A search for nearby counterparts to the moving objects in the Hubble Deep Field

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ABSTRACT
Ibata et al. have recently discovered very faint, moving objects in the Hubble Deep Field (HDF). The number, apparent magnitudes and proper motions of these objects are consistent with old white dwarfs making up part of the Galactic dark halo. We review a number of ground-based proper motion surveys in which nearby dark-halo white dwarfs might be present, if they have the colours and absolute magnitudes proposed. No such objects have been found, whereas we argue here that several times more would be expected than in the HDF. We conclude that it is unlikely that hydrogen-atmosphere white dwarfs make up a significant fraction of the Galactic dark matter. No limits can be placed as yet on helium-atmosphere dwarfs from optical searches.

Key words: Galaxy: structure – dark matter.

1 INTRODUCTION
Ibata et al. (1999; hereafter IRGS) have detected faint moving objects in the Hubble Deep Field (HDF). These objects have proper motions, apparent magnitudes and colours that are consistent with a Galactic dark halo made of old white dwarfs (WDs).

There are, however, reasons to suppose that white dwarfs make up only a limited amount of dark matter. They would overpollute the Universe with carbon by a factor of 100 (Fields, Freese & Graff 1998). Although Chabrier (1999) has suggested that the above result may be model dependent, robust limits on the cosmic density of white dwarfs can be placed using helium and deuterium abundances (Fields, Freese & Graff 1999) and limits on the background infrared photon number density (Graff et al. 1999). These limits caused Hansen (1999a) to postulate the existence of beige dwarfs, degenerate massive objects that are not stellar remnants, and would escape the above restrictions. None of these objections are so robust that ways of circumventing them cannot be found (see, e.g., Richer 1999).

If the IRGS objects are halo white dwarfs, several nearby counterparts to such objects might be located in ground-based, wide-area proper motion surveys, in which they would appear as faint, high proper motion objects. Several such white dwarfs may have been found already. Hodgkin et al. (1999) report a very cool, white dwarf with a velocity consistent with membership of the Galactic halo. Harris et al. (1999) have also located a very low-luminosity, cool white dwarf, although its population type (disc or halo) is not yet known. Such objects could be related to the objects found by IRGS.

In this paper, we examine the population of dark-halo white dwarfs proposed IRGS by searching for nearby counterparts in existing, ground-based proper motion surveys. In Section 2, we discuss how we could locate nearby counterparts to the proposed white dwarfs in proper motion surveys. In Section 3, we examine two photographic surveys of proper motions, the Luyten Half Second Catalogue (1979, LHS) and the survey by Knox, Hawkins & Hambly (1999; hereafter KHH). We show that both surveys appear to have greater power to detect intrinsically faint high proper motion objects than the IRGS survey. In neither ground-based survey do we find candidates for local counterparts to the proposed dark-halo WDs in HDF. The probability of finding objects in the less powerful HDF and not in the ground-based surveys is low, suggesting that the HDF objects are not dark-halo white dwarfs. In Section 4 we discuss our results in terms of models of cooling white dwarfs, and in Section 5 describe briefly some on going work. In Section 6 we draw our conclusions.

2 PROPER MOTION SEARCH FOR DARK-HALO WHITE DWARFS
Several authors have already searched for nearby stellar objects from the dark halo, but have found no candidates, allowing upper limits to be placed on their luminosity. The Luyten Half Second Catalogue has been analysed in this manner by Graff, Laughlin & Freese (1998), Fuchs & Jahreiß (1998) and Hansen (1999b). We
follow here a similar approach as these authors while adapting it to the particular details of the IRGS proposal.

2.1 Number of nearby dark-halo white dwarfs

The power of a survey to detect objects of absolute magnitude $M$ visible to limiting magnitude $m$, and assumed to have a constant density, is the effective volume of the survey,

$$v_{\text{eff}} = \frac{\Omega}{3} \cdot 10^{0.6(m-M)+3} \cdot \epsilon \cdot \text{pc}^3,$$

where $\epsilon$ is the efficiency (completeness) of the survey and $\Omega$ its solid angle in steradians.

Assuming that some fraction $F_{\text{WD}}$ of the dark halo is composed entirely of white dwarfs of mean mass $M_{\text{WD}}$, and that $F_I$ of these dwarfs have hydrogen atmospheres (the white dwarfs with helium atmospheres would be essentially undetectable using currently available data), then the number $N_{\text{WD}}$ of WDs we expect in the survey is

$$N_{\text{WD}} = \frac{\rho_{\text{H}}}{M_{\text{WD}}} v_{\text{eff}} F_{\text{WD}} F_I,$$

where $\rho_{\text{H}}$ is the local halo dark matter density. The dark halo is assumed here to have constant density over the survey volume, an adequate approximation for the surveys discussed in this paper (the deepest survey, the HDF, probes for dark-halo WDs up to $\sim$1 kpc from the Sun).

