1 INTRODUCTION

The dynamically inferred mass of the Galaxy seems to exceed current estimates of the contribution by stars, gas and dust (Fich & Tremaine 1991). Evidence for non-luminous matter exists in other galaxies, particularly large spirals with well-determined rotational velocity curves (Faber & Gallagher 1979; Rubin, Ford & Thonnard 1982). Contrary to the other, cosmologically more relevant, 'missing mass problems', the amount of Galactic dark matter can still comfortably lie within the upper limit of baryonic matter imposed by the standard big bang nucleosynthesis model (Silk 1990; Walker et al. 1991; Mathews, Schramm & Meyer 1993; Carr 1994). Thus it is certainly wise to consider low-mass stars or gas as possible candidates for the Galactic missing matter.

In recent years, some evidence has been found for a steeply rising stellar luminosity function in several of the halo globular clusters (Richer et al. 1991; Richer & Fahlman 1992). Despite the uncertainties in the mass–luminosity relation for low-mass, low-metallicity stars (cf. Elson et al. 1995), these results have suggested that the mass of the stellar populations in the halo of the Galaxy may be larger than previously thought. However, ground-based studies of globular clusters are severely affected by crowding, and thus necessarily involve large completeness corrections. Similarly, field star-count studies and searches for new stellar populations, especially in the Galactic spheroidal component, are seriously limited by the difficulty of separating stars from extragalactic objects at magnitudes beyond \( V \approx 20 \) (Kron 1980; Reid & Gilmore 1982; Stobie & Ishida 1987; Reid 1990). This limitation prevents strong observational constraints being placed on the number of low-mass main-sequence stars with \( M_V \geq 13 \), since such objects are probed only within fairly local volumes, out to distances of no more than 250 pc. Thus, besides being hampered by

ABSTRACT

We use star counts from 17 deep fields imaged with the Wide Field Camera 2 (WFC-2) as part of the HST Medium Deep Survey key project in order to constrain the amount of dark matter in the Galaxy that can be in the form of low-mass main-sequence stars or white dwarfs. Based on the number of red stars found in our fields, we exclude the possibility that more than 15 per cent of the massive dark halo in the Galaxy is made up of M dwarfs or subdwarfs; fairly massive \(( M \approx 0.2 \, M_\odot )\) and yet extremely faint \(( M_V \approx 14.5 )\) stellar candidates would have to be invoked in order to make the observed number of stars compatible with that predicted by a stellar dark halo. White dwarfs must also be intrinsically very faint \(( M_V \approx 14 )\) in order to be consistent with the observed number of faint stars in the HST fields. We rule out an increasing or flat stellar luminosity function beyond \( M_V \approx 13 \). The inferred disc luminosity function is intermediate between that derived with complete parallax samples of nearby stars and the results of photometric studies of more distant ones. Finally, the magnitude counts are well fitted by existing models for the structure of the Galaxy, except for an excess of stars with \( 23 < V < 23.5 \). The colour distribution, however, is not as well reproduced by the models, especially if the thick disc component is neglected. However, the overall agreement between models and the data precludes the need to add any significant new stellar population to the ones assumed to exist.

Key words: stars: low-mass, brown dwarfs – stars: statistics – white dwarfs – Galaxy: halo – Galaxy: stellar content – Galaxy: structure.
small-number statistics, ground-based field star counts of low-luminosity stars do not reach distances beyond one disc scaleheight, even in high-latitude fields. Another important issue for such studies is the existence of selection effects caused by photometrically unresolved binaries, leading to a possible confusion in the conversion from observed to true star counts.

Much progress on both globular cluster and field star count studies can be achieved with the Hubble Space Telescope (HST). Recent globular cluster faint star counts have been carried out by De Marchi & Paresce (1995a,b), Elson et al. (1995), Paresce, De Marchi & Romaniello (1995) and Santiago, Elson & Gilmore (1996), all requiring relatively small completeness corrections. No evidence for a steeply rising luminosity function was found. In the field, with HST’s much improved spatial resolution, star–galaxy separation can be reliably performed down to $V \sim 24-26$, allowing us to probe the faint end of both disc and halo main sequences within distances of about 1–2 kpc. The larger depth achievable by the HST field star counts opens up the possibility of further constraining the current models for the structure of the Galaxy (Bahcall & Soneira 1980, 1984; Gilmore & Reid 1983; Reid & Majewski 1993). Because of the difficulty in probing well into the spheroidal component, relatively poor constraints have been obtained so far for the luminosity function and density profiles of the stellar halo of the Galaxy. Another poorly defined region in parameter space describing the structure of the Milky Way is the intermediate Population II component, or thick disc, although considerable progress has recently been made in quantifying its properties (Ojha et al. 1994).

In this paper we present star counts for 17 deep Wide Field and Planetary Camera 2 (WFPC-2) high-galactic-latitude fields. In Section 2 we describe our data, the reduction and calibration methods, and the stellar sample selection. We also discuss the issues of star–galaxy separation and sample completeness corrections. In Section 3 we present our results. We compare the observed number of red stars with predictions based on the assumption that the dark halo of the Galaxy is made up of such objects. The case for white dwarfs as a dark matter candidate is also discussed. We use the counts of red stars to constrain the slope of the faint end of the stellar luminosity function, and compare it with previous estimates. Finally, we compare the entire observed magnitude and colour distributions with the predictions made by existing models of Galactic structure. Our conclusions are presented in Section 4.

2 THE STELLAR SAMPLE

2.1 The data and sample selection

The 17 WFPC-2 fields used in this work were obtained as part of the Medium Deep Survey key HST project (MDS). They are all fairly deep, high-galactic-latitude fields, as can be assessed from Table 1. Column 1 lists the MDS field identification name, columns 2 and 3 give their galactic coordinates and columns 4 and 5 list the exposure times in both HST I and V wide filters (F814W and F606W, respect-
HST fields are the result of parallel observations made during the HST General Observing time. For more information about MDS itself and its many applications we refer the reader to Griffiths et al. (1993, 1994).

