Starcounts redivivus II: Deep starcounts with Keck and HST and the luminosity function of the Galactic halo

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Abstract

We have combined deep starcount data with Galaxy model predictions to investigate how effectively such measurements probe the faint end of the halo luminosity function. We have tested a number of star/galaxy classification techniques using images taken in 0.5 arcsecond seeing with LRIS on the Keck telescope, and we find that different combinations of these techniques can produce variations of 10% in the inferred starcounts at R=22.5 and 30% at R=24.5 magnitudes. The decreasing average angular size of galaxies with fainter magnitude effectively limits ground-based work to R<25.5 magnitudes. The higher angular resolution provided by HST allows one to probe at least 2 magnitudes fainter, but the small field-size is a significant limitation. In either case, our models show that the contribution from halo subdwarfs is effectively limited to colours of (R-I)<1.0, with the redder stars being members of the Galactic disk. The apparent increase in number density for M_V>10 in the derived luminosity function is a result of contributions from disk stars at fainter absolute magnitudes and does not provide evidence for an upturn in the halo subdwarf mass function. Indeed, starcount data alone are not an effective method of probing the shape of the halo luminosity function close to the hydrogen-burning limit. Finally, we examine how the Hubble Deep Field observations can be used to constrain the contribution of various stellar components to the dark-matter halo.

1. Introduction

Over the past decade considerable effort, both observational and theoretical, has been directed towards deriving a more accurate determination of the stellar luminosity function of the Galactic disk, with particular emphasis on the behaviour at low luminosities. Most recent derivations (Tinney, 1993; Kirkpatrick et al, 1994; Reid, Hawley & Gizis, 1995) show a broad peak at M_V∼12 (or equivalent) and subsequent decline, with the hint of an upturn at the faintest magnitudes. Converting to a mass function is more controversial, largely reflecting the poor observational constraints on the (disk) mass-luminosity relation at low masses, but the majority of studies show a turnover well before the hydrogen-burning limit, while even the most optimistic analyses (Kroupa, 1995) find a mass function increasing no faster than \( \Psi(M) \propto m^{-1} \) for \( M < 0.5M_\odot \). In either case, it is clear that low-mass stars \( (M < 0.2M_\odot) \) and brown dwarfs make only a minor contribution to the total mass of the Galactic disk.

The situation is less well defined for the Galactic halo, primarily because of the greater difficulties involved in identifying a pure sample of halo stars.\(^2\) Observational efforts have followed two main paths: studies of globular cluster members and surveys of field halo subdwarfs. The initial results from the former approach (Richer et al, 1991; Drukier et al, 1993) suggested strongly a luminosity function that continued to increase steeply towards lower luminosities, with no suggestion of a turnover. However, more recent, higher spatial-resolution HST observations (Paresce et al, 1995; Elson et al, 1995; King & Anderson, 1996) contradict this result, finding a broad maximum at M_V∼+11. HST observations are required of clusters such as NGC 6752, where the

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\(^2\) Recent years have seen some confusion caused by the use of the term ‘halo’ to refer to the dark matter whose presence is indicated by rotation curve analyses. In this paper we adopt the conventions of the 1957 Vatican conference (O’Connell, 1958) and use the term to refer to the old stellar population that represents the field counterpart of the globular cluster system. All discussions of the dark-matter halo are specifically identified as such.
ground-based data suggest steeply increasing luminosity functions (Richer et al, 1991) before this issue can be resolved.

Given the likelihood of internal dynamical evolution, as well as possible selection effects in the cluster disruption process, globular clusters cannot necessarily be taken as representative of the halo at large, but studies of the field have yielded the same dichotomy of results. Dahn et al (1994 - DLHG), studying a sample of nearby (r ≤ 300 pc.) high proper-motion stars, have derived a luminosity function similar in form to the Paresce et al NGC 6397 function. On the other hand, Richer and Fahlman (1992) have used deep CCD starcounts to attempt to isolate a sample of stars at large distances above the disk and, based on that sample, have argued that the halo luminosity function increases steeply and continuously to at least $M_V \sim +14$ - close to the H-burning limit for metal-poor halo subdwarfs. There are possible shortcomings associated with either of these approaches: the proper motion stars are selected from the Luyten LHS catalogue (Luyten, 1979), and it is possible the results could be biased through kinematically-related selection effects. Alternatively, the deep starcount analysis may suffer from errors introduced either through uncertainties in star/galaxy separation or through misclassification of disk stars as halo subdwarfs. In this paper we address the latter issues, combining both ground-based starcount data from the Keck 10-metre telescope and fainter data from the Hubble Deep Field with predictions derived from improved starcount models. Section 2 discusses the uncertainty inherent in applying various star/galaxy separation techniques to good-seeing ground-based data; in section 3 we consider the expected colour-magnitude distribution of the different stellar populations, with particular emphasis on the redder, lower-mass stars; section 4 compares our deep starcounts with the predictions of several models; and section 5 presents our conclusions.

2. Star-Galaxy separation at faint magnitudes

Accurate star-galaxy separation is essential at faint magnitudes. Reid & Majewski (1993 - RM93) discussed this problem extensively in the context of deep (B, $I \sim 22$) photographic data towards the NGP. Figure 1 shows a more general illustration of the magnitude of the problem, comparing the stellar and galaxian distributions in fields at relatively high galactic latitude (b=45°, 60° and 90°). The galaxy counts are taken from Metcalfe et al. (1995) and Smail et al (1995: S95). The star counts are taken from one of the models described in the following section, but the total counts are relatively insensitive (< 10%) to the choice of parameters. It is clear that the surface density of stars equals that of galaxies at relatively bright magnitudes - B ~ 21, R ~ 18.8 and I ~ 18.5. Moving to fainter magnitudes, galaxies increase in number by a factor of at least 2 per magnitude (S95) while the slope of the stellar counts flattens significantly as one moves to larger distances and runs out of Galaxy. Thus, by R ~ 24 galaxies outnumber stars by a factor of ~40:1, and a small error in galaxy classification becomes a substantial uncertainty in the starcounts.