2.2 Proper motion window

In all the surveys examined, there are minimum and maximum detectable proper motions, $\mu_{\text{min}} < \mu < \mu_{\text{max}}$. In order to estimate the number of WDs within this proper motion window, we require a simple kinematic description of the dark halo. We assume the dark-halo WD system has an isothermal velocity distribution, with one-dimensional (1D) velocity dispersion $\sigma = 220/\sqrt{3} = 127\text{ km s}^{-1}$. We assume the system to be non-rotating, have local density $\rho_{\text{H}} = 0.0076 \text{ M}_{\odot} \text{ pc}^{-3}$ and that the mean WD mass is $M_{\text{WD}} = 0.66\text{ M}_{\odot}$. This model allows us to determine the fraction of stars within the proper motion window of each survey $\mu_{\text{min}} \leq \mu < \mu_{\text{max}}$, while accounting for the Solar motion [i.e. we use equation (6) of Fuchs & Jahreiß 1998]. In practice, $\mu_{\text{max}}$ is the important constraint on detecting nearby dark-halo WDs, while for the HDF $\mu_{\text{min}}$ plays a small role and the effect of $\mu_{\text{max}}$ is negligible.

2.3 Recovering dark-halo white dwarf candidates

We search for nearby counterparts to the proposed HDF white dwarfs using the reduced proper motion, $H$ (Luyten 1922; Evans 1992), which is the proper motion equivalent of absolute magnitude. For a star of absolute magnitude $M$ and transverse velocity $V_T$ (in $\text{km s}^{-1}$), or apparent magnitude $m$ and proper motion $\mu$ (in arcsec yr$^{-1}$), $H$ is

$$H = M + 5 \log V_T - 3.379 = m + 5 \log \mu + 5.$$

The reduced proper motions of the objects detected by IRGS in the HDF lie in the range $24 < H_R < 26.5$, as expected for objects with velocities characteristic of the dark halo and absolute magnitude at $M_V = 17.5$ (typical of the WDs proposed by IRGS). Nearby counterparts to the HDF objects would also have reduced proper motions in this range, while no known Galactic population of stars has reduced proper motions in this range.

3 THE THREE PROPER MOTION SURVEYS

We describe three surveys in which one can search for dark-halo white dwarfs, two of which are ground-based and would locate nearby objects, and the third being the HDF itself (which has been searched by IRGS). For each survey we calculate the effective volume probed (equation 1). For the two ground-based surveys we search for but locate no dark-halo white dwarf candidates.

3.1 The Hubble Deep Field

The HDF is the deepest search to date for any object, and covers a comparatively small solid angle, only $4.4 \text{ arcmin}^2$, or $5 \times 10^{-8}$ of the angle covered by the larger of the two ground-based surveys (LHS). IRGS effectively run two experiments in searching for faint moving objects in HDF. They are most confident of their results for $I < 28$, and find two objects with $I < 28$. One of the objects varies in magnitude, and has the wrong $B - V$ colours to be a white dwarf, leaving one good candidate object, 4–551. Extension of the survey out to $I < 29$ reveals three additional candidates, though only one of these has a secure proper motion.

The completeness of the survey by IRGS is $42 \pm 2$ per cent for objects in the range $27 < I < 28$. The effective volume probed by HDF (using equation 1) for objects at $M_V = 17.5$ is $v_{\text{eff}} = 225 \times 0.42 = 95\text{ pc}^3$. To be conservative (i.e. to maximize the effective volume probed by HDF), we make no correction for the proper motion window of the HDF survey even though the measured proper motions are only $\sim 2$ times larger than the minimum measurable proper motion. IRGS do not discuss the upper proper motion limit of their survey, but it is likely to be so much larger than the typical proper motions of the WDs that none should be excluded.

3.2 ESO/SERC Area 287

KHH have recently surveyed ‘ESO/SERC Area 287’, searching for faint high proper motion objects in order to locate the end of the disc white dwarf cooling sequence. They used about 100 UK Schmidt $R$-band exposures taken over a range of epochs, which they stacked in three different manners either to go as deep as possible ($R = 22$) or to be able to recover stars with high proper motions ($10\text{ arcsec yr}^{-1}$).

The three KHH proper motion experiments have different apparent magnitude $R$-band limits and upper proper motion limit $\mu_{\text{max}}$, and are denoted by (i), (ii) and (iii). Hambly (1999, private communication), has undertaken a careful re-analysis of the original data as a result of the IRGS results, and has advised us

| ID | $\mu_{\text{max}}$ (arcsec yr$^{-1}$) | $R_{\text{lim}}$ | $\epsilon$ | $v_{\text{eff}}$ (pc$^3$) |
|----|-------------------------------|----------------|----------|-----------------|
| (i) | 10 | 21.2 | 1.00 | 198 |
| (ii) | 1.9 | 21.2 | 0.83 | 168 |
| (iii) | 0.5 | 22.0 | 0.24 | 146 |

Table 1. Three proper motion surveys of ESO/SERC field 287 from Knox et al. (1999), showing the upper proper motion limit $\mu_{\text{max}}$, apparent $R$-band magnitude limit, fraction of sources expected in the proper motion window $\epsilon$ (i.e. with $\mu < \mu_{\text{max}}$) and the effective volume $v_{\text{eff}}$ for WDs at $M_R = 17.5$. 