All fields consist of multiple exposures which were put through the standard HST pipeline reduction method (Holtzmann et al. 1995). This method applies overscan, residual bias and dark current subtractions, flat-fielding, and corrects for several instrumental effects. The individual calibrated frames were then co-added and median-filtered in order to eliminate cosmic ray events. For that purpose, use was made of an IRAF package written by K. Glazebrook. Some fields were dithered, so that hot pixels were also eliminated during the stacking process. The others had the hot pixels identified and masked out using software kindly provided by N. Tanvir. The number of individual frames available in each field and for each bandpass is listed in columns 6 and 7 of Table 1.

Throughout this work we have restricted ourselves only to the three Wide Field Camera (WFC-2) chips, since the Planetary Camera (PC) chip, besides covering only a small area in the sky, would require a different star/galaxy classifier (see discussion below). Also, we have not applied any correction for Galactic absorption to the magnitudes and colours; all the magnitude values quoted correspond to uncorrected data. However, according to a standard Galactic (cosec) reddening distribution, the maximum value of $A_V$ among our fields is 0.13 mag ($A_V \sim 0.23$ mag) for sources outside the Galaxy.

Object detection was carried out using the APM software IMAGES. We adopted a detection threshold of $1.5 \sigma_{\text{sky}}$, where $\sigma_{\text{sky}}$ is the standard deviation in the background counts for each field and WFC-2 chip. We detected objects in both F814W and F606W frames, and defined as our primary object list those objects common to both. This helped to eliminate cosmic ray residuals from our sample. The adopted threshold of detection corresponded to surface brightness levels in the ranges $23.0 \leq \mu_{\text{814}} \leq 25.0$ mag arcsec$^{-2}$ and $24.0 \leq \mu_{\text{606}} \leq 26.0$ mag arcsec$^{-2}$ for the HST $I$ and $V$ bands, respectively. The output files of IMAGES list positions, shape parameters, magnitudes and a central intensity to total flux ratio for each object detected, $I_{\text{peak}}/I_{\text{tot}}$.

The initial star object list for each field consisted of faint galaxies, substructure belonging to larger galaxies (H II regions, spiral arms, etc.), stars, substructure around the point-spread function (psf) of bright stars, chip defects and cosmic ray residuals. In order to define a stellar sample, we tried two different approaches. The first consisted of using $I_{\text{peak}}/I_{\text{tot}}$ as a discriminant between stars and other objects: stars are expected to have larger $I_{\text{peak}}/I_{\text{tot}}$ values and rounder shapes than most other detected features. The second alternative was to fit each object to the WFC-2 psf and to use the quality of the fit (expressed as both a formal magnitude error and a $\chi^2$ value) to select the stars. The stellar samples derived both ways are largely overlapping. Since the psf-fitting method uses the information contained in all pixels belonging to each object, we opted to use this latter as our official classification method. However, the analysis described in Section 3 was also carried out with the alternative stellar sample (selected on the basis of $I_{\text{peak}}/I_{\text{tot}}$), leading to similar results.

The shape of the psf was obtained by fitting a Moffat function (with $\beta = 1.5$) to bright isolated stars in fields at low galactic latitudes. The psf was seen to be stable over time and from chip to chip. We used the IRAF package DAOPHOT to derive the psf and to fit it to the objects detected in the high-latitude fields. In Fig. 1 we show the formal magnitude errors (in the F814W filter) and $\chi^2$ values as a function of $I_{\text{tot}}$ for one of the low-latitude fields from which we derived the shape of the psf. There are basically three distinct loci in both panels. Real stars tend to be well fitted by the WFC-2 psf and have low $\delta I$ and $\chi^2$ values. Faint galaxies, spiral arms and other galactic substructures have higher values of both parameters. The clump of bright objects with similarly high $\delta I$ and $\chi^2$ is made up of structure along the psf of bright saturated stars. Our official classifier consisted of objects with $\delta I < 0.15$ and $\chi^2 < \min \{-0.3 I_{\text{tot}} + 8, 2\}$. This classifier is shown by the straight lines in Fig. 1. Notice that the separating lines cut through the upper part of the stellar locus, yielding to some loss of likely stellar candidates. This conservative classifier aims at reducing galaxy contamination. All fields were visually inspected in search of contaminating non-stellar objects wrongly included in the sample. No significant number was found.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) The $\delta I_{\text{tot}}$ versus $I_{\text{tot}}$ relation for a low-latitude MDS field. The solid line corresponds to $\delta I_{\text{tot}} = 0.15$ mag. Both magnitudes and associated errors were derived from psf fitting. (b) The relation between the psf-fit quality parameter $\chi^2$ and $I_{\text{tot}}$ for the same objects as in panel (a). The two solid lines correspond to $\chi^2 < \min \{-0.3 I_{\text{tot}} + 8, 2\}$.

© 1996 RAS, MNRAS 281, 871-882
The psf-fitting method has the advantage that it automatically eliminates saturated stars (since they will not provide good fits to the WFC-2 psf). Yet, in order to compare the observed star counts to model predictions, we need to specify nominal magnitude limits at both the bright and faint ends. The limit at the bright end for each field was chosen on the basis of panels like those of Fig. 1, as well as on the run of $I_{\text{peak}}/F_{\text{tot}}$ with $I_{614}$ magnitudes. Stars in our high-latitude fields typically saturated at $I_{614} < 18-19$. The faint cut-off limit was chosen as the one for which the completeness function (as discussed in Section 2.2) dropped below 0.4. This cut-off value is in the range $I_{614} = 23.5-25.0$ for all fields. The faint limit defined in this way is always brighter than the magnitude at which the stellar and galaxy loci merge in Fig. 1(b), which again helps in preventing significant contamination of the stellar sample by galaxies. Our choice of star/galaxy classifier is arbitrary and requires an objective way of assessing issues like completeness of the stellar sample. This is done in the next section.

