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Counting the Ghosts: Optical Field Surveys for Low Surface Brightness Galaxies

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Abstract. Given the difficulties in detecting even a single LSB, surveying statistically significant numbers of LSBs presents a daunting task. Large, systematic surveys with well understood selection criteria are necessary for assessing the full cosmological significance of the LSB population. Here I briefly review some of the progress which has been made in the last ten years, and suggest strategies which may prove fruitful in the future.

1. Introduction

Now that the community of low surface brightness astronomers has grown to the point of supporting an IAU meeting, it is clear that what we have learned about low surface brightness galaxies (LSBs) is of general interest to the community of astronomers at large. The size of these proceedings demonstrates the astounding progress which has been made towards understanding these peculiar objects, and towards revealing their links with better known populations of galaxies. The question still arises, however, as to their importance to larger questions in cosmology. Can the matter associated with previously hidden LSBs provide sufficient mass to close the universe, or to challenge the predictions of big bang nucleosynthesis? Can LSBs play a role in explaining observations of the universe at higher redshifts? Can their distribution affect measurements of large scale structure, and does their absence from nearby surveys affect measurements of the power spectrum? How do they relate to well-studied normal galaxies, in properties, numbers, and distribution?

As with normal galaxies, such questions are best answered through large systematic surveys. At the minimum, any survey can provide a database of galaxies to study, and given the paucity of information on LSBs until recently, simply providing the community with objects to observe has been a tremendous boon. Few of the articles in this volume would have been possible without the existence of large catalogs of LSBs from which to draw. At their best, however, large surveys can provide much more, by placing the population of galaxies in a broader, well-quantified cosmological context. Such surveys are critical for considering low surface brightness galaxies in continuity with normal galaxies, and elevating them above being freakshow oddballs, or solely laboratories for testing interesting physics.

2. Optical Field Surveys to Date

Over the past 20 years, long, arduous work by many astronomers has given us a number of incredibly useful catalogs of low surface brightness galaxies. While much work has been done on low surface brightness galaxies in clusters, or on low surface brightness dwarf galaxies in particular, for this review I will be concentrating on the surveys of the general field population. These field surveys have typically covered hundreds of square degrees, and have largely relied on Schmidt plates to map these large areas.

The classic of such surveys is the Uppsala General Catalog (UGC; Nilson 1973), which catalogs all galaxies northward of $\delta = -2°30'$ with angular diameters greater than $1'$ on the original Palomar Sky Survey plates. While the UGC was not selected to be a low surface brightness galaxy catalog per se, its galaxies were chosen to be above a fixed diameter limit, without including a more traditional magnitude cut. This criteria admitted a large fraction of low surface brightness galaxies, which could be then studied either as a subset of the larger catalog (e.g. Romanishin et al. 1983, Knezek 1993), or in continuity with the normal galaxies in the catalog (e.g. de Jong & van der Kruit 1994).

When the second generation Palomar Sky Survey plates became available, Schombert and collaborators (Schombert & Bothun 1988, Schombert et al. 1992) repeated the same search criteria as the UGC, but on the deeper plates, for declinations between 0° and +25°. Their survey revealed several hundred new galaxies, and decreased the limiting average surface brightness by an additional magnitude per square arcsecond beyond the surface brightness limit of the UGC. Most of the recent work on LSB colors, dynamics, and gas content have used galaxies drawn from both this catalog and the UGC.

More recently, Impey and collaborators (Impey et al. 1996) have used a combination of visual searches and APM machine scans to identify nearly 700 galaxies from 24 equatorial fields of the United Kingdom Schmidt Telescope (UKST) survey plates; 500 of these galaxies were previously uncataloged. As the newest large survey, the APM catalog has not yet been exploited to the degree of the earlier POSS-II LSB survey, but with its large size, and copious redshifts and HI observations, it should prove as fertile a field in the years to come.

These large field surveys have been complemented by many smaller field surveys which either push to fainter limiting surface brightnesses than can be reached in large plate surveys (for which $\mu_0 < 24\, B\, mag/\square''$, typically), or which use different methods for galaxy selection. Most of these surveys sacrifice area in exchange for the increased sensitivity and linearity of CCDs (e.g. Dalcanton et al. 1996, O'Neil et al. 1997), and/or use stacked plates and/or novel search techniques to reach fainter surface brightnesses (e.g. Schwartzenberg et al. 1994, Davies et al. 1994). While lacking the numbers and generality of the large surveys, such smaller surveys can push into previously unexplored territory, revealing extremely low surface brightness galaxies, or LSBs with unusual colors (e.g., see contributions by O'Neil in this volume). These mini-surveys can be extremely useful complements to the largest LSB catalogs, and will be important input for designing the next generation surveys.

2.1. The Density of LSBs

These large optical surveys have built a tremendous base for examining the properties of LSB galaxies. The galaxies within them are all relatively nearby (typically with 1000 km/s$< V_{\odot} <$ 10000 km/s), and thus they can be studied in a fair bit of detail. The surveys have also given us the means to start placing LSBs into their full cosmological context, by assessing the size of the LSB population as a whole.

