Optical Galaxy Selection

Stacy McGaugh

Department of Astronomy, University of Maryland, USA

Abstract. Our view of the properties of galaxies is strongly affected by the way in which we survey for them. I discuss some aspects of selection effects and methods to compensate for them. One result is an estimate of the surface brightness distribution. I believe this is progress, but considerable uncertainty remains.

1. Limits and Selection Effects

A basic goal of galaxy research is to identify and characterize the galaxy populations which inhabit the universe. Astronomers undertake large surveys to discover galaxies, but this is only part of the battle. In order to transform from the observed, apparent distributions of galaxy properties and recover the desired intrinsic distributions, one must understand and correct for the selection characteristics of galaxy surveys.

An essential fact about galaxies, as they appear on survey plates, is that they are not point sources. Some of the consequences of this simple fact were first quantified by Disney (1976), who pointed out that the intrinsic distribution could be very different from the apparent one. At the least, it is necessary to generalize the formal procedures developed for point sources (Disney & Phillipps 1983; McGaugh et al. 1995).

The appearance of galaxies requires many parameters to approximate: they have multiple components (bulge and disk); they have spiral arms and dust lanes; their morphology can be a strong function of wavelength depending on their recent star formation history; etc. So, we simplify. Here I will pretend that a tolerable approximation can be had with axially averaged radial surface brightness profiles. This reduces the dimensionality of the problem immensely. The surface brightness profiles of galaxies obtained in this way are tolerably described as a combination of bulge and disk (4 parameters) or with a generalized (Sérsic 1969) profile (3 parameters). For brevity, I will reduce this further to 2 parameters by limiting the discussion to galaxies dominated by exponential disks:

$$\mu(r) = \mu_0 + 1.086\frac{r}{h}. \tag{1}$$

This reduces complex galaxies to a characteristic central surface brightness μ_0 and scale size h. In some cases this is a fair approximation.

Galaxies inhabit a large range in surface brightness and scale length (Figure 1). Real limits appear at high surface brightness and luminosity. Here, objects are prominent and are easily selected by surveys. The limit at L^* represents
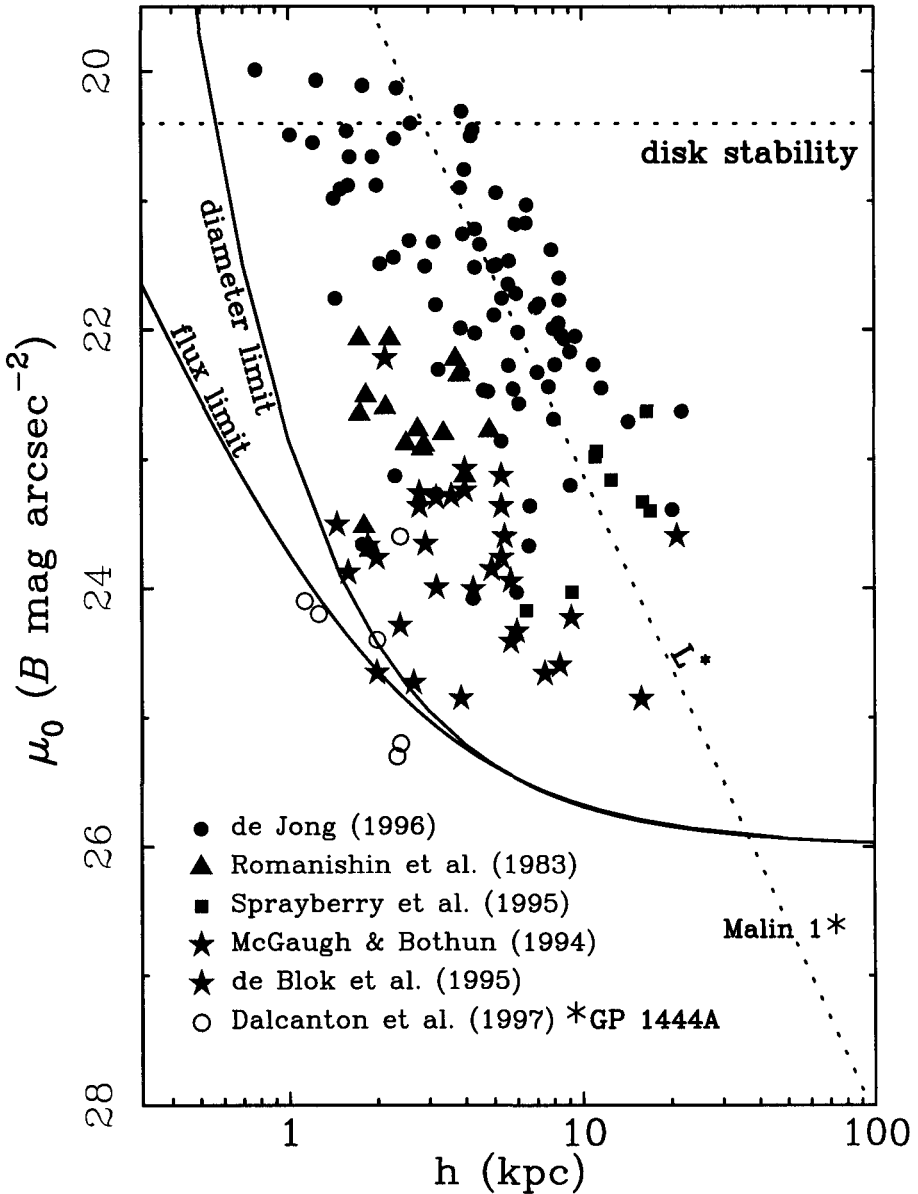
Figure 1.   The distribution of disk galaxies in the central surface brightness-scale length plane. Disks exist at all (μ_0, h) up to maxima in μ_0 and L. Lower bounds are imposed by observational selection limits. Illustrative selection lines are drawn for $\mu_\ell = 26$, typical of good photographic plates.