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that the effective area of the survey should be conservatively set at 12 deg$^2$. The three experiments are summarized in Table 1, where we show the upper limit on proper motion $\mu_{\text{max}}$, the $R$-band apparent magnitude limit and effective volumes probed for each survey (including the effect of the proper motion window) $V_{\text{eff}}$. The most effective of the surveys is (i), for which the effective volume is $V_{\text{eff}}^{\text{KHH}} = 198$ pc$^3$ for white dwarfs at $M_R = 17.5$.

KHH show plots of reduced proper motion $H_R$ (in the $R$-band) versus colour index for their sources (their figs 9–11). Inspection of their plots shows there are no sources with $H_R > 24$ (blue or otherwise). KHH would be able to detect sources with $H_R$ as high as 31.2 if they were present in survey (i). Almost all their sources have $H_R < 20$, as expected for late-type dwarfs and disc white dwarfs. We conclude there are no candidate dark-halo WDs in KHH.

### 3.3 Luyten Half Second Survey

The Luyten Half Second Catalogue (LHS, Luyten 1979) is a proper motion survey covering over half the sky, complete in the range $0.5 < \mu < 2.5$, which was obtained by blinking Palomar plate pairs. Dawson (1986) has studied in detail the completeness of the LHS, finding that it is 90 per cent complete to Luyten $R$-band magnitude $R_L = 18$ (for declination $\delta > -30^\circ$, and Galactic latitude $|b| > 10^\circ$).

Salim & Gould (1998) have recently studied the completeness of the NLTT (‘New Luyten Catalogue of stars with proper motions larger than Two Tenths of an arcsec’) in order to estimate the self lensing rate of field stars for astrometric microlensing. The NLTT is the extension to lower proper motions of the LHS catalogue, and we have used the NLTT to determine the completeness of LHS. We find that LHS is essentially (>90 per cent) complete at $R_L = 18.0$ and 60 per cent complete down to Luyten $R$-band magnitude $R_L = 18.5$. In Appendix A, we give a detailed presentation of this determination. Furthermore, in Appendix B, we calibrate the Luyten $R$-band magnitude, $R_L$, finding that it is actually closer to Johnson $V$ than to Cousins $R_C$. The calibration is

$$ R_L = V - 0.37(V - R_C) + 0.06. \hspace{1cm} (4) $$

This relation allows us to compare the LHS survey directly with HDF’s $V$-band magnitude (and is particularly useful since HDF was imaged in $U$, $B$, $V$ and $I$ but not $R$). A ground-based calibration of the Hubble Space Telescope (HST) $V$- and $I$-bands, which are non-standard, by Salim & Gould (1998), shows that the zero-points for the transformation of the $HST$ $V$-band filter are very close to the ground-based system.

Richer et al. (2000) discuss the colours of the white dwarfs proposed by IRGS. In the age range of interest, 7–15 Gyr, the models have $V - R$ colours in the range $0 < V - R < 0.5$. We discuss in much more detail the colours of the models in the next section, but at this point if we conservatively adopt $V - R = 0$, then the $V$-band limit of LHS is (from equation 4) $V = 18.4$. Taking this magnitude limit, accounting for the fraction of sky covered, $\sim 8.5$ sr, and the completeness (60 per cent), the Luyten catalogue probes an effective volume of $V_{\text{eff}}^{\text{LHS}} = 5700$ pc$^3$ for $M_V = 17.5$ dark-halo white dwarfs. Applying the proper motion window for sources in LHS ($0.5 < \mu \text{arcsec yr}^{-1} < 2.5$) we obtain a survey efficiency of $\epsilon = 0.22$, which reduces the effective volume to $V_{\text{eff}}^{\text{LHS}} = 1290$ pc$^3$.

Figure 1. The reduced proper motions $H$ in the Luyten $R$-band for the stars in the LHS survey versus colour index $B_J - R_I$. The maximum detectable reduced proper motion in LHS is $H = 25.4$, shown as a solid horizontal line, while most dark-halo white dwarfs would be expected to lie in the range $H = 23$–25 with a peak at $H = 24$ (shown as a dashed horizontal line). No sources at all are found with $H > 24$. Note that the vertical stripes are an artefact arising from the limited colour resolution of the LHS survey, and that a small random number has been added to the Luyten colours to reduce crowding in the figure.

which is much greater than the effective volume of both the KHH survey (198 pc$^3$), and the HDF survey (95 pc$^3$).