2.2 Completeness corrections, aperture corrections and photometric calibration

We tested the adopted star/galaxy classifier and the sample completeness by means of simulations. We again used the IRAF DAPHOt package for that purpose. Stellar images following the derived shape of the WFC-2 psf were created in each of the 17 fields. Several hundred stars with magnitudes in the range $20 < I_{614} < 25$ were added to the original images in several realizations (to minimize crowding effects), allowing a completeness function to be independently obtained for each field. This completeness function is shown in Fig. 2(a) for several of the fields, and incorporates the loss of stars due to detection as well as that due to classification. It is clear from the figure that there are non-negligible differences in completeness among the fields studied, reflecting variations in exposure time, background noise and crowding.

$V_{606}$ completeness functions were determined in a similar way. Since star selection was done in the $I_{614}$ band, however, the $V$-band completeness functions account only for the loss of objects due to detection. They are shown in Fig. 2(b) for the same fields as in Fig. 2(a). Most fields are more than 50 per cent complete at $V_{606} = 26.5$. The final completeness function assigned to each star in the sample was the product of both $I_{614}$ and $V_{606}$ completeness functions. As explained in Section 2.1, the $I_{614}$ magnitude cut-off limit was chosen on the basis of the $I$-band completeness function. This adopted limit automatically eliminated all sources with $V_{606} > 27$. Thus the joint $I_{614}/V_{606}$ completeness was never smaller than 0.2 for any star in the sample.

The magnitudes derived from psf fitting are a result of scaling the total flux in the psf template (derived from bright isolated stars) to that of each object being fitted. However, the magnitude assigned to the template psf itself corresponds to an aperture of 2-pixel radius (0.2 arcsec). This small aperture size was used in order to avoid contamination by remaining cosmic ray residuals, hot pixels or neighbouring objects. Thus we needed to apply an aperture correction of 0.3 mag to account for the light lying outside the adopted aperture (WFPC-2 Instrument Handbook version 2.0). This aperture correction was applied to both $HST I$ and $V$ magnitudes, and was observed to be quite stable for different chips or fields.

The aperture-corrected instrumental magnitudes were converted to the standard Johnson–Cousins system using the transformations given by Holtzman et al. (1995). Since we are mainly interested in faint red stars, we used the synthetic transformations listed by those authors to convert our magnitudes to the standard system. Photometric calibration may be uncertain, especially in the blue and red ends of the stellar colour distribution. We thus checked our results with an alternative calibration method, using the transformations given by Bahcall et al. (1994).

The two calibration methods agree fairly well: Bahcall et al. $I$ magnitudes are systematically fainter by 0.10 mag at the most. In the $V$ band, the alternative method leads to brighter (fainter) magnitudes for blue (red) stars. The discrepancy, however, is again no more than 0.1 mag. However, since $(V-I)$ is a strong function of the effective temperature for low-mass main-sequence stars, we refrain from using the observed differential colour counts in both red and blue extremes for any purpose in the next section. We will rely only on integral numbers, as given by the standard calibration method proposed by the WFPC-2 team. The effect of adopting the alternative photometric calibration may be uncertain, especially in the blue and red ends of the stellar colour distribution.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** (a) $I_{614}$ completeness functions for five of the 17 MDS fields in this paper. The completeness functions were obtained by adding simulated stars to the field images and applying to them the same detection and star selection procedures applied to the data. (b) $V_{606}$ completeness functions for the same five fields shown in panel (a).
transformations of Bahcall et al. (1994) will be assessed in each section.

In Fig. 3 we show the colour–magnitude diagram (CMD) for our stellar sample. It contains a total of 329 objects. With completeness corrections, this number increases to 419. The red end of the CMD spans a large range of apparent magnitudes, indicating the presence of both disc and halo red dwarfs. One can also distinguish two main, though very wide, clumps of objects, one clustered in the region around $V - I \approx 2, I \geq 21$, and the other seen at redder colours ($2 \leq V - I \leq 3$). The first corresponds to halo stars close to the main-sequence turn-off, whereas the second is dominated by thick disc and disc G and K dwarfs (Reid 1992).

3 STAR COUNTS

3.1 Limits on the stellar dark matter

In this section the observed numbers of red low-mass main-sequence stars are compared to model predictions under the assumption that the massive halo of our Galaxy is made up of such objects. We use the dark matter halo model proposed by Bahcall, Schmidt & Soneira (1983). This model assumes a spherical dark matter distribution with a mass density profile given by

$$\rho(r) \propto \left(\frac{r}{r_0}\right)^{-1.8},$$

where $r_0 = 2$ kpc, and whose normalization is given by a mass density of $0.009 M_\odot$ pc$^{-3}$ at the solar distance. The gravitational field generated by adding this model dark matter component to the distribution of luminous material provides a good fit to the observed rotational velocity profile of the Galaxy. Once the dark matter distribution is specified, the expected number of stars which would be seen in our 17 HST fields depends only on the absolute magnitude $M_\ell$ and mass $M$ of the dark matter stellar candidate. The first quantity defines the maximum distance (and hence the volume) out to which the candidate stars can be detected in each field. To be consistent with the observed star counts, the effect of extinction was incorporated when estimating this maximum distance. The predicted number of stars is then simply the total dark halo mass within this volume divided by $M$.

In Fig. 4(a) we show these numbers for several values of $M_\ell$ and $M$. The upper curve utilizes masses taken from Kroupa, Tout & Gilmore (1993). Ideally, we would like to use a mass–luminosity relation more appropriate for metal-poor stars (as expected for a halo population). However, these are rather uncertain, and do not cover the very faint absolute magnitudes we are interested in in this work. Notice that the Kroupa et al. relation should provide a lower limit to the expected number of dark halo stars, since metal-poor stars would tend to be less massive at a fixed luminosity. Kroupa et al. derive a relation in the $M - M_\ell$ plane. $V$-band absolute magnitudes were taken from the $M_\ell$ values of each candidate under the assumption that

Figure 3. Colour–magnitude diagram for the stellar sample selected from the 17 MDS fields. Both magnitudes and colours are in the Johnson–Cousins system. Conversion from the HST passbands was done using the 'synthetic' transformations quoted by Holtzmann et al. (1995).