the well known turndown in galaxy numbers at this point. The limit at high μ_0 may represent a physical restriction based on the requirement that disks be stable (Milgrom 1989; McGaugh & de Blok 1998), though a massive bulge or dark halo could in principle stabilize even higher surface brightness disks. At the dim and small end, there is no clearly defined physical limit: our knowledge here is circumscribed by selection effects. Galaxies which are intrinsically small or low surface brightness are hard to find, regardless of how common they may be. Examples of very low surface brightness galaxies are known to exist, implying that the sparsely populated space in Figure 1 is just waiting to be filled.

In addition to a survey diameter or flux (magnitude) limit, there must (at the least) be a second survey parameter quantifying the limiting isophote μ_ℓ at which these are measured (Disney 1976). These are shown in Figure 1 by extracting from equation 1 the radius or flux of a galaxy at the limiting isophote:

$$r > r_\ell = 0.92h(\mu_\ell - \mu_0) \tag{2}$$

for diameter selection and

$$m < m_\ell = \mu_0 - 5\log h - 2.5\log[f(\mu_0, \mu_\ell)] + C \tag{3}$$

for selection by apparent magnitude. See McGaugh et al. (1995) for the definition of $f(x)$.

The problem becomes obvious: to reach small scale lengths is difficult; to find galaxies dimmer than the isophotal limit is impossible. However, the situation is even worse than illustrated in Figure 1, where it is assumed that galaxies can be detected right down to the formal survey limit. Even maintaining this fiction, one is really battling the volume sampling function $V(\mu_0, h)$ (Disney & Phillipps 1983; McGaugh et al. 1995) illustrated in Figure 2. This is much more restrictive than the lines in Figure 1 imply.