We obtained the LHS catalogue from the SIMBAD data centre, and show in Fig. 1 for each object the reduced proper motion $H$, computed in Luyten’s $R$-band magnitude $R_L$ versus $B_J - R_I$ colour index. The disc main sequence (running from upper left to lower right) and the disc white dwarf cooling sequence (lower left) are seen in the figure. There are no sources with $H > 24$, while the maximum detectable reduced proper motion in LHS is $H = 25.4$. Under the constraint of the proper motion window ($0.5 < \mu \text{arcsec yr}^{-1} < 2.5$) and the kinematic model of Section 2.2, dark-halo white dwarfs in LHS are expected to have a distribution of reduced proper motion in the range $23 \leq H \leq 25$ and peaked at $H = 24$.

While there are no objects in LHS with $H > 24$, there are a few objects in the range $24.0 > H > 23.5$. A literature search using SIMBAD showed that all but one of these have been classified as either disc M dwarfs or disc white dwarfs through parallax, photometry and/or spectroscopic methods (McCook & Sion 1987; Bessell 1991). The exception is the white dwarf LHS 542, which has a high transverse velocity of 276 km s$^{-1}$, and is thus a ‘halo’ white dwarf. The absolute magnitude of this object is $M_R = 15.1$, and as such is much brighter than the putative halo objects in the HDF (for which $M_R \approx 17.5$). The kinematics of white dwarfs in the LHS have recently been analysed by Liebert et al. (1999) and are consistent with the kinematics and relative normalization of the Galactic disc and stellar halo. If the dark matter were composed of objects as luminous as LHS 542, they would be present in the LHS in huge numbers, and so we regard this object as a member of the stellar halo, rather than a nearby candidate for a dark-halo white dwarf. We conclude from the lack of high reduced proper motion objects (i.e. $H_R > 24$) that there are no obvious counterparts in the LHS to the moving sources in the HDF, confirming previous studies (Graff et al. 1997; Fuchs & Jahreiß 1998; Hansen 1999b).
The type of objects seen by IRGS should be present in significant numbers in the LHS catalogue with $H_R \geq 24$. The lack of such objects in LHS argues against the interpretation that they are dark-halo white dwarfs.

4 DISCUSSION

The three surveys are summarized in Table 2. The combined ground-based surveys probe an effective volume which is larger than that probed by HDF by a factor of

$$18 \times 10^6 [R_L - I] \frac{\epsilon_{\text{LHS}}}{\epsilon_{\text{HDF}}} + 1.7 \times 10^6 [R - I] \frac{\epsilon_{\text{KHH}}}{\epsilon_{\text{HDF}}}$$

where $R_L$ is the Luyten $R$-band magnitude, $\epsilon$ is the survey efficiency, which includes the completeness and the proper motion window, and $R - I$ is the WD colour.

As can be seen from equation (6), the two important parameters in determining the relative strengths of the ground-based surveys to the HDF are the efficiency, $\epsilon$, and the colour of the dwarfs. We next discuss the effect of the colours of the WDs in detail.

4.1 White dwarf models

IRGS propose that the faint blue sources which they have found in the HDF might be old, hydrogen-atmosphere white dwarfs, which have the surprising property of being blue (Hansen 1999b) owing to $H_2$ opacity (old helium-atmosphere white dwarfs would have cooled so effectively that they would not be visible in any existing survey). Hansen (1999b) has computed $V$- and $I$-band absolute magnitudes for old white dwarfs for a range of ages. Over the age range of interest, 11–16 Gyr, the $V$-band absolute magnitude of hydrogen-atmosphere white dwarfs is in the range $17 \leq M_V \leq 18$, while the colours lie in the range $-1 \leq V - I \leq 1$. These properties are consistent with the interpretation of the moving HDF objects as old dark-halo white dwarfs.

We adopt the white dwarf models of Hansen (1999b), who kindly made unpublished $B$-band colours available to us. Other observables of these models are discussed in Richer et al. (2000). Within these models, once the temperature of the white dwarf cools below 4000 K, the spectral energy distribution becomes extremely non-blackbody. Most of the light is emitted in the $V$ and $R$ bands with the peak shifting to the blue as the star cools, and the absolute $M_V$ mag of the star stays roughly constant. Thus, the effective volume probed by the photographic catalogues does not strongly depend on models, while the IRGS volume, which has an $I$ band magnitude limit, depends strongly on the temperature of the white dwarf. When computing the relative strengths of the different surveys, the most important parameter is the $V - I$ colour.

We will discuss three models which cover the $V - I$ colours of cool white dwarfs. We examined several other models with different ages and white dwarf masses, but the three models we discuss illustrate a reasonable parameter space since only the $V - I$ colour plays a significant role. The three models are denoted O, R and B, where model O is a fit to the observed candidate white dwarf 4–551, model R represents a dwarf which is red in $V - I$, and model B, a dwarf which is blue in $V - I$. The parameters chosen for these dwarfs are shown in Table 3.