Most galaxies have colours of (V-R) ~ 0.5 ± 0.25. Hence, while one can expect contamination by only a few (unusual) galaxies in a sample of red, low-mass star candidates, there is substantial overlap between the galaxies and the locus of halo subdwarfs in both the colour-magnitude and colour-colour plane. We have illustrated this in figure 2. Figure 2a shows the two-colour (V-R)/(R-I) relation defined by nearby disk stars (Bessell, 1991) and halo subdwarfs (photometry by Bessell, priv. comm.). The latter stars follow a similar two-colour relation, lying at most 0.15 mag. to the blue in (R-I) at a given (V-R) colour. In constructing their faint stellar sample, Richer & Fahlman
(1992) applied both image structure and photometric criteria, rejecting objects lying more than 2σ from the Population I/II (disk/halo) stellar locus. We can estimate the effectiveness of that technique by applying the same criterion to our sample.

Figure 2b plots the two-colour diagram for galaxies brighter than R=25 in the PSR 1640 field, where we have superimposed the disk stellar sequence. The solid lines outline the locus corresponding to 2σ uncertainties of ±0.14 magnitudes in either colour - matching the formal uncertainties for R ~ 23.5 ± 0.5. Of the 204 galaxies in this magnitude range, 138 (67%) lie within 2σ of the stellar sequence. The formal uncertainties at R~ 23 are lower, ~ 0.035 magnitudes in each colour, but 115 of 158 galaxies with 23 ≤ R ≤ 24 mag. fall within the ±2σ stellar locus. Thus, while VRI colours are an efficient means of identifying some quasars and low-redshift AGNs, we conclude that if used alone they provide only weak star/galaxy discrimination.

Overall, morphology remains the most effective means of discriminating between stars and galaxies. However, S95 have shown that the median galaxian half-light radius is ~ 0.4 arcseconds at R=24 and declines to 0.2 arcseconds by R=25.5 (S95, figure 4). As a result, a significant fraction of galaxies with R > 25.5 are indistinguishable from point sources in ground-based data, and any selection criterion based on morphology cannot be expected to be successful at such faint magnitudes.

We have undertaken an investigation of the accuracy of star/galaxy classification at brighter magnitudes using images taken in excellent seeing with the Low Resolution Imaging Spectrograph (LRIS, Oke et al, 1995) on the Keck telescope. The observations cover two fields at intermediate galactic latitude, (l=41°, b=38° - PSR 1640) and (l=88°, b=-26° - PSR 2229), with LRIS providing a pixel scale of 0".22 and a field of view of 5'7 by 7'.3. Full details of the data reduction are given elsewhere (S95). The exposure times and FWHM are listed in Table 1. The V-band exposure time is relatively short in field PSR2229, we have not used these observations in our analysis. All other observations have similar limiting magnitudes as the Richer and Fahlman (1992 - RF) CFHT observations. Photometric calibration is based on observations of Landolt (1992) standards, and we have adopted line-of-sight reddening values of E_B−V = 0.07 mag. in both fields (Stark et al, 1992). Note that while the PSR 1640 field is in the first quadrant, the closest that this line-of-sight approaches the Galactic Centre is 6.4 kpc (at a heliocentric distance of 4.8 kpc and at 3 kpc. above the Galactic Plane). Thus possible contamination by bulge stars is not a problem.

Given the fundamental limit imposed on star/galaxy separation by the decreasing average half-light radius of field galaxies (S95), we have restricted our sample to sources brighter than R= 25 magnitude. The formal photometric uncertainties in field PSR1640 are 0.08 mag. at R=25 and V=25, and 0.15 mag. at I=25 magnitude, but the uncertainty in V rises to ~ 0.2 magnitudes at V=26. Thus, a typical halo-star at R=25 has uncertainties of ~ 0.22 magnitudes in (V-R) and ~ 0.13 magnitudes in (R-I). In field PSR2229 the uncertainties are slightly higher, with σ_R = 0.1 mag. at R=25 mag. and σ_I = 0.23 mag. at I=25 magnitude.

We have applied a number of star/galaxy separation techniques to these data and compared the results in an attempt to determine their relative utility and reliability. In both fields the R-band data were taken in the best seeing conditions, and we have used these frames as the primary source of our morphological classification. These data are sufficiently deep that the limiting factor for star/galaxy separation is the spatial resolution (seeing) rather than either photon statistics or incompleteness.
In addition to analysing the real stellar images, we have also generated 200 artificial stars (using the point spread function given by DAOPHOT) in each field, distributing their magnitudes between R=20 and R=25. These stars have been placed at carefully chosen, relatively clear locations in each frame, with the appropriate photon- and sky-noise added. We have analysed these fake objects using the same techniques that are applied to the real data, and use the results to provide an indication of both the stellar locii and the dispersions as a function of magnitude. This analysis does not allow for the additional scatter caused by merged and overlapping images, but the source density is low enough that these problems are relatively insignificant (< 5%) even at R=25 magnitude. The results of the simulations are plotted, with the real data, in figure 3-6.

We have used the following morphological parameters to define stellar samples:

1) image ellipticity, defined as \( e = (a/b) - 1.0 \), where \( b \) and \( a \) are the semi-major and semi-minor axes of the best-fit isophotes as determined by the profile-fitting routines of the SExtractor image analysis package (Bertin, 1995). S95 describe the package in more detail. The resulting ellipticity distribution as a function of magnitude is plotted in figure 3a for PSR 1640 and figure 3b for PSR 2229. Figure 3c shows the distribution of the artificial stars and, based on that, we have rejected all objects with ellipticity greater than 0.3 from the sample as galaxies.

2) the \( \chi \) parameter from DAOPHOT (Stetson, 1987). We defined the reference point-spread function (PSF) using twelve isolated, bright (and unsaturated) stars in each field, and the \( \chi \) parameter describes the goodness of fit between each image and the reference template. The optical design of LRIS leads to small variations in the PSF across the field, and ideally, one would prefer a larger number of reference stars, but crowding in these intermediate latitude fields limits the number of calibrators. While our tests show that DAOPHOT takes the psf variations successfully into account, systematic effects may make a small additional contribution to the observed scatter. Figures 4a and 4b plot this parameter against magnitude for the two fields, with figure 4c showing the artificial star distribution. All objects with \( \chi > 3\sigma \) are rejected as galaxies.

