:1 are within the 2σ errors. The essential point is that the distribution is very different from a δ-function — the existence of a broad distribution containing many low surface brightness galaxies is unavoidable.

2.1 Systematic Uncertainties

A trend of h with μ_0 will introduce an additional factor in the correction for volume sampled. This goes in the sense that if lower surface brightness galaxies tend to be smaller, then there is another factor due to h acting against their selection and there are even more of them than indicated by figure 1. If instead low surface brightness galaxies are on average bigger than galaxies of high surface brightness, then there are relatively fewer of them. There is no strong evidence for either case as yet, though there are hints in both directions.

Another concern is the effect of cosmological dimming. Though this cancels out of the equation for relative volume, some apparently low surface brightness galaxies might actually be brighter ones at high redshift. This would tend to make the distribution more sharply peaked. On the other hand, bona-fide low surface brightness galaxies can be detected to much smaller distances, so it is the objects observed in the highest surface brightness bins which need the most correction. This broadens the distribution. It is unclear which effect is more important, but this is probably less significant than the assumption of no correlation between h and μ_0.

3 Implications

The assumption that the surface brightness distribution is essentially a δ function is implicit in much of extragalactic astronomy. That this turns out not to be the case has important ramifications for many aspects of the field. Two of these are briefly considered here.

3.1 The Luminosity Function

When constructing the luminosity function one inevitably gives large weight (through a volume correction) to the small subset of the data that represents the faintest galaxies. This is appropriate, but obviously any systematic errors in the magnitudes of these galaxies will be greatly magnified. This can have a dramatic effect on fit parameters like the normalization and faint end slope of $\Phi(M)$.

Isophotal magnitudes by definition measure a different fraction of the total flux of galaxies of different surface brightnesses. (Other flux measurement schemes are generally worse in that it is harder to define what fraction of the total flux is actually measured.) When there is a broad distribution of surface brightnesses, a different fraction of the total flux is measured at each one. The deficit between measured and total magnitude will be greatest for precisely those galaxies which receive the largest weight in the volume correction. This will cause the normalization ϕ^* and potentially the slope of the faint end to be underestimated. Indeed, a change of α from $-1.0 \rightarrow -1.5$ is possible, and shifts of this magnitude have been determined directly in nearby clusters when examined to very faint isophotal levels.

Such a steepening of α has a strong effect on the predicted number counts. However, the luminosity density is only strongly affected if α becomes very steep, or ϕ^* is grossly in error. There is difficulty in estimating what extant galaxies surveys have actually measured, but for the surface brightness distribution of figure 1, the luminosity density has probably been underestimated by a factor of ~ 1.3, though a factor of two cannot be ruled out. Properly, the luminosity function should be obtained by integration of the bivariate distribution $\Phi(h, \mu_0)$. If there is no correlation between μ_0 and h, as assumed above, then only ϕ^* is affected. If μ_0 and h are correlated, α can be strongly affected as well.

3.2 Number Counts

A classic test of astronomical world models is the number of objects in the sky as a function of flux. This is a readily observable quantity, and the expected counts follow from convolving the luminosity function and spatial distribution over the volume surveyed. This is usually stated in the form

$$A(m) = C \int_r \Phi(M) D(r, M) dV(r),$$

which allows computation of the expected counts

$$N(m) = \int_m A(m) dm$$

for a luminosity function $\Phi(M)$, spatial distribution $D(r, M)$, and volume element $dV(r)$. Early in the twentieth century this exercise was performed for stars, the assumption then being that the geometry was Euclidean ($dV = 4\pi r^2 dr$) and that the structure of the galaxy $D(r, M)$ was being probed. This exercise failed (the Kapteyn Universe) because the extinction by interstellar dust renders the effective geometry non-Euclidean (i.e., light is dimmed faster than indicated by the inverse square law).

Later this century, this exercise was performed for galaxies. The assumption now was that the spatial distribution of galaxies was homogeneous and the it was the geometry that was being probed. To perform this exercise, the above equations have to be modified to account for the redshifting of galaxy spectral energy distributions (the K–correction). Thus

$$A(m,t) = C \int_z \Phi(M,t) D(z,M,t) dV(z,q_0)$$

and one must now perform a double integral over brightness and galaxy spectral type t (often equated with galaxy morphological type, though these are not necessarily related) in order to predict the counts $N(m)$. This exercise failed because the effects of evolution in $\Phi(M,t)$ demanded by stellar physics were difficult to distinguish from variations in q_0.

Recently galaxy counts have probed to extremely faint levels, and $N(m)$ greatly exceeds the predictions of models for what had been considered reasonable amounts of evolution and values of q_0. Drastic revision of either basic cosmology or evolution seem required, challenging some of the fundamental successes of observational cosmology and stellar and nuclear physics. However, the above equation remains incomplete. As well as incorporating the neat cosmological effects of the redshifting of the spectral energy distributions, it is also necessary to consider the more mundane aspects of what is actually being measured when the target is not a point source. It is therefore also necessary to integrate over the distribution of galaxy surface brightness. That is

$$A(m,\mu_0,t) = C \int_z \Phi(M,\mu_0,t) D(z,M,\mu_0,t) dV(z,q_0)$$

and the number counts $N(m)$ must be obtained from the triple integral over m, μ_0, and t. So it is no surprise that this exercise fails today!

The faint portion of the the surface brightness distribution contains objects with physical properties (color, luminosity, and clustering) very similar to the "excess" population seen in the counts. This is very suggestive, and consideration of the surface brightness distribution may alleviate much of the apparent problem posed by faint galaxy counts. The large number of low surface brightness galaxies reported here is a necessary but not sufficient condition for this, which depends also on the color distribution and the shape of the bivariate distribution (see Ferguson & McGaugh, this workshop). If low surface brightness galaxies contribute significantly to the counts, we predict that a large fraction of edge-on, fuzzy, and irregular galaxies will be resolved by HST at $I \approx 23$, as observed.

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