© 1996 RAS, MNRAS 281, 871–882
Figure 4. (a) Predicted number of M dwarfs and subdwarfs with different absolute magnitudes $M_V$ and masses $M$. Masses for the open squares and the dashed line were taken from Kroupa et al. (1993) $M_V$–$M$ relation, assuming $V-I=3.0$ for all candidates. The solid symbols and line represent predictions for a fixed mass of 0.2 $M_\odot$. The horizontal lines correspond to the observed number of MDS stars with $V-I<3.0$ (solid) and its 99 per cent Poisson deviate (dotted). (b) Predicted number of 0.65–$M_\odot$ white dwarfs of different $M_V$ magnitudes. The horizontal lines are the observed number of $V-I<0.8$ stars (solid) and its corresponding 99 per cent Poisson deviate (dotted).

$V-I=30$ in all cases. This again tends to underestimate the number of stars, since the true colours should be redder than $V-I=3.0$ for $M_V>11.5$, leading to fainter $M_V$ and, consequently, smaller masses. The lower curve makes the ultraconservative assumption of $M=0.2 M_\odot$ for all candidates, regardless of their luminosity. Finally, the solid horizontal line gives the observed numbers of $HST$ stars with $V-I>3.0$. The dotted line represents the 99 percentile position of a Poisson distribution with mean value given by the observed number. We conclude that most faint stellar candidates are ruled out at more than 99 per cent confidence level. In order to reproduce the observed numbers, one needs to invoke stars with $M_V\geq 14.5$ but still fairly massive. This violates what we know about the mass–luminosity relation for main-sequence stars, since $M_V=14.5$ should be very close to the hydrogen-burning limit ($\sim 0.08 M_\odot$).

Another stellar dark matter candidate could be white dwarfs (Larson 1986; Tamanaha et al. 1990). In Fig. 4(b) we show the predicted number of white dwarfs as a function of $M_V$. We assume that $M=0.65 M_\odot$ independently of the absolute magnitude. This value is well bracketed by the mass range found in several different studies (Liebert 1980). The observed number (and its corresonding 99 per cent Poisson deviate) now corresponds to objects in the blue end of the colour–magnitude diagram shown in Fig. 3 ($V-I<0.8$). Again, very faint ($M_V\geq 14$) white dwarves are required if they are to account for the entirety of the dark matter in the Milky Way. It is an interesting coincidence that this luminosity limit is comparable to that of the lowest luminosity (disc) white dwarves yet known (Liebert, Dahn & Monet 1988). Current cooling models provide an age for such cool degenerates of about 10 Gyr (Wood 1992; cf. von Hippel, Gilmore & Jones 1995). Of course, any white dwarf descendants of an early halo population will have an age of that population. Such stars will have $M_{bol}(\sim M_V)\sim 16$ (cf. fig. 3 of von Hippel et al. 1995), about 1 mag fainter than our present limits. However, any stars with mass initially below $\sim 1 M_\odot$ which might have formed would have been visible in this survey.

There are two reasons to believe that the derived constraints on the stellar dark mass candidates are much stronger than the ones inferred from Fig. 4. First, not all objects with $V-I>3.0$ (or $V-I<0.8$) are actually stars. Both red and blue stellar counts may be contaminated by some unresolved galaxies. The blue sample should also be contaminated by quasars. Given our conservative star/galaxy classifier described in Section 2.1, however, galaxy contamination should be negligible. Secondly, in comparing the predicted and observed numbers, we are implicitly assuming that the latter is made up of dark halo stars only; obviously, both red dwarf and white dwarf samples should be contaminated by disc, thick disc and stellar halo stars. In fact, models for the Galaxy predict that most of the faint red stars we observe actually belong to the disc and thick disc components (see Section 3.2).

An alternative way of estimating the contribution of red subdwarfs to the total Galactic mass is by constraining the slope of the faint end of the halo luminosity function. More specifically, we can compare the inferred value for this slope, derived under the assumption that faint stars account for the Galaxy’s missing mass, to the slope obtained from star counts constraints.

For a given domain in absolute visual magnitudes $M_V<M_V-M_n$, we assume that the dark halo stellar luminosity function, $\Phi(M_V)$, is a power law,

$$\Phi(M_V)\propto 10^{y_s M_V}, \quad M_n<M_V<M_A, \quad (2)$$

where $y_s$ is the slope. We normalize $\Phi(M_V)$ locally at the bright end of the specified domain ($M_A$) to 1/500 of the observed disc luminosity function, $\Phi(M_V)$ (Bahcall & Soneira 1984). Since $\Phi(M_V)$ is known with reasonable accuracy only down to $M_V\sim 13$, we adopt $M_n=13$ as the normalization point. In reality, the 1/500 normalization comes from studies of high-velocity stars that are assumed to be in the stellar halo of the galaxy (usually described by a de Vaucouleurs density law). In this experiment we are again making the conservative assumption that all such high-velocity stars are actually members of the dark matter halo for $M_V>13$. This is equivalent to postulating that the stellar halo luminosity function drops sharply to zero beyond $M_n$. We also assume expression (2) to be valid down to $M_n=19$, which should be very close to the hydrogen-burning limit. Adopt-
ing the local normalization for the mass density of the dark halo as given by Bahcall et al. (1983) \((\rho = 0.009 \, M_\odot \, pc^{-3})\) and demanding it to be in the form of low-mass stars with \(13 < M_\ast < 19\), and with a mass–luminosity relation given by Kroupa et al. (1993), we derive a slope of \(\gamma_s = 1.56\). Assuming that \(M = 0.2 \, M_\odot\) for all faint stars, we find that \(\gamma_s = 1.35\). These results are summarized in the first two lines of Table 2. We list the nature of the constraint on \(\gamma_s\), the assumed range in \(M_\ast\), the adopted mass–luminosity relation and the inferred slope of \(\Phi_h(M_\ast)\).