For example, using several large field surveys, McGaugh (1996) has used visibility corrections to reconstruct a *relative* surface brightness distribution for galaxies, and shown that the distribution is largely flat, with an exponential cutoff at bright surface brightness. For angular diameter or magnitude limited surveys, these reconstructions do not require that the redshifts of the galaxies are known, and thus they can be instantly applied to any large field survey. However, the methods applied by McGaugh (1996) rely upon assuming that the distributions of surface brightness and of scale length are disjoint and independent, which unfortunately they do not seem to be. Thus, these results can only be taken as as a rough indication that the population of LSBs is not negligible, at least in numbers.

The best progress towards measuring the full bivariate luminosity function (i.e. the number density of galaxies as a function of luminosity and surface brightness) has been made by Sprayberry et al. (1997), using the APM LSB survey of Impey et al. (1995). Using a subset of CCD observations to calibrate the plates, and after measuring the selection function of the survey with fake galaxy tests (Sprayberry et al. 1996) , Sprayberry et al. (1997) derived a steeply rising luminosity function for the APM LSB sample, which encompassed surface brightnesses between $22 < \mu_0 < 25\, B\, mag/\Box''$. Their derived luminosity function is similar in form and normalization to the luminosity function of the irregular galaxies from the CfA survey, derived by Marzke et al. (1994), both of which suggest that LSBs make up only a small fraction of bright L_* galaxies, but that their numbers overtake normally cataloged galaxies at magnitudes fainter than roughly -15 in B. However, because of the paucity of bright LSBs, Sprayberry's results suggest that the luminosity density in uncataloged LSBs contributes less than 1/3 of the luminosity density known to be in normal galaxies. These results will need to be confirmed as full redshift information for their sample becomes available; while most of the galaxies in the APM sample have a central surface brightness of $\mu_0 \sim 24\, B\, mag/\Box''$, the redshifts at this surface brightness are only 20% complete. A significantly smaller survey with complete redshift information by my collaborators and I (Dalcanton et al. 1997) derived similar upper limits to the luminosity density of lower surface brightness LSBs ($23 < \mu_0 < 25\, mag/\Box''$ in V), suggesting that the APM result will not change drastically with complete redshift information.

3. How Can We Improve?

While these nearby, wide-field surveys have provided us with samples of galaxies which are near enough to study in detail, for the seemingly simple task of "counting" LSBs, these surveys are not the easiest approach. To date, existing analyses of the number density of LSBs have suffered from some combination of very incomplete redshift information, woefully small sample sizes, and limited range of surface brightness. These limitations are nearly unavoidable consequences of focusing our attentions on the nearest LSBs, a focus which has arisen from our need to identify galaxies with large diameter limits (typically $> 30''$).

The difficulties with nearby LSB surveys are several. First, field surveys of nearby galaxies require both deep exposures and large areas to uncover large enough samples to be statistically meaningful. The volume of a survey is proportional to the mean distance cubed, and thus when restricting a search to nearby galaxies, astronomers must cover prodigious areas to find even a few hundred galaxies. For LSB galaxies, which have additional selection biases restricting their mean distance (see contributions by McGaugh in this volume), these volume limits are even more stringent. The second difficulty is that distances to nearby LSBs must be determined one by one, as the galaxies are near enough that there are a scant handful per square degree. This inability to multiplex makes follow-up observations incredibly time-consuming, testing the willpower of both the astronomer and the Time Allocation Committee. Finally, the large survey areas needed make it difficult to maintain a consistent selection efficiency across the survey data, which in turn makes an accurate analysis of the sample challenging and subject to large systematic errors.

I believe that many of these problems could be avoided by instead targeting LSB surveys towards slightly higher redshifts ($z \sim 0.1$, comparable to the LCRS (Shectman et al. 1996) redshift survey). At these larger distances (which are still close enough to be considered a reasonable sample of the nearby universe), individual galaxies will require more telescope time to be observed with the same signal-to-noise as they would be seen with nearby. However, the number of galaxies per unit area will go up dramatically, allowing hundreds to thousands of LSBs to be revealed in a single image. With multi-slit and multi-fiber spectrographs available on most telescopes, the spectroscopic follow-up required for a survey becomes much more efficient as well. This capability is vital, given the hideously long exposure times needed to measure redshifts of such low surface brightness objects. A move to higher redshifts also has the added benefit of allowing one to survey both normal and LSB galaxies simultaneously, giving us not only the bivariate luminosity function, but also the correlation function of LSBs as well. The resulting sample can also be used to study galaxy properties continuously over surface brightness and luminosity, instead of treating LSBs as a disjoint class of galaxies.

