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White dwarfs and Galactic dark matter

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ABSTRACT

We discuss the recent discovery by Oppenheimer et al. of old, cool white dwarf stars, which may be the first direct detection of Galactic halo dark matter. We argue here that the contribution of more mundane white dwarfs of the stellar halo and thick disc would contribute sufficiently to explain the new high velocity white dwarfs without invoking putative white dwarfs of the dark halo. This by no means rules out that dark matter has been found, but it does constrain the overall contribution by white dwarfs brighter than $M_R \approx 16$ to significantly less than 1 per cent of the Galactic dark matter. This work confirms a similar study by Reylé, Robin & Crézé.

Key words: dark matter – Galaxy: structure.

1 GALACTIC DARK MATTER AS FAINT STARS?

The Massive Compact Halo Object (MACHO) and Experience pour la Recherche d'Objets Sombres (EROS) microlensing projects have detected a microlensing signal from dark objects in the Galactic halo (Alcock et al. 2000, MACHO collaboration), and (Lasserre et al. 2000, EROS collaboration). The MACHO results show that the microlensing can be explained by a Galactic dark halo, 20 per cent of which is in the form of approximately 0.5 $M_\odot$ objects, and this is consistent with the EROS data; see, for example, Milsztajn & Lasserre (2000). It is worth noting that EROS quote 95 per cent confidence *upper limits* on the mass fraction of the dark halo within the mass range probed, 10^{-7} to 10 $M_\odot$, rather than an estimate of the dark halo content at a particular mass, as MACHO do. The results suggest that the responsible objects could be low-mass main-sequence red dwarf stars, or white dwarf stars; but, in order to have escaped detection to date, they must be very faint.

Red dwarfs are now thought to be too luminous, or they would have been detected directly in wide area star count analyses (Reid et al. 1996; Graff & Freese 1996) or the *Hubble Deep Field* (HDF) (Flynn, Gould & Bahcall 1996; Elson, Santiago & Gilmore 1996; Mendez et al. 1996). White dwarfs were considered more difficult to rule out directly, until the surprising discovery was made that white dwarfs, which have had long enough to cool, cease to become fainter and redder, but remain at approximately constant luminosity while becoming *bluer*. This is due to the development of H_2 in their atmospheres, which induces very non-blackbody spectra (Isern et al. 1998; Hansen 1999a,b).

The possibility arose that very faint, blue objects had been found when the HDF was imaged at a second epoch and analysed by Ibata et al. (1999). The number of moving objects, their colours, magnitudes and proper motions were all consistent with the detection of a significant fraction of the dark halo matter in the form of old, cool white dwarfs. However, a third epoch observation of the HDF did not confirm the proper motions of the objects (Richer 2002), but the idea that dark matter had been detected had already spurred many groups to search for local counterparts – with some degree of success. As a result, 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), Scholz et al. (2000), Goldman (1999), de Jong, Kuijken & Neeser (2000) and Oppenheimer et al. (2001, hereafter OHDHS), along with a very low luminosity white dwarf identified by Ruiz et al. (1995), now viewed with new significance. A colour–magnitude diagram for these objects is shown in Fig. 1. The recently discovered white dwarfs are shown as squares – they are all fainter than the end of the white dwarf cooling sequence at $M_R \approx 15.5$, and have velocities typical of the spheroid white dwarfs.

OHDHS have conducted the largest of these recent surveys. They discovered 38 high velocity white dwarfs and derived a space density for their objects which corresponds to approximately 2 per cent of the Galactic dark halo density at the Sun (approximately 0.01 $M_\odot$ pc^{-3}). This is a small but significant fraction of the dark halo density, not high enough to explain the microlensing events (which require that about 20 per cent of the dark halo be in the form of $\approx$0.5 $M_\odot$ objects, but still significantly higher than the expected contribution of white dwarfs from all the well-understood Galactic stellar populations – disc, thick disc, and stellar halo (or spheroid).