These values for \(\gamma_s\) can then be compared with that needed to match the observed number of stars with \(V - I > 2.40\) \((M_V > 13, \ M_I > 10.6)\) in our MDS fields. We again assume very conservatively that all such stars belong to the dark halo of the Galaxy, with the same density profile and luminosity function used in the previous experiment, even though most of these stars are expected to be thick disc or disc stars. We also use the same normalization at the bright end of the luminosity function. For a given slope \(\gamma_s\), the predicted number of stars depends on the assumed range of \(M_\ast\), \(10.6 < M_\ast < 14.1\), since the sample selection was based on the F814W magnitudes. This range of \(M_\ast\) was obtained from the \(M_\ast\) versus \((M - I)\) relation given by Bahcall et al. (1994) for spheroid and halo stars. We again take extinction into account in our computations. We obtain \(\gamma = 1.39\). The results are listed in the third line of Table 2. In the last column, we list the fraction of the dark matter that would correspond to the given slope, for both Kroupa et al. (1993) (first value) and \(M = 0.2 \, M_\odot\) (second value) masses.

Again we account for the Galaxy dark matter only if we assume that \(M \sim 0.2 \, M_\odot\) for all stars with \(M_\ast > 13\).

The slope value depends slightly on the interval in \(M_\ast\), within which they are fitted, but the constraints on the amount of stellar dark matter do not. The same argument applies to the normalization used for the halo luminosity function at \(M_\ast\): a value of 1/800 has been used in several star-count studies (Bahcall & Soneira 1980; Gilmore 1984), and is favoured by most recent star-count analyses of Galactic structure (e.g. Soubiran 1993; Perrin et al. 1995). Had we adopted this latter normalization, the slopes would be larger in both estimates (based on dark matter and star-counts constraints), bearing no effect on our main conclusion.

We conclude that the results of both experiments described above (and in Fig. 4 and Table 2) show qualitative agreement in that very faint but fairly massive stellar candidates have to be assumed to account for the Galaxy’s dark matter. Besides, an additional strong assumption about halo membership of the entire observed faint star counts has to be made. More realistic estimates on the amount of dark halo mass consisting of faint stars can be obtained by dropping these assumptions. Rather than trying to incorporate the contribution of the disc and the thick disc, which would be a model-dependent approach, we now restrict ourselves to the six fields with \(|b| > 50^\circ\) located more than 60° away from the direction of the centre of the Galaxy: ucs0, ub11, uad0, ua-0, uax1 and ucl1. The slope of the halo luminosity function now is 1.01, accounting for 8 per cent of the dark halo’s mass if we use the mass–luminosity relation of Kroupa et al. (1993). As a last experiment, we have estimated the slope using the 99 per cent Poisson deviate from the observed number of stars in these six fields with \(V - I > 2.4\), obtaining \(\gamma_h = 1.18\). An upper limit of 16 per cent for the fraction of stellar dark matter results from this last experiment. The results are summarized in the last two lines of Table 2.

In brief, only under the extremely conservative assumptions that stars as faint as \(M_\ast \sim 19\) have \(M = 0.2 \, M_\odot\) and that all MDS red stars are in the dark halo, the fraction of the dark halo mass due to the M sub dwarfs can approach unity. Under more realistic assumptions on the stellar masses and halo membership, we derive an upper limit of about 16 per cent with 99 per cent confidence. This is in good agreement with recent deep infrared surveys, which derive tight upper limits on the number of faint halo M dwarfs (Hu et al. 1994; Bahcall et al. 1994).

Our results would be essentially unchanged had we used the alternative photometric calibration of Bahcall et al. (1994). Using this latter would lead to a larger number of white dwarfs and a smaller number of stars with \(V - I > 3\), but without changing the basic conclusions. The results presented in this section are also insensitive to the method used to define the stellar sample; had we used the \(I_{peak}/F_0\) ratio as discussed in Section 2.1, the constraints obtained here would have been very similar.

### 3.2 The stellar luminosity function

We now consider what constraints the observed counts of red stars impose on the faint end of the stellar luminosity function under the more realistic assumption that disc, thick disc and halo stars are contributing to these counts. For the disc and thick disc we consider the \(\Phi_s(M_\ast)\) slope \((\gamma_s)\) in the interval \(13 \leq M_\ast \leq 19\), which corresponds to \(10.1 \leq M_V \leq 14.2\). Thus \(\gamma_s\) is determined by matching model

### Table 2. Constraints on the slope of the halo \(V\)-band luminosity function.

| Nature of constraint | Domain in \(M_V\) | Mass         | \(\gamma_s\) |
|----------------------|------------------|--------------|--------------|
| Stellar DM           | 13.0 – 19.0      | Kroupa et al | 1.56         |
| Stellar DM           | 13.0 – 19.0      | 0.2 \(M_\odot\) | 1.35 |
| 17 fields - obs. counts | 13.0 – 19.0      | 1.39         | 0.44/1.21  |
| 6 fields - obs. counts | 13.0 – 19.0      | 1.01         | 0.08/0.20  |
| 6 fields - 90% counts  | 13.0 – 19.0      | 1.18         | 0.16/0.44  |

© 1996 RAS, MNRAS 281, 871–882
predictions to the observed counts with $V-I \geq 2.9$. The corresponding range for the stellar halo $\gamma_h$ is then $14.3 \leq M_v \leq 19.0$ (11.4 $\leq M_v \leq 14.1$). These magnitude and colour intervals assume $M_v$ versus $(V-I)$ relations taken from Monet et al. (1992) and Bahcall et al. (1994). We use standard density laws for the three components of the Galaxy. The thin and thick discs both have exponential profiles with a scalelength of 3.5 kpc and scaleheights of 325 and 1300 pc, respectively. For the stellar halo we adopt a de Vaucouleurs profile with effective radius $r_e = 2700$ pc.