Note that model R is the reddest possible hydrogen-atmosphere white dwarf. Both cooler and hotter dwarfs are bluer.

Calculations of effective volumes for different models and different surveys are shown in Table 4. In all cases, the LHS catalogue is the most potent survey, then the KHH survey, and the IRGS survey is the least potent. The combined photographic surveys are 7–18 times as powerful as IRGS to $I = 28$.

### Table 2. Summary of the limits of the three experiments discussed in this paper. The efficiency includes the survey completeness and the probability that an object at absolute magnitude 17.5 will have a proper motion within the proper motion window of the survey.

| Survey | Area $\Omega$ (str) | Magnitude limit | Efficiency $\epsilon$ |
|--------|---------------------|-----------------|-----------------------|
| HDF    | $3.7 \times 10^{-7}$ | $I < 28$        | 0.42                  |
| KHH (i)| $7.6 \times 10^{-3}$ | $R < 21.2$      | 1.00                  |
| LHS    | 8.5                 | $R_L < 18.5$    | 0.13                  |

### Table 3. Three models of halo white dwarfs from Richer et al. (2000). We consider a red (‘R’) and a blue (‘B’) model, and a model that is a match to one of the observed (‘O’) objects in the HDF (object 4–551).

| Parameter | White dwarf model |
|-----------|-------------------|
| O         | R                 |
| Mass ($M_\odot$) | 0.66 | 0.70 | 0.80 |
| Absolute magnitude $M_V$ | 17.49 | 17.40 | 18.01 |
| Age (Gyr) | 12.0              | 12.1 | 12.0 |
| $V - I$   | 1.10              | 0.40 | 0.02 |
| $V - R$   | 0.96              | 0.57 | 0.73 |

### Table 4. The first three rows show the effective volume of the three surveys to the three WD types considered in Table 3. The effective volume includes the survey completeness and the reduction owing to the proper motion window. Row 4 shows the combined effective volume of the surveys. Row 5 shows $N_{\text{WD}}$, the number of hydrogen-atmosphere white dwarfs expected in the combined surveys (see Section 4.3) assuming they make up 50 per cent of the dark-halo density. Row 6 shows the ratio of effective volume for the combined ground-based surveys to the HDF survey: they are typically 10–20 times more powerful than the HDF survey. Row 7 shows the (maximized) probability that objects would be detected in the HDF but not detected in the ground-based surveys, and is typically below 5 per cent. The probability has been maximized by fitting for the dark-halo mass fraction in white dwarfs, which is shown in row 8.

| WD model | Description | $v_{\text{eff}}$ (pc$^3$) | $v_{\text{eff}}$ (pc$^3$) | Total volume (pc$^3$) | $N_{\text{WD}}$ |
|----------|-------------|---------------------------|---------------------------|-----------------------|----------------|
| R        | LHS+KHH/HDF | 438                       | 189                       | 3571                  | 27             |
| O        | LHS+KHH/HDF | 2730                      | 3220                      | 3530                  | 26             |
| B        | LHS+KHH/HDF | 403                       | 121                       | 932                   | 7              |

| (LHS + KHH)/HDF | Probability (%) | Halo fraction (%) |
|-----------------|-----------------|-------------------|
| 7.2             | 17.7            | 18.4              |
| 5.0             | 2.0             | 2.0               |
| 2.0             | 2.0             | 3.0               |
4.2 Combining the surveys

Naively, if the object 4–551 detected by IRGS is typical of the halo population, there should be tens of dwarfs in the ground-based surveys. Instead, there is none. We calculate the probability of such a mismatch between surveys as follows:

Let \( \lambda \) be the mean expected number of dwarfs seen by IRGS. We define \( \alpha \) to be the ratio of effective volumes probed by the different surveys:

\[
\alpha = \frac{v_{\text{HDF}}}{v_{\text{phot}}} + \frac{v_{\text{MR}}}{v_{\text{phot}}}
\]

so that the mean expected number of dwarfs in the combined photographic surveys is \( \alpha \lambda \). Then the probability that at least one dwarf will be seen in the HDF is \( P_{\text{HDF}} = 1 - e^{-\lambda \alpha} \), while the probability that no dwarfs will be seen in either photographic surveys is \( P_{\text{phot}} = e^{-\lambda \alpha} \).

The combined probability of both events is

\[
P = P_{\text{HDF}} P_{\text{phot}} = (1 - e^{-\lambda \alpha}) e^{-\lambda \alpha}.
\]

This probability is maximized when

\[
\lambda_{\text{max}} = \ln \frac{\alpha + 1}{\alpha}
\]

and has a value of

\[
P_{\text{max}} = \frac{\alpha^\alpha}{(\alpha + 1)^{\alpha + 1}} \cdot \frac{1}{\epsilon(\alpha + 1)}.
\]

Note that, as shown in Table 4, even for the reddest model, the HDF is relatively most effective, the probability of seeing a star in the HDF and no stars in the more powerful photographic surveys is only 5 per cent. In the case of the actual star observed, 4–551, the probability is lower (2 per cent) that no other stars of the same type would be observed in the photographic surveys.