3) \( \log \left( \frac{I_{\text{peak}} - I_{\text{sky}}}{I_{\text{sky}}} \right) \) vs. isophotal magnitude - i.e., a measure of the compactness of the image profile. This is the parameter defined by Jones et al (1991) and used (with methods 1 and 2) by RF as their primary star/galaxy discriminant. (They imposed the additional criterion of requiring that stars lay within 2\( \sigma \) of the VRI stellar locus.) Data for objects in our two fields are plotted in figures 5a and 5c (note that stars saturate at R < 20.5 magnitudes). We have computed the mean relations defined by the artificial stars (plotted in figures 5b and 5d respectively) and the lines delineate the \( \pm 5\sigma \) envelope about those relations.

4) \( I_{\text{peak}}/\Phi(<0''.6) \), where \( \Phi(<0''.6) \) is the total flux within a 0''.6 diameter aperture centred on the source. Again, this is a measure of the compactness of the stellar profile and the results are shown in figures 6a and 6c, where the \( \pm 5\sigma \) envelope defined by the artificial star samples (figures 6b and 6d) are also plotted.

Table 2 lists the relative numbers of stars and galaxies as a function of magnitude if we apply various combinations of these criteria to our data. Applying the first two criteria gives only a crude star/galaxy separation, with only the obviously-extended galaxies being removed from the sample. Methods 3 and 4 are obviously more stringent, even when using a \( \pm 3\sigma \) cut rather than the \( \pm 5\sigma \) limits plotted in figures 5 and 6. Table 2 shows the results both of applying these two methods separately (but in conjunction with
methods 1 and 2) and of demanding that ‘stars’ are objects which meet all four criteria. As one might expect, the last set of requirements (1+2+3+4) gives the smallest sample, with number counts that are lower than those derived based on the RF criteria (1+2+3) by ~ 10% at R=22.5, ~ 20% at R=23.5 and ~ 30% at R=24.5 magnitude. Applying additional criteria can only reduce the size of the final sample, and it is likely that the (1+2+3+4) sample is over-conservative in definition. Nonetheless, we conclude that, at least for our Keck ground-based data, uncertainties in the morphological classification imply uncertainties in the final starcounts of ±10% at R=23.5 and ±15% at R=24.5. The addition of colour criteria should reduce these uncertainties by approximately two-thirds - note the excellent agreement in total numbercounts between the RF observations and the predictions of the starcount models described in section 4.1.

3. Faint red stars and the halo

Given a reliable faint stellar sample, the next step is segregating sheep and goats - sorting which stars are members of the disk and which are members of the halo population. The first point that should be made is that, despite recent analyses (Bahcall et al, 1994; Santiago, Gilmore & Elson, 1996), the lowest-luminosity halo subdwarfs are not found at colours comparable with those of their disk counterparts. This fact has also been emphasised recently by Graff & Freese (1996). The field halo is a metal-poor population with an average abundance of [Fe/H]~−1.5±0.3 (Kraft, 1989). Theoretical calculations by VandenBerg et al (1983), D’Antona (1987), Burrows, Hubbard & Lunine (1989) and Baraffe et al (1995) all indicate that stars of this abundance have both higher temperatures and higher luminosities than solar-abundance stars of the same mass. Thus, Baraffe et al find that a 0.1 M⊙ subdwarf with [Fe/H] = -1.5 has $M_{bol} = +12$ and $T_{eff} \sim 3300K$, while a disk dwarf of the same mass has $M_{bol} = +12.5$ and $T_{eff} \sim 2700K$. These differences are enhanced when converting to the observed (M$_V$, colour) plane, since the lower line blanketing in the metal-poor stars leads to a greater proportion of the total flux emitted in the optical region of the spectrum, and hence both substantially bluer colours ((V-I) < 3.0) and higher optical luminosities.

These theoretical predictions are in good agreement with observations of both the lower main-sequence stars in globular clusters (RF; Paresce et al, 1995) and of local parallax subdwarfs (Monet et al, 1992). The faintest extreme subdwarf in the latter sample (LHS 1742a) has $M_V = 14.4$ and (V-I) = 2.74, but $M_{bol} \sim 12$, comparable with the disk dwarf VB 10 (M$_V$=18.5, (V-I) = 4.33). Thus, counting the number of star at faint magnitudes with (V-I)>3.0 can probe only the metal-rich ([Fe/H] <～ −1) tail of the halo abundance distribution and tells one essentially nothing about the bulk of the Galactic halo.

Second, it is important to consider the volume-sampling effects inherent in any pencil-beam starcount analysis. As illustrated by RM93 (their figure 3), the convolution of a monotonically-decreasing density law with the sampling volume of a pencil-beam survey leads to a ‘preferred’ distance modulus for each stellar component, with that distance modulus (and the dispersion) dependent on the slope of the density law along the particular Galactic line of sight. In the case of a slightly-flattened (axial ratio ~ 0.8), r$^{-3.5}$ halo sampled at moderate to high latitude, the median distance is 12.5 kiloparsecs (distance modulus 15.4 mag.) Fifty percent of the halo stars lie between 8.2 and 21.0 kpc. (distance moduli 14.5 and 16.6 mag. respectively) while 80 % of the halo stars fall between 7.0 and 25.0 kpc. (m-M) = 14.2 and 17.0 mag.). We emphasise that this is a general property of starcounts - the spheroidal nature of the halo produces little variation in the predicted number-magnitude distribution, even at low Galactic
latitudes. The result is that at magnitudes brighter than $R \sim 24$, late-type subdwarfs ($M_V > 11, M_R > 10$) are outnumbered more than ten to one by more luminous halo stars lying closer to the main-sequence turnoff.