In Table 3, we list the results. Column 1 gives the model components whose contributions to star counts were matched to the observed numbers. Column 2 lists the number of stars redder than $V-I = 2.9$, and column 3 lists the derived slope at the faint end. If we assume the same power-law shape and slope for the luminosity functions of all components, we derive $\gamma_d = -0.45$. Assuming that all stars belong to the disc, we obtain $\gamma_d = -0.18$. We have also derived the slope values that match the 99 per cent Poisson deviates of the observed numbers (last two lines). Even if we overlook the contribution by thick disc and halo stars, we still obtain $\gamma_d = -0.04$. The inclusion of the halo has a small effect on the derived slope, but the thick disc contribution should not be neglected. Thus our data are inconsistent with a flat or increasing faint end for the stellar luminosity function with more than 99 per cent confidence. Apart from statistical fluctuations, the main source of error is probably the uncertainty in the MDS red star counts due to photometric calibration. This uncertainty, however, is not large enough to affect the conclusion of a decreasing luminosity function. Other factors influencing the slope include uncertainties in the CMD of low-mass stars (which affect the observed numbers through the $V-I$ colour range associated with $M_v > 13$) and the $M_v$ interval used for fitting $\gamma$.

Our best estimate of the disc luminosity function based on the star counts is shown as the solid line in Fig. 5, along with the results of previous works (Wielen, Jahreiss & Kröger 1983; Dahn et al. 1986; Jahreiss 1987; Stobie, Ishida & Peacock 1989; see also Bessel & Stringfellow 1993). It represents the derived value of the disc + halo + thick disc luminosity function slope ($\gamma_d = \gamma_h = -0.45$). The two dashed lines correspond to the extreme cases of using the 1 and 99 per cent Poisson deviates of the observed number counts.

| Components                  | # of stars | $\gamma$ |
|-----------------------------|------------|----------|
| Disk + Thick Disk + Halo    | 71         | -0.45    |
| Disk                        | 71         | -0.18    |
| Disk + Thick Disk + Halo    | 91 (99%)   | -0.26    |
| Disk                        | 91 (99%)   | -0.04    |

**Table 3.** The faint end of the stellar luminosity function from star counts.

![Figure 5](https://example.com/figure5.png)
Clearly, no strong constraint can be placed on the disc luminosity function without better statistics. Our best estimate of $\Phi_d(M_v)$, however, lies in between those of parallax surveys and the estimates based on ground-based photometric samples. Our best slope is more consistent with these latter studies. However, this may be an artefact of our normalization: at $M_v=13$ mag, $\Phi_d$ based on the parallax surveys is significantly different from that inferred from photometric samples. Had we adopted a lower normalization (more consistent with the photometric data), the slope would be necessarily shallower in order to accommodate the observed number of stars with $V-I>2.9$. It has been shown that the photometric samples are incomplete by $\sim 20-50$ per cent because of unresolved binaries (Kroupa, Tout & Gilmore 1991; Reid 1991). Our derived disc luminosity function based on HST data, being less affected by this problem, consistently lies above the ground-based photometric luminosity function shown in the figure. We are also at variance with the HST results of Gould, Bahcall & Flynn (1995). Part of the discrepancy with this later work lies in the different calibration methods. The transformation to the standard system used by Bahcall et al. (1994) and Gould et al. (1995) would reduce by 20 per cent the number of stars with $V-I>2.9$ in our sample.

3.3 Comparison with models for the Galaxy

The star counts for the 17 MDS fields are shown in full in Fig. 6. Panel (a) shows the magnitude counts, whereas panel (b) shows the colour distribution. Both distributions include completeness corrections and Poissonian error bars. We also show the predicted counts from two models for the Galaxy; the dotted lines assume only two Galactic components (disc and halo) and correspond to a model historically proposed by Bahcall and collaborators (Bahcall & Soneira 1980, 1984, hereafter BS, and references therein), whereas the solid lines include the thick disc, originally suggested by Gilmore & Reid (1983, hereafter GRW). The density laws, luminosity functions and colour–magnitude diagrams are summarized in Table 4. They correspond to standard assumptions used by previous star-count studies (see Gilmore, Wyse & Kuijken 1989, Gilmore, King & van der Kruit 1990 and Reid & Majewski 1993 for reviews). The density laws are the same as used in the previous section. The model predictions use $M_v$ versus $(B-V)$ colour–magnitude diagrams and $V$-band luminosity functions. The $V$-magnitude counts were converted to the $I$ band by means of several $M_v$ versus $(V-I)$ relations. The $(V-I)$ colour distributions were obtained in the same way. For faint and bright disc stars, fits to the $M_v$ versus $(V-I)$ main sequence given by Monet et al. (1992) and Prosser (1992) were used, respectively. The corresponding halo main-sequence fits were taken from Bahcall et al. (1994) and Richer & Fahlman (1992). In the case of GRW model, we assumed the average between the halo and disc colour–magnitude diagrams for the thick disc component. The contribution of red giants was obtained by converting their $(B-V)$ colours to $(V-I)$, using fits to the relations given by Prosser (1992) for disc...
stars, and by Brewer, Fahlman & Richer (1993) and Sarajedini & Milone (1995) for Population II stars.

The two standard model predictions for the magnitude counts are similar and in good agreement with the observations (Fig. 6a). We derive low confidence levels (CL) of inconsistence between models and magnitude counts for both BS and GRW (< 90 per cent). In fact, both models are in superb agreement with the data if the highly deviant bin at I = 23.25 is excluded from the analysis (CL ≤ 50 per cent). The source counts in the I = 23.25 bin are twice as large as those predicted by the models.