2. Volume Sampling and Intrinsic Properties

The volume sampled by any given survey is a strong function of both the survey parameters $(\mu_\ell, r_\ell$ or $m_\ell)$ and the intrinsic properties of galaxies (μ_0, h). A progressively larger volume is sampled for intrinsically larger and higher surface brightness galaxies. Such galaxies will always dominate the apparent numbers of objects in catalogs regardless of the intrinsic bivariate distribution $\Phi(\mu_0, h)$ (McGaugh 1996).

It is possible, in principle, to correct for $V(\mu_0, h)$ and recover the intrinsic distribution from the observed one. A good example is given by de Jong (1996 and these proceedings). Here I restrict myself to the projection of the bivariate distribution $\Phi(\mu_0, h)$ along the surface brightness axis, which I call the surface brightness distribution $\Phi(\mu_0)$ (Figure 3). I derive this by *assuming* μ_0 and h are uncorrelated (see Figure 1). While almost certainly not true in detail, this procedure does not produce a result which is grossly at odds with the results of the more complete analysis of de Jong.

The surface brightness distribution is broad, being *roughly* flat below the Freeman (1970) value. Low surface brightness galaxies are numerous, with approximately equal numbers of galaxies in each bin of central surface brightness.
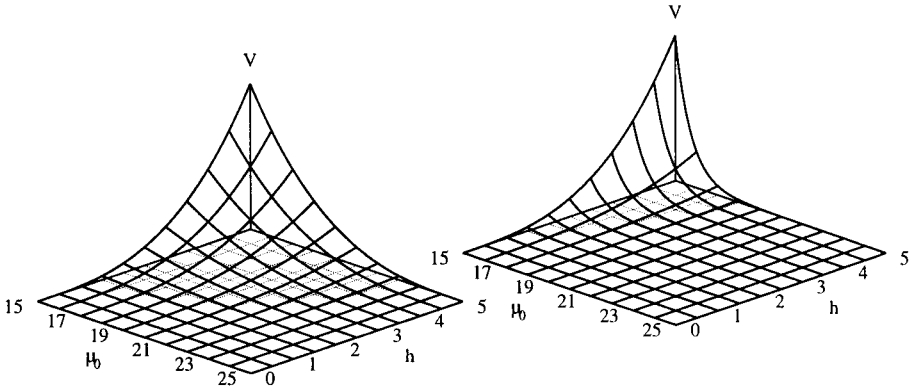
Figure 2.   The volume sampled by (a) diameter and (b) flux limited surveys as a function of surface brightness and scale length.

The surface brightness distribution falls off rather more steeply at the bright end.

If the assumption made about the independence of μ_0 and h fails, it has a predictable effect on the shape of $\Phi(\mu_0)$. If galaxies become systematically smaller as surface brightness decreases (as some unwritten lore presumes), then the surface brightness distribution will *rise* towards lower surface brightnesses. Since both surface brightness and size act against such dim, small galaxies, the required volume correction is larger than made here. On the other hand, if galaxies tend to be larger at lower surface brightnesses, the surface brightness distribution will fall more rapidly than shown. There is some hint of such a trend in Figure 1 (see also McGaugh & de Blok 1997). However, we base all this on incomplete data which is fraught with the very selection effects for which we would like to correct!

Different data in Figure 3 are consistent, given the large uncertainties. I do see some potential for controversy at the dim end. In an HI selected sample, Zwaan (these proceedings) reports a sharp turn down faintwards of $\mu_0 \approx 24$. Yet Dalcanton et al. (1997) not only detect galaxies dimmer than this, but also claim to measure a rather high density of them. One possibility is that the HI column densities of very low surface brightness galaxies are so low that the HI is ionized by the extragalactic UV radiation field. However, I do not think this can work. Only slightly brighter low surface brightness galaxies have abundant HI (McGaugh & de Blok 1997; Schombert et al. 1997), and the column densities are only a little lower than in high surface brightness spirals (de Blok et al. 1996). Moreover, by this reasoning, the $10^{11} \mathcal{M}_\odot$ of neutral hydrogen in Malin 1 should all be ionized.