Deep starcount surveys, however, reveal a significant number of moderately red ($(V-I) > 1.5$ mag.) stars. What population do these stars belong to? We have argued that late-type halo stars are rare, thus the implication is that they are members of the disk population, and this hypothesis is supported by starcount predictions. There is still no unanimity over the appropriate physical description of the old disk/thick disk/intermediate population II (IP II) relationship, but provided that one has an adequate representation of the overall density law perpendicular to the Plane (i.e. one that satisfies data from other surveys), that debate is unimportant for present purposes. In justification of this, we have computed starcounts towards the Galactic Pole for two models chosen to characterise two different interpretations of the disk component. First, a model based on the RM93 discussions which adopts exponential distributions for both old disk and IP II, with respective scaleheights of 350 and 1500 pc. and a local normalisation IP II/old disk of 2%; second, and closer in construction to the Robin et al. (1996) Besancon models, calculations based on adopting a sech$^2 z_0$ density law for the disk, with $z_0$ of 350 pc. for the old disk and 1500 pc. for IP II, with the local normalisation set at 5.0%. (Note that the IP II constitutes close to 20% of the total mass of the disk in the latter model.) Exponential density laws have long been popular in galaxy modelling, despite the lack of an obvious physical basis, while sech$^2$ distributions imply an isothermal population. Figure 7 plots the density distributions predicted by both models against the observed density law derived from photometric parallax analysis of the Gilmore & Reid (1983) SGP starcounts, restricting the sample to $6.0 < M_V < 7.0$. While there are substantial differences in the relative proportions of the two components at any given height, in both models the overall run of density gives a reasonable match to the observations.

Since the density distribution of the disk populations falls off faster with height above the Plane than does that of the halo, the disk stars lie at a smaller average distance. Looking towards the Galactic pole, the old disk stellar distribution peaks at $(m-M)=9.0$ and the IP II at $(m-M) = 12.5$ in model A, while the respective distance moduli are 8.5 and 11 in model B. These distances scale with the inverse of the sine of the Galactic latitude for the disk populations. At high latitudes ($b \sim 60^\circ$), if one selects stars at a given apparent magnitude, say $V=20$, model A predicts a sample that consists predominantly of $M_V=4.5$ ($\pm 1.0$) mag. halo subdwarfs, $M_V=7.5$ mag. IP II dwarfs and $M_V=11.0$ mag. old disk dwarfs. Model B predicts $M_V \sim 9.0$ mag. and $M_V \sim 11.5$ mag. for the two disk populations. The net result is that at a given apparent magnitude, we expect the average absolute magnitude of a disk star (either old disk or IP II) to be significantly fainter than that of a halo subdwarf i.e. disk dwarfs are redder than halo subdwarfs. This is the source of the bimodal colour distribution in $(B-V)$ at faint magnitudes originally detected by Kron (1980).

As regards the other parameters of our disk-population models, we have adopted an NGC 2420-like ([Fe/H]=-0.4) colour-magnitude diagram for the IP II (taking 47 Tuc as the template moves the colours to the blue by 0.05 magnitudes at most), while the disk CMDs are based on nearby star data (Bessell, 1990). The halo population has been modelled using colour-magnitude relations derived from observations of NGC 6752 (Thompson et al, in prep.), with the luminosity function taken from RM93 and an adopted local normalisation of 0.15 % the local disk star density. Figure 8 shows the $(R, (R-I))$ colour-magnitude distributions predicted by our models for two fields -
(l=40, b=40) representing PSR 1640 and (l=110, b=75), close to the RF field.

There are three important conclusions one can draw from these figures: first, the colour-magnitude distributions graphically demonstrate the systematic progression to fainter \textit{absolute} magnitudes (redder (R-I)) with fainter \textit{apparent} magnitudes for each component. Second, the relative invariance in the position of the halo colour-magnitude distribution is clear, despite the substantial difference in galactic latitude. (There are more stars in the lower latitude field since one is looking inward, past the Galactic Centre.) Finally, it is clear that even at R=24 magnitudes, the overwhelming majority of stars redder than (R-I)=1.0 magnitude are contributed by the disk populations. This is the crucial circumstance that mitigates against the use of faint starcounts to probe the halo luminosity function for late-type M subdwarfs. In the following section we undertake a more detailed examination of the predicted colour distribution at faint magnitudes, matching the models against both the Keck data and the deeper but smaller field HST observations.

\section{4 A comparison between observations and model predictions}

\subsection{4.1 Ground-based observations}

Figure 9 matches the starcounts derived from the Keck images of field PSR 1640 against the predictions of the two models described in the previous section. We have identified the contribution of the three main components in the latter models using separate symbols. Given the relatively small sample size, either model provides an adequate fit to the data to at least R=24 magnitude. Both models clearly identify stars redder than (R-I)~1 as from the disk - either an almost-equal mixture of old disk and IP II (model A) or predominantly IP II (model B). This is important, since although RF eliminated the extremely red stars from their sample ((V-I)\textgreater 3.8), they do not distinguish between halo subdwarfs and IP II stars. Their justification for this approach (and, implicitly, for their including stars with heights above the Plane as low as 1.25 kpc.) is based on arguments for a similarity between the IP II and M71 colour-magnitude diagrams and, by inference, luminosity functions. It is our proposition that this analysis is incorrect since the starcount models show that one is combining halo and disk stars from distinct, non-overlapping ranges in absolute magnitude.

We can use our models to illustrate this directly for the high-latitude RF field. Figure 10 plots the observed (V, (V-I)) distribution for the stars identified by RF, together with the predicted colour-magnitude diagram for a 0.0122 square-degree field at (l=109°, b=73°). We predict 54 stars brighter than I=24.5, as compared with 49 observed. The horizontal dotted line in the figure indicates the apparent magnitude limit of V=25; the vertical dotted line marks (V-I)=1.75. Our model predicts that all of the V < 25 stars redward of the latter limit are from the disk (IP II in the case of model B). The solid points identify stars which lie above 1.25 kpc (using the (M_V, V-I) relation in RF) - all of the halo stars and 65 % of the IP II. Thus, a luminosity function constructed from these data represents a composite based on blue halo subdwarfs and red IP II stars, with the transition between the two at (V-I)~ 1.7, or M_V ~ 10.0 magnitudes (using the RF (V-I) calibration). The reddest IP II stars are predicted to have (V-I)~2.8 mag., M_V(RF)~13.75, matching the faintest stars in the RF luminosity function. Since the IP II has a higher local density normalisation than the halo, one might expect a luminosity (or mass) function derived from the composite starcounts to rise towards lower luminosities and smaller masses. Indeed, the luminosity function derived by RF shows a sharp upturn in number density at M_V ~ +10 - exactly the
transition between the halo-dominated and disk-dominated colour régimes.