A very similar survey to that of OHDHS, in terms of the local volume of space surveyed for high proper motion stars, is the Luyten Half Second (LHS) catalogue (Luyten 1979). Flynn et al. (2001) have searched the LHS catalogue and two other older proper motion surveys for nearby dark halo white dwarf candidates. The LHS

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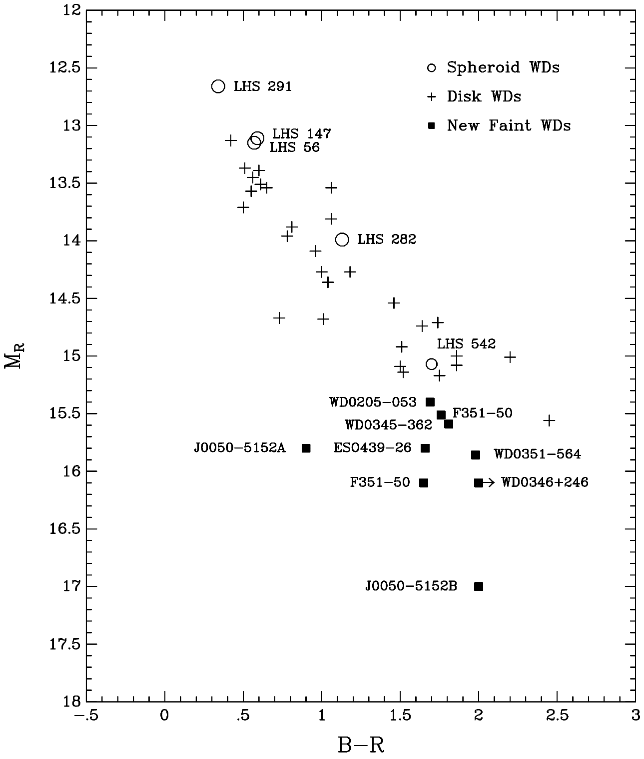

Figure 1. Colour ($B - R$) versus absolute magnitude (in the R-band) diagram of nearby white dwarfs. Disc white dwarfs are shown by crosses, and spheroid white dwarfs as circles. Until recently, the faintest white dwarfs known were at $M_R \approx 16$, but recently several white dwarfs have turned up in new surveys designed to probe for them (squares). One object, J0050-5152, is a binary, the secondary being much fainter, and its status as a white dwarf is still to be confirmed. All of these new white dwarfs are still relatively bright, and probably not faint enough to be good dark matter candidates.

catalogue covers more than half the sky, has a limiting magnitude of $V = 18.4$, with proper motions in the range 0.2 to 0.5 arcsec yr^{-1}. A recent independent analysis (Monet et al. 2000) shows that the LHS catalogue is substantially (90 per cent) complete within these limits, based on a new, deeper survey over a small area within the LHS catalogue.

Gibson & Flynn (2001) have searched the LHS catalogue for objects of the type detected by OHDHS, but found at most a few, even though the survey covers a similar volume. If 2 per cent of the local dark matter is composed of white dwarfs, then a few tens of objects had been expected in the LHS catalogue, whereas Flynn et al. (2001) had earlier analysed the LHS catalogue and two other proper motion surveys in detail, and had found no convincing evidence that any of the high proper motion objects could be associated with ‘dark halo white dwarfs’. All the objects were broadly consistent with coming from the visible Galactic populations.

An alternative explanation for the OHDHS white dwarfs is that they are from existing Galactic populations, and do not represent a new population from the dark halo. Reid, Sahu & Hawley (2001), Hansen (2001) and Koopmans & Blandford (2001) have argued that they are dominated by members of the thick disc. We also argue for this view in this paper by modelling the expected numbers of white dwarfs which would be found in proper motion surveys from the known Galactic populations. Our work supports a similar, independent study by Reylé, Robin & Crézé (2001).

2 MODEL OF LOW LUMINOSITY STARS IN THE SOLAR NEIGHBOURHOOD

We have built a model of the low-mass stellar content of the Solar neighbourhood, including the luminosity function, density and kinematics, in order to simulate actual proper motion surveys via a Monte Carlo technique. The model allows us to predict the expected number of low-mass stars which would be recovered in a proper motion survey directed toward any point in the sky, covering a given area, with a given apparent magnitude limit and a detection window of proper motions. For example, the LHS catalogue covers a little more than half the sky centred on the Northern hemisphere, has an apparent magnitude limit of $R = 18.6$, and recovered proper motions μ in the window $0.5 < \mu < 2.5$ arcsec yr^{-1}.

We model a sphere centred on the Sun with a radius of up to 288 pc, which is sufficiently distant from the Sun for all the surveys we consider. Only low luminosity ($M_V > 12.5$) stars are included in the model.

2.1 Populations in the model

The local Galactic components represented in the model are the disc, the thick disc, the stellar halo and the dark halo.

(i) *The disc* component consists of M dwarfs and white dwarfs. The M dwarfs are drawn from a luminosity function shown in Table 1, which has been measured from faint star counts with the *Hubble Space Telescope* (*HST*) (Zheng et al. 2001). The white dwarfs are drawn from the luminosity function shown in Table 2, which comes from Liebert, Dahn & Monet (1988).