That low surface brightness galaxies are *numerous* does not necessarily mean that they contribute a large amount to the integrated luminosity density (Figure 4). If the assumption I have made holds, low surface brightness galaxies are on average the same size as high surface brightness galaxies, and are therefore less luminous. The luminosity density thus declines with surface brightness.
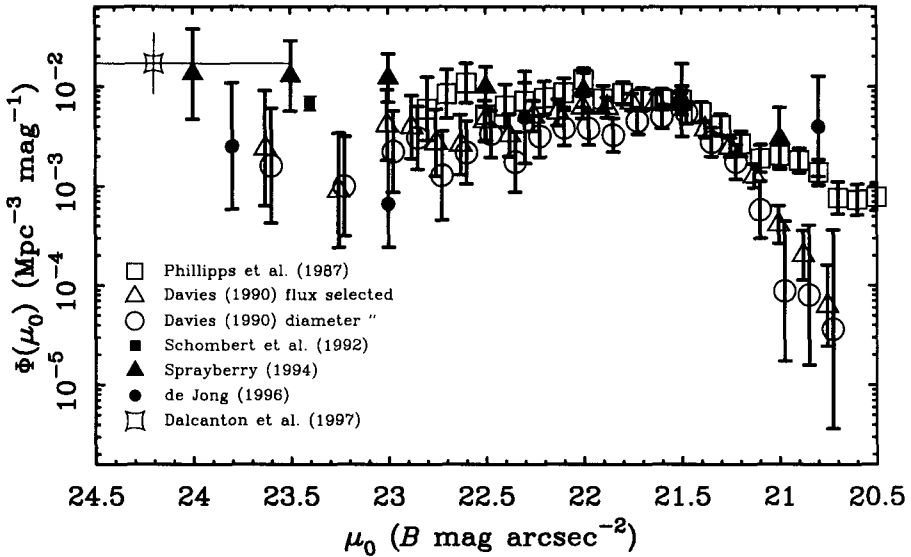
Figure 3. The surface brightness distribution, i.e., the number density of galaxies at each central surface brightness. There is a sharp feature at the bright end corresponding to the Freeman value, perhaps corresponding to a threshold for disk stability. At the dim end large numbers of low surface brightness galaxies are indicated. There is considerable uncertainty in $\Phi(\mu_0)$ at all surface brightnesses. Neither the shape nor the precise value of the Freeman limit are well determined.

This estimate of the luminosity density (Figure 4) as a function of surface brightness is more robust than the number density (Figure 3). If low surface brightness galaxies are larger on average than high surface brightness galaxies, they give away less in luminosity. However, they must then be less numerous in Figure 3, and the effects tend to offset. They do not offset perfectly (McGaugh 1996); because of the severity of the volume sampling function, it is easier to conceal luminosity in the small, dim population than in Malin-1-like giants.

3. Complications

While I have emphasized the severity of selection effects and the magnitude of the volume corrections required, I have so far actually painted a fairly rosy picture. I have made simple assumptions about the properties of $\Phi(\mu_0, h)$ and $V(\mu_0, h)$, and have further assumed that one can simply apply the volume sampling correction to galaxy samples which are complete as advertised. In reality, none of these things are likely to be realized, and there are a number of other important effects which have been completely neglected.

To mention a just few:

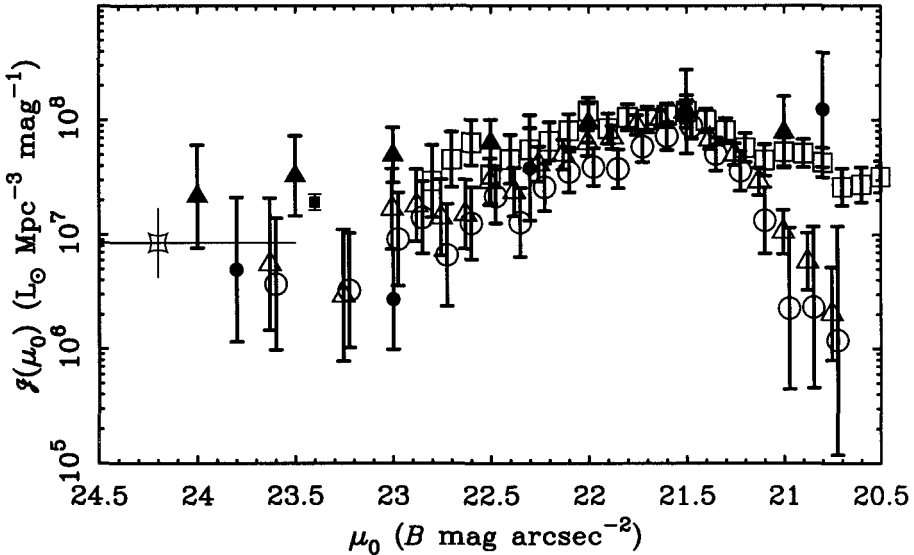- Galaxies are not axially symmetric exponential disks.

Figure 4.   Similar to the previous figure, but now the luminosity density. The luminosity density declines with dropping surface brightness. This happens simply because lower surface brightness galaxies are fainter *on average* than high surface brightness galaxies. There is a significant fraction of the total luminosity density due to all disks in the low surface brightness tail ($< 30\%$), but it seems unlikely that a large or even divergent population remains hidden.

- The galaxy SED matters for both bandpass and redshift effects.

- There are systematic measurement, as well as selection, effects.

- Inclination and internal extinction matter.

- Large scale structure may render meaningless a 'fair' volume.

While it is convenient to assume the exponential profile as the next best thing to pretending galaxies are point sources, there is no guarantee that this is adequate for purposes of selection. Early type galaxies are generally bulge dominated. Though the disk may well dominate in the regions of the selection isophote, the steep inner profile of the bulge makes these galaxies more prominent than assumed, especially to flux limited surveys. For late type galaxies the exponential profile is a better description of the radial profile, but these galaxies tend to be irregular and have large deviations from axial symmetry. These effects tend to exacerbate further the already large difference in accessible volume between bright and dim galaxies. Moreover, features like spiral arms, star forming regions, and dust lanes can complicate matters in a way which is difficult to generalize.

    Another issue is the actual spectral energy distribution (SED) of galaxies. While I have assumed a generic μ_0 in the survey band which defines μ_ℓ, one

would really like to know the bolometric surface brightness. As $\mu_0^{bol} \to \mu_\ell$, the visibility of a galaxy depends quite sensitively on color (McGaugh 1996). This may be a partial explanation for why the multi-band CCD survey of O'Neil et al. (1997) turns up more red low surface brightness galaxies than had previous surveys conducted on blue sensitive photographic plates (Schombert et al. 1992; Impey et al. 1996). If typical galaxy redshifts for a survey are high enough for K-corrections to be important, things are even more complicated (Ferguson, these proceedings).

One crucial thing in trying to recover the galaxy luminosity function is the systematic underestimate of the luminosities of low surface brightness galaxies made by measuring at some limiting isophote (McGaugh 1994; Dalcanton 1998). This is a particularly pernicious effect, because it is severe only for a very small percentage of galaxies in a complete sample. Yet these are precisely the objects for which large volume corrections are necessary. This magnifies systematic errors which in turn have a disproportionate effect on the derived luminosity function. All fit parameters (L^*, ϕ^*, α) can be affected, but the faint end slope is particularly susceptible to underestimation. Worse, many analyses still assume galaxies are point sources, which is tantamount to drawing the flux selection boundary in Figure 1 as a straight line parallel to that for L^*.

So far, I have assumed all galaxies are face on. This is bad, but not too terrible *if* galaxies are optically thin. This is probably the case for low surface brightness galaxies (McGaugh 1994; Tully et al. 1998). It is probably not the case for high surface brightness spirals. Just how optically thick spirals may be remains controversial. For the purposes of selection, internal extinction can have a significant inclination dependent effect on the position of a galaxy in Figure 1 (see Lu 1998).