Any attempt to use starcounts to study low-luminosity stars in the halo must take proper account of the contributions of both old disk and IP II at the appropriate colours. This demands both large areal coverage (given the low surface-density of intrinsically-faint subdwarfs at even $R=25$) and a more accurate knowledge of the density laws of the dominant disk population than we have at present.

4.2 The Hubble Deep Field - starcounts

Ground-based starcounts are limited to magnitudes brighter than $R=25$ by the coarse spatial filtering imposed by atmospheric seeing. The obvious method of circumventing this problem is to rise above the Earth’s atmosphere - a condition which is met by the Hubble Space Telescope. The field of view of the WFPC2 is extremely small (only 0.00157 sq. degrees), so the expected number of stars in a typical ‘deep’ single field is small ($< 10$ to $R \sim 26$). Nonetheless, the recently-completed observations of the Hubble Deep Field (Williams et al, 1996) permit the first test of starcount models at levels as faint as $R=27$ magnitude.

The HDF observations consist of multi-orbit exposures in four filters (F300, F450, F606, F814) of a single low-reddening WFPC2 field at $l=126^\circ$ and $b=55^\circ$. The latter two filters are the most interesting for starcount work and, as in the study by Flynn, Gould & Bahcall (1996 - FGB), we have restricted our analysis to these two bands, which have effective limiting magnitudes of $V \sim 30$ and $I \sim 30$ on the Johnson/Cousins system. We have used the SExtractor package to determine magnitudes and morphological parameters for all of the sources in the V- and I-band frames, and all of the objects classed as stellar were also checked by eye. The magnitude zeropoints are as specified by STScI, adopting the aperture corrections and colour-terms (particularly significant in F606W) given by Holtzman et al (1995). Saturation limits our sample to stars fainter than $I \sim 18.5$ magnitude.

Our star/galaxy classification is based on a single technique - plotting the peak brightness against the total magnitude measured on the F814W frames. The position of the stellar sequence is defined by taking a bright (unsaturated) star as a PSF template and scaling the intensities (adding the appropriate noise) to match stars at fainter magnitudes. The results are plotted in figure 11, where the simulated stellar sequence is plotted as open circles; objects classed as stars are plotted as solid triangles; probable stars are plotted as solid squares; and galaxies are plotted as crosses. The benefit of 0.1 arcsecond ‘seeing’ is obvious - the stellar sequence is clearly distinct from the galaxy population to at least $I=26$ magnitudes, and we would predict relatively little contamination even at $I=27$. This represents an effective gain of at least 2 magnitudes over ground-based R-band observations.

As expected, however, the total number of stars is very small. Out of a total of $\sim 700$ objects, we find only 16 definite and 4 probable stars in the range $20 < I < 27$. Figure 12 plots the ($I, (V-I)$) colour-magnitude diagram for these objects. This can be compared directly with the colour-magnitude diagram derived by Flynn et al (1995) (their figure 2), results obtained using entirely independent, and more sophisticated, methods. We find one additional faint red star ($I=25.7, V-I=2.3$ - lying within the FGB selection zone), but otherwise the two diagrams are identical for $20 < I < 26$ magnitudes - a testament to the robustness of the morphological classification techniques.
Figures 13a and 13b show the \((I, (V-I))\) colour magnitude diagrams predicted by our models A and B. The latter were computed for a solid angle of 0.0157 sq. deg. - ten times the HDF solid angle - to better display the relative contributions of the different stellar populations. Note how the contribution from the Galactic disk (either old disk or IP II) peters out at \(I \sim 26\) magnitudes in both models as we reach the bottom of the (metal-rich) hydrogen-burning main-sequence. Only at fainter magnitudes is the halo the dominant stellar population at all colours. However, even the HDF data are incapable of discriminating between a continuously increasing halo luminosity function (RF) and the DLHG function. At \(I \sim 26\), the typical halo subdwarf has \((V-I) \sim 2\) and \(M_V \sim 11 \pm 1\), while the two luminosity functions diverge only at \(M_V > +12\). In general, the total starcounts predicted by both models are in reasonable agreement with the observations - for \(20 < I < 26\), model A predicts 10 stars (1.5 disk, 2.5 IP II, 6 halo) while model B predicts 13 stars (0 disk, 7 IP II, 6 halo). This compares with the 13 to 15 stars observed in the same magnitude range.

Similarly, the observed and predicted colour distributions are in reasonable agreement, with the redder stars identified as disk or IP II and the intermediate-colours objects as halo subdwarfs. There is a marginal deficit of faint, red stars - both models predict \(~ 4\) stars with \((V-I) > 1.0\) magnitudes and \(25 < I < 27\), while only two stars are observed (one of which may be a misclassified galaxy). Clearly, further observations covering more fields are required to establish whether this is anything more than small number statistics.