The model V - I distributions shown in panel (b) exhibit larger differences than in the case of the magnitude counts. The difference at the red end (with BS being much flatter than GRW for V - I > 3) can be explained by the assumption of a flat rather than declining disc luminosity function in the BS model. The other differences, however, result basically from the inclusion of the thick disc in GRW.

There is a reasonable agreement between the GRW model predictions and the data colour counts. The predictions are at least marginally within the error bars for most bins, although the disagreement between model and data is much larger than that obtained from panel (a) (typically 98 per cent CL of incompatibility). The main reason for the discrepancy is the systematic deficiency in the colour counts in the range 1 < V - I < 2. For V - I > 2, CL drop to 84 per cent. BS yields a much flatter colour distribution than the data. The lack of a thick disc in this latter leads to a large underestimate of the colour counts within 2 < V - I < 3. Thus the colour distribution of BS model is entirely inconsistent with the data (CL > 99 per cent).

Similar results to those described above apply if we adopt the alternative calibration of Bahcall et al. (1994). Also, our conclusions are fairly robust to usage of alternative transformations from the Mv versus (B - V) to the Mv versus (V - I) plane. We tested that by adopting the ω Cen and 47 Tuc Mv versus (V - I) relations obtained by Elson et al. (1995) and Santiago et al. (1996) as representative of the halo and thick disc stars, respectively. A small increase in the discrepancy between GRW and the data colour counts occurs, but with no further consequence to our conclusions. A similar effect, although of larger amplitude, would arise if we had used the stellar sample defined on basis of the Ipeak/Ftot ratio rather than on psf fitting.

### Table 4. Models for the Galaxy.

|                      | Bahcall & Soneira | Gilmore, Reid & Wyse |
|----------------------|-------------------|----------------------|
|                      | Thin Disk         |                      |
| Scale length (pc)    | 3500              | 3500                 |
| Scale height (pc)    | 90-325            | 90-325               |
| C-M diagram          | Johnsen 1965      | M67                  |
| Lum. Function        | Wielen            | Wielen, Gilmore & Reid |
|                      | Thick Disk        |                      |
| Scale length (pc)    |                    | 3500                 |
| Scale height (pc)    |                    | 1300                 |
| C-M diagram          |                    | 47 Tuc               |
| Lum. Function        |                    | 47 Tuc               |
| Local normalization  |                    | 1/50                 |
|                      | Halo              |                      |
| de Vaucouleurs radius (pc) | 2670             | 2700                 |
| C-M diagram          | M13               | M 5                  |
| Lum. Function        | Wielen            | 47 Tuc               |
| Local normalization  | 1/500             | 1/800                |
| Axis ratio           | 0.80              | 0.80                 |

4 CONCLUSIONS

HST field star counts were used in this paper to estimate the amount of the missing matter in the Galaxy that could be in the form of low-mass stars. Main-sequence M dwarfs and subdwarfs do not account for more than 16 per cent of the Galaxy's dark matter, unless candidates with Mv ≥ 14.5, M~0.2 M⊙, are invoked or it is assumed that all red stars in our data belong to the dark halo. Such stellar candidates would violate our current understanding of the mass-luminosity relation for low-mass stars (Brewer et al. 1993; Kroupa et al. 1993). The assumption that all red stars observed in the MDS fields are distributed in the dark halo is also very conservative, since it would imply that the disc, thick disc and stellar halo luminosity functions all drop sharply at the faint end Mv > 13. Likewise, white dwarfs
HST star counts at high galactic latitudes

could be responsible for a substantial fraction of the dark matter only if fairly large numbers of very cool (old) objects exist, with the additional constraint that stars of mass lower than $M_* \sim 1 M_\odot$ should not contribute to these numbers.

Bahcall et al. (1994), in a similar analysis, find even more stringent limits on the amount of dark matter in the form of low-mass stars ($< 6$ per cent). However, they used only one, very deep WFPC-2 high-latitude field, directed away from the centre of the Galaxy, which may explain the discrepancy in the nominal upper limits. They also applied a different, although similar, photometric calibration to their data. Our results are also in qualitative agreement with those of Hu et al. (1994) and Boeshaar, Tyson & Bernstein (1994), although the latter authors again place stronger upper limits on the amount of stellar dark matter than those quoted here.

The slope of the stellar luminosity function fainter than $M_* \sim 13$ is negative to more than 99 per cent confidence. Mostly because of limited statistics, we are unable to constrain the slope of the disc luminosity function strongly. However, our best estimate for this quantity is intermediate between those based on volume-limited (parallax) samples and those derived from photometric surveys. This is consistent with unresolved stellar binarity being the cause of the apparent inconsistency between the luminosity functions of nearby stars and of more distant disc stars. However, in a recent paper, Gould et al. (1995) use a large sample of HST M dwarfs and find a stellar luminosity function in close agreement with ground-based photometry work. It is not clear what the reason for such discrepancy may be, although it is partly due to differences in the photometric calibration. Another difference is that Gould et al. (1995) simultaneously fitted the disc luminosity function and the vertical density profiles, whereas we kept the latter fixed to the standard model assumptions. Our inferred range of slopes also disagrees with the values derived by Richer & Fahlman (1992) for globular clusters. The difference may, at least in part, be caused by crowding of their ground-based data; HST globular cluster star counts have consistently also failed to reveal large numbers of low-mass stars (Elson et al. 1995; Paresce et al. 1995).

Our main conclusions are largely independent of uncertainties in the photometric calibration or assumed colour–magnitude diagrams for the different stellar populations. Most results presented in this paper are also robust to variations in the process used in separating stars from extragalactic objects when defining the data sample.