4.3 Halo fraction

Having calculated the effective volumes of the surveys, we can calculate the number of dwarfs that would be visible assuming the halo were composed of white dwarfs. This assumption is not entirely consistent with the microlensing results – the MACHO and EROS microlensing experiments currently suggest that approximately 20 per cent of the dark halo could be in the form of \( \approx 0.5 M_\odot \) mass objects (Alcock et al. 2000; Lasserre et al. 2000). We do not constrain the calculations in this section by these results, but rather use the results of the HDF proper motion search itself as our starting point. We adopt a local halo density of \( 0.0076 M_\odot \text{pc}^{-3} \) and assume that 50 per cent of this density is caused by hydrogen-atmosphere white dwarfs and that the remaining 50 per cent of the dark halo is in helium-atmosphere white dwarfs, which will have cooled far below the detection limits of the surveys.

The number of hydrogen-atmosphere white dwarfs expected in the combined surveys \( N_{\text{WD}} \) is shown in row 5 of Table 4. The probability that one or more white dwarfs would be seen in HDF while none are seen in the photographic surveys is very low for all the models. Using equation (8), all three models in which hydrogen-atmosphere white dwarfs make up half of the dark halo can be ruled out with greater than 99 per cent confidence.

We tested models in which the dark-halo white dwarf fraction maximizes the probability that one or more white dwarfs would be seen in HDF, while none are seen in the photographic surveys (equations 9 and 10). Model R has the highest probability of explaining the combined survey results, albeit with a low probability of only 5 per cent and a dark-halo white dwarf fraction of just 2.0 per cent. For the other two models the probability of there being at least one object in HDF and none in the ground-based surveys is \( P_{\text{max}} = 2 \) per cent, and the corresponding fraction of dark-halo white dwarfs is also very low (less than 3 per cent).

4.4 Survey in progress: EROS 2 wide field imager

A V-band limit on the luminosity of putative dark-halo white dwarfs has been set by Goldman (1999), using the first 140 deg\(^2\) of the EROS-II survey (a V- and I-band wide field imager), which will cover 350 deg\(^2\) and reach \( I = 20.5 \) and \( V = 21.5 \) when completed. No high proper motion objects were detected, and Goldman (1999) uses this to set a V-band absolute magnitude limit of \( M_V > 17.2 \) on dark-halo WDs. This is consistent with the WDs proposed by IRGS, since they lie in \( 17 \leq M_V \leq 18 \). The survey is currently approaching completion and will be very sensitive to nearby white dwarfs, surveying some 5000 pc\(^3\) (Goldman 2000).

5 ON-GOING WORK

After this paper was submitted, several interesting developments have taken place.

First, a number of very low-luminosity white dwarfs have turned up in new proper motion studies by Ibata et al. (2000), Hodgkin et al. (2000) and Scholz et al. (2000). In addition, we have become aware of a low-luminosity white dwarf identified by Ruiz et al. in 1995. These objects are of great interest both in constraining the amount of matter in low-luminosity white dwarfs and also testing white dwarf cooling models. A preliminary analysis of these objects indicates that although they are fainter than the end of the classical disc white dwarf cooling sequence (at \( M_R \approx 15.5 \)), they would appear to be too intrinsically luminous to be good candidates for the Galactic dark matter population. We shall present this work in a companion paper (Flynn & Graff 2000, in preparation).

A second development since we submitted the paper was a deep new survey of proper motions analysed by Monet et al. (2000). These authors measure a very high completeness level (90 per cent) of the LHS, strengthening the conclusions reached in this paper.

A third development is a publication of an analysis of the on-going EROS 2 survey made in Goldman (2000). He places an upper limit on the contribution of hydrogen-burning white dwarfs brighter than \( M_V = 17.2 \) of 18 per cent of a standard dark halo (95 per cent confidence limit), similar to the conclusions reached here.

Finally, and most recently, de Jong et al. (2000) have found a number of very interesting high proper motion white dwarf candidates in a small area of the ESO Imaging Survey, which if confirmed as white dwarfs, should be very intrinsically dim objects indeed. We look forward to more!

6 CONCLUSIONS

IRGS have recently discovered faint moving objects in the HDF, proposing that these might be cool white dwarfs making up the
entire mass of the Galactic dark halo. We have searched for nearby counterparts to these objects in a number of ground-based proper motion surveys. No such objects have been found, even though the combined photographic surveys are tens of times more powerful than the HDF. The probability of this occurring is quite low, <5 per cent, even in the most conservative model. This study leads us to the conclusion that it is unlikely that hydrogen-atmosphere white dwarfs, with luminosities in the range \( M_V = 17-18 \), make up a significant fraction of the halo dark matter. No limits can be placed as yet on helium-atmosphere dwarfs from optical searches.