### 4.3 The Hubble Deep Field - constraints on baryonic dark matter

Flynn et al have used the absence of faint, red stars in the HDF starcount data to set limits on the baryonic (stellar) contribution to the dark-matter halo (DMH). They derive upper limits of \(6\%\) for objects with \(M_I < 15\) and \(1\%\) for \(M_I < 14\). However, while these luminosities are appropriate for very low-mass \((\sim 0.1 M_{\odot})\) solar abundance, disk dwarfs, there are reasonable grounds for assuming that they are not appropriate for the hypothetical DMH dwarfs. Given that the DMH has an extended (spheroidal) distribution, it is probable that it formed before any substantial dissipational collapse occurred in the proto-galaxy. Hence, it also seems likely that any stellar constituents would have metal abundances at least comparable with the conventional Galactic halo - a point also made by Graff & Freese (1996). As described in section 3, the lower blanketing at lower abundances leads to brighter optical luminosities than amongst low-mass disk dwarfs. Thus, a better template for the hypothetical DMH dwarfs is given either by the zero-metallicity models computed by Saumon et al (1994), who find \(M_V=12.8\) and \((V-I)=1.6\) for a 0.092 \(M_{\odot}\) object (the minimum mass for hydrogen burning at this abundance), or by the extreme subdwarfs \((M_V=14.5, (V-I)=2.7)\) included in the Monet et al. parallax stars. (For reference, a 0.1 \(M_{\odot}\) solar-abundance disk dwarf has \(M_V \sim +19, (V-I) \sim 4.5\) magnitudes.) Under either of these assumptions we can set significantly more stringent limits on the baryonic contribution to the DMH.

First, surveys of the local stars are complete to distances of \(~14\) parsecs for stars of \(M_V = 13 \pm 0.5\) and \(\delta > -30^\circ\) (Reid, Hawley & Gizis, 1995). If we ascribe all of the local DMH density \((\sim 0.009 M_{\odot} \text{pc}^{-3} - \text{FGB})\) to stars at the H-burning limit, we have a local density of 0.1 DMH stars \(\text{pc}^{-3}\), or \(~860\) stars within the 14 parsec distance limit appropriate for zero-metallicity stars. None have been found, so we can infer that no more than \(~0.13\%) of the mass of the DMH rests in the form of zero-metallicity M-dwarfs. On the other hand, we can take LHS 1742a \((M_V=14.4, (V-I)=2.74\) magnitudes) as our DMH dwarf template. Nearby stars surveys are complete only within a distance of
7 parsecs for stars of this absolute magnitude. Again, there are no plausible candidates currently known, limiting the contribution of these stars to \(\sim 1\%\) of the local dark-matter density.

Second, if we assume that the DMH has an \(r^{-2}\) distribution, we can use the HDF starcounts to tighten these limits. With a local density of 0.1 DMH stars pc\(^{-3}\), we would expect \(\sim 7000\) DMH dwarfs of 0.092 M\(_{\odot}\) brighter than \(I=26.25\) in the HDF sample. We observe three stars with the appropriate colours \(\langle V-I\rangle = 1.6 \pm 0.2\) mag., implying that no more than 0.04 \% of the dark matter halo can be found as zero-metallicity, main-sequence stars near the hydrogen-burning limit. Alternatively, if we take LHS 1742a as a DMH dwarf template, then we predict 2600 DMH dwarfs in the HDF field. Again, there are only three candidates within the appropriate colour range, limiting the contribution of low-mass, metal-poor subdwarfs to no more than 0.12 \% of the total DMH mass. These results are similar to those derived by Graff & Freese (1996) based on re-analysis of the Bahcall et al (1994) HST data and appear to rule out a significant contribution to the DMH by hydrogen-burning, main-sequence stars of any abundance.

The only remaining stellar option for the dark-matter halo is white dwarf stars. Our HDF colour-magnitude diagram includes a cluster of three blue objects at \(I \sim 26\), \(\langle V-I\rangle \sim 0.5\) magnitudes. These objects are also identified as being stellar in morphology by FGB, although they derive slightly bluer colours. White dwarf stars, mainly from the disk, are the only objects predicted at these colours and luminosities - but at significantly lower surface densities. Based on our models, one expects 0.2 disk white dwarfs and 0.01 halo white dwarfs per WFPC field. Thus, the most conservative conclusion is that these faint, blue, compact objects are either low-luminosity active galactic nuclei or barely-resolved cores in faint, star-forming galaxies. However, the most recent analysis of the (relatively few) MACHO detections gives a most probable mass for the lensing objects of \(\sim 0.5M_{\odot}\) (Alcock et al, in prep.) - consistent with white dwarfs. Are the \(I \sim 26\) mag. blue objects consistent with expectations if a significant fraction of the mass of the dark-matter halo is in the form of white dwarfs?

If we interpret the 26th magnitude objects as white dwarfs, then the observed colours imply temperatures of \(\sim 10,000\) K and relatively short cooling times of \(< 10^9\) years. Our observations rule out any substantial contribution to starcounts from lower-mass, main-sequence counterparts of these white dwarfs, so we have to postulate both a sharp break in the initial mass function and fine tuning such that stars above the break evolved only recently onto the white dwarf sequence. If these white dwarfs have an average mass of 0.6 M\(_{\odot}\), then a local number density of 0.015 M\(_{\odot}\) ps\(^{-3}\) is sufficient to match the inferred local DMH mass density. If we further assume that the observed objects mark the upper end of a luminosity function similar in shape to the local disk white dwarf function (Liebert, Dahn & Monet, 1988), then we predict 32 stars with \((V-I) < 1.2\) mag. and 23 \(< I < 26\) in the HDF field and a further 60 with \(26 < I < 27\) magnitudes. Figure 12 includes only three stars in the relevant colour range with \(I < 26\) mag., implying a contribution of no more than 10 \% to the dark-matter halo mass in this model - and probably substantially less, since all three observed stars are more likely to be main-sequence subdwarfs in the conventional halo.

There remains at least one model for an all-baryonic dark-matter halo which is consistent with the low number density of stars at brighter magnitudes in the HDF. If we construct the dark-matter halo solely from old, low-luminosity \((M_V = 16)\) white dwarfs, the we predict only one DMH white dwarf with \(I < 26\) and only a further nine objects with \(26 < I < 27\). All would have \((V-I)\) colours of 1.2 to 1.5 magnitudes. However,
the predicted counts rise steeply towards fainter magnitudes, with a maximum surface density of $\sim 450$ stars per WFPC field at $I \sim 32 \pm 0.5$. We would expect 70 objects in the HDF at $I = 28.5 \pm 0.5$ mag. (approximately 10% of the galaxy number counts at that magnitude) and $\sim 300$ at $I = 30.5 \pm 0.5$ magnitudes. The major drawback, of course, is that placing even a large fraction of the mass of the dark-matter halo into these old, low-luminosity white dwarfs requires extreme fine-tuning in the initial mass function to minimise both the number of high-mass ($M > 4 M_\odot$) stars (and over-enrichment of the stellar halo from planetary nebulae and supernovae ejecta) and the number of long-lived, low-mass ($< 0.8 M_\odot$) main-sequence stars.