The disc white dwarfs have velocity dispersion components $\sigma = (\sigma_U, \sigma_V, \sigma_W)$ (where U, V and W are the usual space velocities in the directions of the Galactic centre, Galactic rotation and perpendicular to the Galactic plane, respectively) of $\sigma = (40, 30, 20)$ km s^{-1}, and a mean motion (asymmetric drift) relative to the Sun of -20 km s^{-1}. For the disc M dwarfs, we adopt velocity dispersion components of $\sigma = (35, 25, 15)$ km s^{-1}, and an asymmetric drift, $V_{\text{ass}} = 15$ km s^{-1}. These values are slightly lower than for the white dwarfs, because the mean age of the M dwarfs is certainly lower than the white dwarfs. The young M dwarf component is measured to have $\sigma = (30, 17, 12)$ km s^{-1}, and the old M dwarf component $\sigma = (56,$

Table 1. Adopted luminosity function for disc M dwarfs.

M_V	log Φ (M_V) stars pc^{-3} M_V^{-1}	M_V	log Φ (M_V) stars pc^{-3} M_V^{-1}
10.0	−2.12	14.0	−2.30
11.0	−1.92	15.5	−2.67
12.0	−1.89	17.5	−2.61
13.0	−2.19		

Table 2. Adopted luminosity function for disc white dwarfs.

M_V	log Φ (M_V) stars pc^{-3} M_V^{-1}	M_V	log Φ (M_V) stars pc^{-3} M_V^{-1}
11.0	−4.02	14.0	−2.93
11.5	−3.92	14.5	−3.03
12.0	−3.82	15.0	−2.98
12.5	−3.54	15.5	−3.09
13.0	−3.22	16.0	−4.14
13.5	−3.06	16.5	−4.50

34, 31) km s^{-1}, in an analysis of the *Hipparcos* results by Upgren et al. (1997). In both surveys analysed in this paper, the number of M dwarfs recovered from the proper motion windows is quite sensitive to the kinematics adopted; our values have been chosen to produce about the right number of M dwarfs. Our aim here is to predict the number of white dwarfs in the proper motion surveys, while the M dwarfs are only included as a consistency check on the modelling. The number of white dwarfs predicted in the surveys is significantly less sensitive to the adopted kinematics, because the white dwarfs are generally closer than the M dwarfs.

(ii) *The thick disc* component of the model consists of white dwarfs selected from the same luminosity function as the disc white dwarfs, but with space density of 5 per cent of the disc (Reylé & Robin 2001). This is consistent with recent estimates of the thick disc density as between 2 and 10 per cent of the disc density (Kerber, Javiel & Santiago 2001). We adopt an uncertainty in the thick disc local normalization of about a factor of 2. The thick disc stars are given velocity dispersion components $\sigma = (80, 60, 40)$ km s^{-1}, and an asymmetric drift $V_{\rm ass} = 40$ km s^{-1}; see, for example, Morrison, Flynn & Freeman (1990). We also include thick disc M dwarfs, selected from the same luminosity function as the disc M dwarfs, with a normalization of 5 per cent of the disc, and with the same kinematic parameters as the thick disc white dwarfs.

The significantly larger space motions of the thick disc stars means that they are several times more likely to be found in a typical proper motion survey than disc stars. Reylé et al. (2001) model the thick disc in their study of white dwarf proper motions as $\sigma = (67, 51, 42)$ km s^{-1} and $V_{\rm ass} = 53$ km s^{-1}. We have found that adopting either our kinematics or that of Reylé et al. for the thick disc ends up giving quite similar results, i.e. the model predictions are not very sensitive to the adopted thick disc kinematics.

(iii) *The stellar halo*, (or spheroid) part of the model consists of M dwarfs and white dwarfs. The latter are drawn from a luminosity function due to Liebert (2001, private communication). This luminosity function is based on seven white dwarfs, identified as members of the 'halo' on the basis of a high tangential velocity, $V_{\rm tan} > 160$ km s^{-1} obtained as part of an ongoing analysis of all the faint stars in the LHS catalogue. The luminosity function is shown in Table 3. Note that we have converted bolometric magnitudes to V-band magnitudes using equation (1) of Liebert et al. (1988). The total number density in these objects is 3.2×10^{-5} stars pc^{-3}, which corresponds to a mass density of 1.9×10^{-5} M$_\odot$ pc^{-3} for a white dwarf mass of 0.6 M$_\odot$. This is approximately 15 per cent of the local mass density of the stellar halo (as derived from subdwarfs) of 1.5×10^{-4} M$_\odot$ pc^{-3} (Fuchs & Jahreiß 1998).