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APPENDIX A: COMPLETENESS OF NLTT (LHS)

In this appendix we will perform a statistical test to investigate the completeness of the faint end of NLTT down to its nominal cut-off of \( \mu = 200 \) mas yr\(^{-1} \), and additionally to \( \mu = 500 \) mas yr\(^{-1} \), which is the cut-off of LHS. It should be noted that the data in LHS is a subset of data present in NLTT. In this test we assume that the local luminosity function is constant, and that the number density of stars does not change appreciably within the volume occupied by the majority of proper motion stars. We will discuss the validity of this assumption later on.

Consider two spheres centred around the Sun, the volumes of which are in the ratio 2:1. This is equivalent to the radii being related by \( r_1/r_2 = 1.259 \), or a distance modulus difference of 0.5 mag. If we define the outer edge of the bigger sphere as the distance at which a star of apparent magnitude \( R_{1, \text{lim}} \) produces a proper motion \( \mu_1 = 200 \text{ mas yr}^{-1} \), then this same star, if placed at distance \( r_2 \), would have a proper motion of \( \mu_2 = (r_1/r_2) \mu_1 = 252 \text{ mas yr}^{-1} \). Also, it would be 0.5 mag brighter. Therefore, \( \mu_2 \) defines a proper motion limit at the distance \( r_2 \) that is equivalent to a proper motion limit \( \mu_1 \) at \( r_1 \). These are the lower limits. For the upper proper-motion limit we adopt \( \mu_{2, \text{lim}} = 2500 \text{ mas yr}^{-1} \), below which we know that the sky was searched homogeneously. NLTT does contain stars with \( \mu > 2500 \text{ mas yr}^{-1} \), possibly all that exist, but these were found by methods other than automated plate scanning. In any case, because of the small relative number of these stars, our statistical test is not very sensitive to the choice of the upper proper-motion limit. So, if we take \( \mu_{2, \text{lim}} = 2500 \text{ mas yr}^{-1} \) as a limit below which we want to check for completeness, then this corresponds to some inner boundary of the smaller sphere (which we can now call a shell). Everything closer than this inner boundary would have \( \mu > \mu_{2, \text{lim}} \) and would not be included in NLTT. Now, in order to keep the volumes of both shells in the appropriate ratio, the outer shell has to have an inner edge corresponding to a proper motion of \( \mu_{1, \text{lim}} = (r_2/r_1) \mu_{2, \text{lim}} = 1986 \text{ mas yr}^{-1} \). This test is performed in the same way when investigating the completeness of the LHS subset of NLTT, but with \( \mu_1 = 500 \text{ mas yr}^{-1} \), and the corresponding \( \mu_2 \).

Now that we have defined the two shells in terms of the limiting proper motions, the statistical test consists of comparing the number of stars \( N_1 \) of a given magnitude \( R_1 \) (in a \( \Delta R_1 = 0.5 \text{ mag bin} \)) in the outer shell (\( \mu_1 < \mu < 1986 \text{ mas yr}^{-1} \)), with the number of stars \( N_2 \) of a magnitude \( R_2 = (R_1 - \Delta R_1) = R_1 - 0.5 \) in the inner shell (\( \mu_2 < \mu < 2500 \text{ mas yr}^{-1} \)). The 0.5 mag shift (equal to one bin) brings the absolute magnitudes of stars in the outer shell to that of the inner shell. The measure of completeness at magnitude \( R_1 \) is given by the ratio

\[
\frac{f(R_1)}{N_2} = \frac{N_1(R_1)}{N_2(R_1 - 0.5)}.
\]
If the sample of stars of apparent magnitude $R_L$ is 100 per cent complete with respect to those of $R_L - 0.5$, then $f(R_L) = (r_1/r_2)^3 = 2$. Now we can define the completeness function $F(R_L)$ for the stars of apparent magnitude $R_L$, in the following way:

$$F(R_L) = \prod_{R'_L = R_{L,\text{comp}} + \Delta R_L}^{R_L} \frac{f(R'_L)}{2},$$

(A2)

where $R_{L,\text{comp}}$ is some bright apparent magnitude at which we believe the catalogue is complete.