In summary, while these results demonstrate the substantial advantage in image classification afforded by the increased resolution of HST data, they also highlight the major limitation - the small field of view. One can use data from a single field to constrain the possible constituents of an $r^{-2}$ dark-matter halo, as FGB previously demonstrated, but the sparser luminous stellar populations of the disk and halo require observations covering at least a factor of ten more in solid angle.

4. Summary and conclusions

We have rediscussed the technique of using faint star counts as a probe of the halo subdwarf luminosity function. We have shown that even good-seeing ground-based observations are limited to $R \leq 25.5$ by star/galaxy separation problems - problems introduced by the intrinsically small size of most galaxies at these faint magnitudes. HST data can extend accurate classification at least two magnitudes fainter, but each WFPC field provides only a handful of stars. Given the small area accessible to adaptive optics correction and the low surface density of (all) faint stars, it is unlikely that such techniques will be of much practical benefit in the near future, and wide-field space-based observations are probably the most effective means of probing to such faint magnitudes.

At brighter magnitudes, star/galaxy separation techniques can be applied ground-based observations taken under good seeing conditions, although with variable success rates. We have examined four different methods and show that, depending on the method adopted and how conservative the final classification is, the number of objects classified as stars can vary by up to $\pm 10\%$ in the magnitude interval $23 < R < 24$.

Turning to analysis of the post-classification stellar sample, we have used starcount models to show, first, that fewer than 60\% of the stars with $20 < R < 24$ are from the Galactic halo and, second, that the vast majority of these subdwarfs are brighter than $M_V = +8$. The red stars ($(V-I) > \sim 2$) at these magnitudes are contributed by the disk, with the relative contributions of the old disk and IP II dependent on the prescription adopted for the deconvolution of the disk. The lowest-luminosity halo subdwarfs, the majority of which have $(V-I) < 3.0$ magnitudes, lie at substantially fainter magnitudes ($I > 28$). We have also compared our model predictions with star counts from the Hubble Deep Field and find general agreement - although the observed stellar sample is extremely small. The HDF data do, however, allow one to set constraints on several possible baryonic contributors to the dark-matter halo.

Deep star counts are most directly applied to studies of the luminous stellar populations in the Galaxy. Based on the results presented in this paper, we conclude that the steep luminosity/mass function deduced by Richer & Fahlman (1992) for the field stars in the Galactic halo is a result of combining observations of intrinsically bright halo stars with intrinsically faint (and more numerous) IP II stars. We would argue...
that there is thus no evidence that the mass function of the halo population is continuously increasing towards the hydrogen-burning limit. In general, deep ground-based starcounts are not an effective means of probing the faint end of the luminosity function of the stellar Galactic halo.

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Figure Captions

Figure 1. A comparison between galaxy counts and star counts at high galactic latitude. The solid points are the galaxy counts, taken from Metcalfe et al (1995) and S95. The lines represent the predicted star counts at \([l=90^\circ, b=45^\circ]\) (dotted line), \([l=90^\circ, b=60^\circ]\) (dashed line) and the Galactic Pole (solid line). These have been calculated using model B (described in section 3 of the text).

Figure 2. a: the \((V-R)/(R-I)\) distribution of nearby disk stars (Bessell, 1991) and halo subdwarfs. b: The VRI distribution of galaxies in the PSR 1640 field. The field-star sequence is also plotted, and the solid lines mark offsets from that sequence of ± 0.14 magnitudes in each colour.

Figure 3. The upper two panels show the distribution of image ellipticity as a function of apparent magnitude in the two Keck fields while the lower panel shows the predicted stellar distribution, based on 200 artificially-generated stars. The horizontal line marks the star/galaxy classification threshold adopted.

Figure 4. The distribution of the DAOPHOT \(\chi\) parameter as a function of magnitude. Again, the upper two panels show the observed distributions in the two fields and the lower panel shows the distribution predicted by the 200 artificial stars. The heavy solid lines in figures 3a and 3b outline the stellar locus, and the horizontal line marks \(\chi = 3\). All objects lying above the latter line were classed as galaxies.

Figure 5a. The observed distribution in the PSR 1640 field of the Jones et al (1991) peak-brightness parameter used by RF as their only star/galaxy criterion. The lower figure shows the distribution predicted by the artificial stars.

Figure 5b. The observed distribution in PSR 2229 of the Jones et al (1991) peak-brightness parameter used by RF.

Figure 6a. The ratio between the peak brightness \((I_P)\) and the total flux within a 0.6 diameter aperture for sources in the PSR 1640 field. As with the Jones et al index, this measures the degree of central concentration of the light distribution. Again, the lines plotted on the upper diagram represent the 3-\(\sigma\) limits on the stellar distribution defined by the artificial stars plotted in the lower panel.

Figure 6b. As figure 5a but for the PSR 2229 field.

Figure 7. A comparison between the observed density distribution of K dwarfs \((6.0 \leq M_V \leq 7.0)\) in the SGP (RM93) and the predicted distributions of the two stellar models described in the text. The solid points show the observed starcounts; the solid line marks the total starcounts predicted by either model; the dotted line represents the contribution from the old disk; the short-dashed line the contribution from the IP II; and the longer-dashed line the predicted number density of halo stars.

Figure 8a. The \((R, (R-I))\) colour-magnitude distribution predicted by models A and B for a 0.05 square degree field at \((l=40^\circ, b=40^\circ)\). The halo population has identical parameters in both models.

Figure 8b. The \((R, (R-I))\) colour-magnitude distribution predicted by models A and B for a 0.05 square degree field at \((l=110^\circ, b=75^\circ)\) field. Note that the colour-
magnitude distribution of the halo stars is very similar to that in the lower latitude field. In both fields the lowest luminosity halo stars make a significant contribution to the star counts only at magnitudes fainter than $R \sim 27$.