To demonstrate the gains possible with such an approach, in Figure 1 I have estimated the time which would be needed to image a constant number of LSBs with constant signal-to-noise, as a function of the typical LSB redshift in a survey. Including the effects of seeing and cosmological $(1+z)^{-4}$ dimming, the middle panel of Figure 1 shows that much longer exposure times are needed to reach LSBs at distances greater than $z > 0.1$. However, the bottom panel, which also considers the increasing volume which is visible at larger redshifts, shows that the total survey time actually *decreases* out to $z \sim 0.25$, because less area is needed to detect the same number of LSBs. This exercise suggests that surveys of LSBs at $z \sim 0.1$ could be hundreds of times more efficient than surveys of LSBs at $z \sim 0.01$. The increase in efficiency will be similar for the spectroscopic follow-up as well.

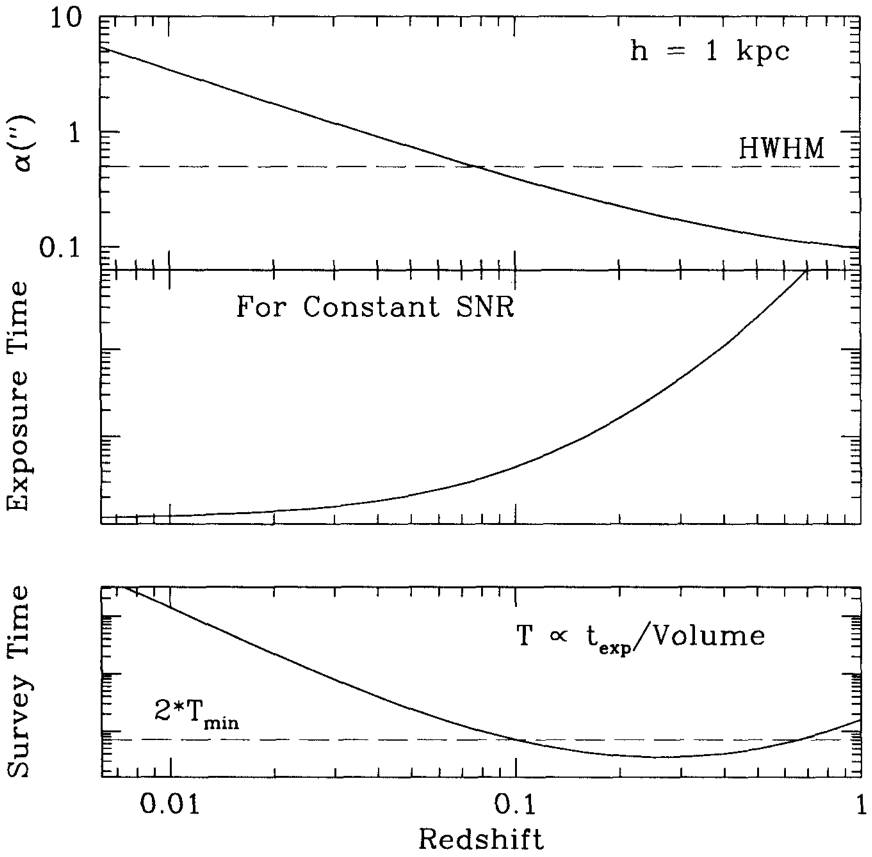

Figure 1. LSB survey properties as a function of typical redshift: The top panel shows the apparent exponential scale length as a function of redshift, assuming a physical scale length of $h = 1$ kpc; the HWHM of a $1''$seeing disk is marked as the horizontal dashed line. The middle panel shows the exposure time needed to reach the same signal-to-noise, as an exponential disk galaxy is moved to higher redshifts. The effects of seeing and cosmological dimming are included in the calculation. The bottom panel shows how the total needed survey time would vary with redshift. The plotted curve is the exposure time calculated in the middle panel, divided by the volume of the universe seen out to each redshift. The minimum survey time T_{min} is reached near $z \sim 0.25$; a survey optimized for $z \sim 0.1$ would take only twice as long as T_{min}.

While moderate redshift surveys for LSBs clearly have a great advantage in observational efficiency, they are likely to require more complicated analysis. For example, because of atmospheric seeing, assigning an accurate surface brightness or scale length to each galaxy becomes increasingly difficult at large redshift. By $z \sim 0.1$, a typical galaxy's scale length will be comparable to the HWHM of the seeing disk (see the top panel of Figure 1), and thus its apparent surface brightness profile will be strongly affected by the PSF. Uncertainty in a galaxy's surface brightness can also cause great difficulty in reconstructing the galaxy's V_{max}, and thus can lead to highly biased derivations of the luminosity function (e.g. Dalcanton 1998). However, the effect of the seeing can easily be modeled, and correcting for such effects may be no more difficult than modeling the selection effects in large area surveys. In fact, it may be somewhat easier, given that the selection function will be much more uniform over the survey area.

I am optimistic that astronomers will find it worthwhile to solve the problems associated with $z \sim 0.1$ LSB surveys. Most of us are in the lucky (or unlucky?) position of having more brains than telescope time, and have to make the best of both. As we have now entered an epoch where we have learned so much about internal LSB properties, I believe we can now sacrifice the detail revealed in nearby LSBs, to gain knowledge about the many unanswered cosmological questions which remain.

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