Finally, the current models of Galactic structure nicely reproduce the observed magnitude counts. A reasonable agreement between model and data is also observed for the colour distributions, provided that the thick disc is included. This general consistency between data and models discards the need to invoke any significant new stellar population to account for the results obtained from HST star counts. However, an excess of stars with $1 < V-I < 2$ was found. This excess is statistically significant and remains regardless of whether the thick disc is incorporated or not. It may, at least partially, artificially result from uncertainties in sample selection, photometric calibration or in the assumed CMDs or luminosity functions for the different components of the Galaxy. Alternatively, these extra objects may reflect real inadequacies in the current models of the Galaxy. We plan to explore these possibilities in the near future.

ACKNOWLEDGMENTS

We thank the entire Medium Deep Survey team, especially those at the JHU branch, for their valuable suggestions and assistance with the MDS data base.

REFERENCES

Bahcall J. N., Soniera R. M., 1980, ApJS, 44, 73 (BS)
Bahcall J. N., Soniera R. M., 1984, ApJS, 55, 67 (BS)
Bahcall J. N., Schmidt M., Soniera R. M., 1983, ApJ, 265, 730
Bahcall J. N., Flynn C., Gould A., Kirkahos S., 1994, ApJ, 435, L51
Bessel M. S., Stringfellow G. S., 1993, ARA&A, 31, 433
Boeshaar P. C., Tyson J. A., Bernstein G. M., 1994, in Dark Matter, Fifth Maryland Astrophysics Conf., AIP Press
Brewer J. P., Fahlman G. G., Richer H. B., 1993, AJ, 105, 2158
Barr C., 1994, ARA&A, 32, 531
Dahn C., Wielen R. Liebert J., Harrington R. S., 1986, AJ, 91, 621
De Marchi G., Paresce F., 1995a, A&A, 304, 202
De Marchi G., Paresce F., 1995b, A&A, 304, 211
Elson R. A. W., Gilmore G., Santiago B. X., Casertano S., 1995, AJ, 110, 682
Faber S. M., Gallagher J. S., 1979, ARA&A, 17, 135
Fich M., Tremaine S., 1991, ARA&A, 29, 409
Gilmore G., 1984, MNRAS, 207, 223
Gilmore G., Reid N., Wyse R. F. G., 1983, MNRAS, 202, 1025 (GRW)
Gilmore G., Wyse R., Kuijken K., 1989, ARA&A, 27, 555
Gilmore G., King I. R., van der Kruit P. C., 1990, The Milky Way as a Galaxy. Univ. Science Books, California
Griffiths et al., 1993, in Wamsteker W., Longair M., eds, Impacts des Surveys du visible sur notre Connaissance de La Galaxie. Strasbourg: Comptes Rendus Journ. Strasbourg 9ème Réunion, p. 73
Holtzmann J. A. et al., 1995, PASP, 107, 1065
Hu E. M., Huang J. S., Gilmore G., Cowie L. L., 1994, Nat, 371, 493
Kron R. G., 1980, ApJS, 43, 305
Kroupa P., Tout C. A., Gilmore G., 1991, MNRAS, 251, 293
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Larson R., 1986, MNRAS, 218, 409
Liebert J., 1980, ARA&A, 18, 63
Liebert J., Dahn C. C., Monet D. G., 1988, ApJ, 332, 891
Mathews G. J., Schramm D. N., Meyer B. S., 1993, ApJ, 404, 476
Monet D. G. et al., 1992, AJ, 103, 638
Ojha D. K., Bienayme O., Robin A. C., Mohan U., 1994, A&A, 290, 771
Paresce F., De Marchi G., Romianni M., 1995, ApJ, 440, 216
Perrin M. N., Friet E. D., Bienayme O., Cayrel R., Barbuy B., Baulon J., 1995, A&A, 298, 107
Prosser C., 1992, AJ, 103, 488
Reid I. N., 1990, MNRAS, 247, 70
Reid I. N., 1991, AJ, 102, 1428

© 1996 RAS, MNRAS 281, 871–882

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System
B. X. Santiago, G. Gilmore and R. A. W. Elson

Reid I. N., 1992, in Majewski S., ed., ASP Conf. Ser. Vol. 49, Galaxy Evolution: The Milky Way Perspective. Astron. Soc. Pac., San Francisco, p. 37
Reid I. N., Gilmore G. F., 1982, MNRAS, 201, 73
Reid I. N., Majewski S. R., 1993, ApJ, 409, 635
Richer H. R., Fahlman G. G., 1992, Nat, 358, 383
Richer H. R., Fahlman G. G., Buonanno R., Fusi Pecci F., Searle L., Thompson I., 1991, ApJ, 381, 147
Rubin V. C., Ford W. K., Thonnard N., 1982, ApJ, 261, 439
Santiago B. X., Elson R. A. W., Gilmore G. F., 1996, MNRAS, in press
Sarajedini A., Milone A. A., 1995, AJ, 109, 269
Silk J., 1990, in Lynden-Bell D., Gilmore G., eds, Baryonic Dark Matter. Kluwer, Dordrecht, p. 279
Soubiran C., 1993, in MacGillivray H., ed., Proc. IAU Symp. 161, Astronomy from Wide-Field Imaging. Kluwer, Dordrecht, p. 435
Stobie R. S., Ishida K., 1987, AJ, 93, 624
Stobie R. S., Ishida K., Peacock J. A., 1989, MNRAS, 238, 709
Tamanaha C. M., Silk J., Wood M. A., Winget D. E., 1990, ApJ, 358, 164
von Hippel T., Gilmore G., Jones D. H. P., 1995, MNRAS, 273, L39
Walker T., Steigman G., Schramm D. N., Olive K. A., Kang H. S., 1991, ApJ, 376, 51
Wielen R., Jahreiss H., Kröger R., 1983, in Davis Philip A. G., Upgren A. R., eds, Proc. IAU Colloq. 76, Nearby Stars and the Stellar Luminosity Function. L. Davis Press, Schenectady, NY, p. 163
Wood M. A., 1992, ApJ, 386, 539

© 1996 RAS, MNRAS 281, 871–882

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System