Figure 9a. A comparison between the observed $(R, (R-I))$ colour-magnitude diagram in the Keck PSR 1640 field and the predictions of model A. Halo subdwarfs in the latter model are identified as solid points; IP II stars as open triangles and disk dwarfs as crosses. The same symbols are used in identifying the contributions of the individual populations to the predicted histogram distributions at each magnitude.

Figure 9b. As figure 9a, but showing the predictions for model B. These are in slightly better accord with the observations.

Figure 10. The observed $(V, (V-I))$ colour-magnitude for stars in the RF CFHT field and the distribution predicted by model B for the 0.0122 square degree RF high latitude field. The stellar populations are coded as in previous figures, with the solid triangles identifying IP II stars lying more than 1.25 kpc. above the Plane (using the RF photometric parallax calibration). The horizontal dotted line marks the magnitude limit of $V=25$ while the vertical line marks a $(V-I)$ colour of 1.7, corresponding to $M_V = +10$. All of the stars in the upper right quadrant are drawn from the IP II.

Figure 11. Star-galaxy discrimination in the HDF field, plotting peak flux against magnitude for all objects identified on the F814 I-band data. We have used a bright unsaturated star as a PSF template and the open circles, derived by scaling this template to fainter magnitudes, define the stellar sequence. Solid triangles are objects classed as definitely stellar; solid squares are possible stars; crosses are galaxies.

Figure 12. The $(I, (V-I))$ colour-magnitude diagram described by objects classed as stars in the Hubble Deep Field. The crosses identify objects where the morphological classification is uncertain.

Figure 13. The $(I, (V-I))$ colour-magnitude diagrams predicted by models A and B for a solid angle ten times that of the HDF. The stellar populations are coded as in figure 8.
Table 1. Summary of Observations

| Field      | α J2000       | δ J2000       | Filter | T<sub>tot</sub> sec | N | FWHM '' |
|------------|---------------|---------------|--------|---------------------|---|---------|
| 1640+22    | 16<sup>h</sup>40<sup>m</sup>18<sup>s</sup>.9  | +22°24′19″.0  | V      | 1500                | 1 | 0.78″   |
|            | l = 41.1°     | b = 38.3°     | R      | 2400                | 2 | 0.55″   |
|            |               |               | I      | 2000                | 4 | 0.53″   |

| Field      | α J2000       | δ J2000       | Filter | T<sub>tot</sub> sec | N | FWHM '' |
|------------|---------------|---------------|--------|---------------------|---|---------|
| 2229+26    | 22<sup>h</sup>29<sup>m</sup>50<sup>s</sup>.9  | +26°43′52″.8  | V      | 900                 | 1 | 0.87″   |
|            | l = 87.7°     | b = −26.3°    | R      | 2100                | 2 | 0.58″   |
|            |               |               | I      | 1000                | 2 | 0.58″   |

Notes to Table 1
The full-width half-maximum listed is the seeing from the final averaged image. T<sub>tot</sub> is the total exposure time for each colour.
# Table 2a. Summary of Star Counts in Field PSR 1640

| Star Selection | R=21−22 | R=22−23 | R=23−24 | R=24−25 |
|----------------|---------|---------|---------|---------|
| $\epsilon$     | 42      | 79      | 228     | 905     |
| $\chi$         | 58      | 142     | 290     | 459     |
| $\epsilon+\chi+I_{\text{peak}}$ (R) | 34      | 41      | 54      | 107     |
| $\epsilon+\chi+I_{\text{peak}}+F_{0.6}$ (R) | 36      | 35      | 51      | 96      |
| $\epsilon+\chi+I_{\text{peak}}$ (RI)    | 33      | 36      | 44      | 76      |
| $\epsilon+\chi+I_{\text{peak}}+F_{0.6}$ (RI) | 30      | 33      | 44      | 75      |
| $\epsilon+\chi+I_{\text{peak}}$ (VRI)   | 30      | 32      | 45      | 28      |
| $\epsilon+\chi+I_{\text{peak}}+F_{0.6}$ (VRI) | 27      | 33      | 38      | 23      |

| $N_{\text{galax}}$ | 99 | 208 | 435 | 911 |
### Table 2b. Summary of Star Counts in Field PSR 2229

| Star Selection | R=21−22 | R=22−23 | R=23−24 | R=24−25 |
|----------------|---------|---------|---------|---------|
| $\epsilon$     | 80      | 141     | 228     | 461     |
| $\chi$         | 69      | 147     | 332     | 1057    |
| $\epsilon+\chi+I_{peak}$ (R) | 45    | 75      | 99      | 203     |
| $\epsilon+\chi+I_{peak}+F_{0.6}$ (R) | 42    | 64      | 46      | 82      |
| $\epsilon+\chi+I_{peak}$ (RI) | 16    | 19      | 16      | 31      |
| $\epsilon+\chi+F_{0.6}$ (RI) | 16    | 24      | 36      | 90      |

**Notes to Table 2**

As described in the text, we have used four techniques to discriminate stars and galaxies. Column 1 identifies the criterion or criteria used to derive the star counts — thus '$\epsilon+\chi+I_{peak}$' means that to be classified as stars, objects must satisfy the ellipticity, $\chi$ and Jones et al (1991) criteria (this matches the classification method used by RF). We have listed the star counts if we base our analysis only on the R-band frames (identified as (R) in the Table); if we insist on detection on the I-band frames ( (RI) ); or detection in all three passbands ( (VRI) ). Note that we require only detection in the other passbands - insisting on classification as stellar would reduce the sample size still further. Finally, we list the galaxy counts derived by S95 for field PSR 1640. These last data have been corrected for incompleteness (see S95 for full details).
Nearby stars

subdwarfs

galaxies R < 25

PSR 1640
PSR 1640 data

Model A

21 < R < 22

22 < R < 23

23 < R < 24

24 < R < 25

N / 0.2 mag. (R-I)
PSR 1640 data

Model B

21 < R < 22

22 < R < 23

23 < R < 24

24 < R < 25