In Fig. A1 we show the completeness function $F(R_L)$ for the faint ends of NLTT (dotted line) and LHS (solid line). More specifically, the test was performed on the subsample of NLTT that is believed to be spatially complete, that is, the part called the Completed Palomar Region (CPR) by Dawson (1986). This region covers northern declinations ($\delta \approx -33^\circ$), and avoids the galactic plane ($|b| > 10^\circ$). We take $R_{L,\text{comp}} = 13$. The choice is somewhat arbitrary, but we have reason to believe that NLTT is complete at this magnitude. First, when we plot $f(R_L)$ against $R_L$, we find a flat region around $R_L = 13$. Going to still brighter magnitudes might bring us into the part of NLTT that was not compiled from the photographic plates. Therefore, Fig. A1 shows the completeness at $R_L$ with respect to $R_L = 13$. Dashed lines represent 100, 75 and 50 per cent completeness levels. The completeness of NLTT drops gradually from 90 per cent at $R_L = 13.5$ to $R_L = 18.0$ and dropping to 60 per cent complete at $R_L = 18.5$, in the last bin. Although one would not expect the completeness to be the function of proper motion, for the stars with $\mu > 500$ mas yr$^{-1}$, i.e. those that are present in LHS, the completeness is much higher – in fact, it seems to be $\sim 100$ per cent complete to $R_L = 18$, and becomes incomplete one magnitude fainter. (The solid line is much less smooth than the dotted one, because of the smaller number of stars that produced it.) The reason for differing completeness of lower and higher proper motion stars might have to do with possibly better detection techniques used in the LHS part of the catalogue.

As mentioned, this test depends on the number density being roughly constant over the volume investigated. Is this volume small enough for this condition to be valid, i.e. how far above the plane do we get? In a proper motion selected catalogue the mean transverse velocity of stars is typically twice the transverse velocity of the population itself, i.e. $v_t \sim 90$ km s$^{-1}$. This means that the stars moving at $\mu > 200$ mas yr$^{-1}$ will all be closer than 95 pc. Such stars will have a disc scaleheight greater than that of a normal population, so the distance of 95 pc is not significant compared with that scaleheight. As for stars that move more slowly, they have to be placed even closer to make their way into NLTT, which means that they will be affected even less. We have tested this by comparing the completeness of the subsamples of NLTT and LHS from low ($10^\circ < |b| < 36^\circ$) and high ($|b| > 36^\circ$) galactic latitudes. We see no significant difference.

### APPENDIX B: PHOTOMETRIC CALIBRATION OF NLTT (LHS)

Throughout the previous section we used Luyten’s red magnitude $R_L$. We derive here a calibration of $R_L$ to standard Johnson magnitudes.

NLTT magnitudes are given as photographic (blue plate) and red plate magnitudes. The Hipparcos catalogue contains most of the NLTT stars to its detection limit ($V < 12$). We matched NLTT stars with the corresponding Hipparcos stars (details are given in Salim & Gould 2000), and found 6084 matches with the complete photometric information. These stars therefore calibrate the bright end of NLTT ($0 < V < 12.5$), as follows:

$$V = R_L - 0.06 + 0.200(B - V)$$

(B1)

and

$$V = R_L - 0.08 + 0.196(B_l - R_L).$$

(B2)
where $B_L$ and $R_L$ are NLTT’s blue (photographic) and red magnitudes, respectively. The first relation is shown graphically in Fig. B1. From Fig. B2 we can easily see that Johnson $V$ and Luyten’s $R_L$ have almost the same zero-points. More importantly, the low colour term of 0.2 puts the $R_L$ magnitude much closer to $V$ than to standard Kron $R$. This is in sharp contrast to Dawson (1986) who finds that $R_L$ and Kron $R$ are almost the same, with the only difference being in the zero-point. Dawson’s calibration would give a colour term coefficient of about 0.6 in equation (B1), not 0.2 as we obtain. The rms scatter in both relations (B1) and (B2) is 0.40 mag. We cannot account for this discrepancy, but note that it does not affect the main conclusions of this paper.

The calibration above is restricted to the bright end of NLTT. Since the photometry of the bright NLTT stars might not entirely come from the plates (some stars might be saturated) it is valid to ask whether this calibration holds for the fainter magnitudes. To that end we have taken standard $B$, $V$ and $R$ mag of $V > 12$ stars from Weis’ (1996) list, and compared them with NLTT (LHS) magnitudes. Weis (1996) list contains a number of LHS stars with $V < 15$, measured in standard filters. For our calibration we included all stars from red and blue ends and a number of stars of intermediate colour. The calibration we get is in excellent agreement with equation (B1) from Hipparcos

$$V = R_L + 0.17 + 0.228(B - V).$$

(B3)

The rms of this relation is 0.55 mag. On the other hand, we see a great difference between NLTT’s red magnitude, and $R$ mag as measured by Weis (1996).

Calibration of the still fainter magnitudes is less straightforward, as there are no readily available standard magnitudes for the majority of faint NLTT stars. However, we were able to roughly calibrate the faint end using the USNO-A2.0 all-sky astrometric survey (Monet 1998). Although USNO-A2.0 itself does not contain standard magnitudes, it can be calibrated independently (see Salim & Gould 2000). USNO-A2.0 represents a much more consistent and accurate ($\sim 0.25$ mag) source of photometry than NLTT ($\approx 0.5$ mag). The next step is finding faint NLTT stars in USNO-A2.0 catalogue and comparing those magnitudes with NLTT ones. Again, we find Luyten’s red magnitude to be very close to $V$. We use the calibration from equation (B1) throughout this paper.

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