Finally, I'd like to mention that a fundamental assumption is that we can probe a large enough volume of the universe for it to be considered homogeneous and representative. Yet as redshift surveys press ever deeper, we discover ever larger features, with no clear convergence as yet (Huchra, these proceedings). While the selection effects embodied in the volume sampling function will always be important, it is not obvious that large scale structure will admit a straightforward correction. Yet again, this problem is particularly severe at the dim end. While large surveys are sensitive to high surface brightness L^* galaxies over impressive volumes, they still probe only modest volumes for small and low surface brightness galaxies.

4.   Conclusions

In spite of some of the daunting problems, substantial progress has been made. There is great scope for further improvement. If any of the difficulties I have mentioned imposes some fundamental limitation, we are as yet far from reaching it.

References

Bothun, G.D., Impey, C.D., Malin, D.F., & Mould, J.R. 1987, AJ, 94, 23

Dalcanton, J.J. 1998, ApJ, 495, 251

Dalcanton, J.J., Spergel, D.N., Gunn, J.E., Schmidt, M. & Schneider, D.P. 1997, AJ, 114, 635

Davies, J.I. 1990, MNRAS, 244, 8

Davies, J.I., Phillipps, S., Disney, M.J. 1988, MNRAS, 231, 69P

Disney, M.J. 1976, Nature, 263, 573

Disney, M.J., & Phillipps, S. 1983, MNRAS, 205, 1253

de Blok, W.J.G., van der Hulst, J.M., & Bothun, G.D. 1995, MNRAS, 274, 235

de Blok, W.J.G., McGaugh, S.S., & van der Hulst, J.M. 1997, MNRAS, 283, 18

de Jong, R. S. 1996, A&AS, 118, 557

de Jong, R. S. 1996, A&A, 313, 377

Freeman, K.C. 1970, ApJ, 160, 811

Impey, C.D., Sprayberry, D., Irwin, M.J., & Bothun, G.D. 1996, ApJS, 105, 209

Lu, N.Y. 1998, ApJ, in press

McGaugh, S.S. 1994, Nature, 367, 538

McGaugh, S.S. 1994, ApJ, 426, 135

McGaugh, S.S. 1996, MNRAS, 280, 337

McGaugh, S.S., & Bothun, G.D. 1994, AJ, 107, 530

McGaugh, S.S., Bothun, G.D., & Schombert, J.M. 1995, AJ, 110, 573

McGaugh, S.S., & de Blok, W.J.G. 1997, ApJ, 499, 66

McGaugh, S.S., & de Blok, W.J.G. 1998, ApJ, 499, 66

Milgrom, M. 1989, ApJ, 338, 121

Phillipps, S., & Disney, M.J. 1983, MNRAS, 203, 55

Phillipps, S., Disney, M.J., Kibblewhite, E.J., & Cawson, M.G.M. 1987, MNRAS, 229, 505

O'Neil, K., Bothun, G.D., Schombert, J., Cornell, M.E., & Impey, C.D. 1997, AJ, 114, 2448

Romanishin, W., Strom, K.M., & Strom, S.E. 1983, ApJS, 53, 105

Schombert, J.M., Bothun, G.D., Schneider, S.E., & McGaugh, S.S. 1992, AJ, 103, 1107

Schombert, J.M., Pildis, R.A., Eder J.A. 1997, ApJS, 111, 233

Sérsic, J.-L. 1969, Atlas de galaxias australes (Observatorio Astronomica, Córdoba)

Sprayberry, D. 1994, Ph.D. thesis, University of Arizona

Sprayberry, D., Impey, C.D., Bothun, G.D., & Irwin, M. 1995a, AJ, 109, 558

Tully, R.B., Pierce, M.J., Huang, J.-S., Saunders, W., Verheijen, M.A.W., Witchalls, P.L. 1998, AJ, 115, 2264