For the stellar halo, we adopt velocity dispersion components of $\sigma = (141, 106, 94)$ km s^{-1} (Chiba & Beers 2000) and an asymmetric drift of 180 km s^{-1} (i.e. there is a small net rotation in the Galactocentric coordinate frame). The adopted values have very little impact on the conclusions of the paper, because stars with such high velocities populate the proper motion selection window quite well. For example, changing these values to $\sigma = (131, 106, 85)$ km s^{-1} and an asymmetric drift of 229 km s^{-1} – as used by Reylé et al. (2001) – only changes the predicted number of white dwarfs by a few per cent.

We further include stellar halo M dwarfs, adopting the luminosity function of Gould (2002), which is determined from a very large sample of local subdwarfs. As discussed by Gould (2002), there is presently a mild disagreement between the locally determined stellar halo luminosity function for M dwarfs and that determined *in situ*, but this has little impact on the simulations in this paper. All the M dwarfs simulated here are local, being within 50 to 100 pc, depending on the survey being analysed. The halo M dwarfs are assigned the same kinematics as assigned to the stellar halo white dwarfs.

(iv) *The dark halo* part of the model consists of white dwarfs only. We adopt velocity dispersion components of $\sigma = (156, 156, 156)$ km s^{-1} and an asymmetric drift of $V_{\rm as} = 220$ km s^{-1}, which simulates an isothermal population with a density fall-off with Galactic radius of $\rho \propto R^{-2}$, i.e. a sufficient but not necessary condition to explain the flat Galactic rotation curve. Our starting point for the mass density of these stars is 2 per cent of the local dark halo density of 0.008 M$_\odot$ pc^{-3} (Gates et al. 1998) with an average white dwarf mass of 0.6 M$_\odot$, as adopted in the OHDHS survey.

We have adopted a very simple luminosity function for the dark halo white dwarfs. We give all the dark halo white dwarfs the same absolute magnitude, $M_R = 15.9$, this being the faintest absolute magnitude of any of the putative dark halo white dwarfs found in the OHDHS survey. We show that this choice, combined with a 2 per cent dark halo, leads to significantly larger numbers of dark halo white dwarfs than actually observed. Any other choice of luminosity function which is still consistent with the white dwarfs in the OHDHS sample (i.e. all stars are brighter than $M_R = 15.9$) would produce an even greater disagreement between the simulations and the LHS catalogue and the number of recovered white dwarfs in the OHDHS sample.

The *dark halo white dwarfs* share similar kinematic properties with the *stellar halo white dwarfs* (i.e. high random velocities), but differ from them in a key respect worth pointing out (although it has no effect on the modelling or conclusion in this paper). The density distribution of the *stellar halo* is well determined by luminous stars, and follows a power law outward from the Galactic centre, $\rho(R) \propto R^{-3.5}$, where R is the Galactocentric radius; see, for example, Wetterer & McGraw (1996). If the dark halo were made entirely of dim white dwarfs, they would require a density distribution which follows $\rho(R) \propto R^{-2}$, in order to generate a gravitational field which would account for the observed flat rotation curves of disc galaxies. However, we know from the microlensing results that they do not dominate the total mass of the halo. In that case, they could still have an $R^{-3.5}$ distribution, as discussed by Gates & Gyuk (2001). In the model of Gates and Gyuk, 'normal' cold dark matter makes up the rest of the mass distribution and does follow an R^{-2} distribution. For the purposes of the modelling here, the local volume surveyed is so small that the density of the white dwarfs over the volume is essentially constant. Gates and Gyuk propose a very interesting model for the distribution of white dwarfs: a Galactic 'shroud' which is thicker than the traditional thick disc, but not as extended as the dark halo. In a future paper, we intend to examine to what extent the newly discovered faint white dwarfs can constrain this type of model.

The luminosity functions for the populations are shown in Tables 1–4 and are plotted in Fig. 2. The kinematic properties of all the model populations are shown in Table 5.

Table 3. Adopted luminosity function for stellar halo white dwarfs.

$M_{\rm bol}$	M_V	$\log \Phi\ (M_V)$ stars pc^{-3} M_V^{-1}
11.75	12.10	−6.15
14.85	15.25	−4.50

Table 4. Adopted luminosity function for halo M dwarfs.

M_V	$\log \Phi\ (M_V)$ stars pc^{-3} M_V^{-1}	M_V	$\log \Phi\ (M_V)$ stars pc^{-3} M_V^{-1}
10.0	−4.26	13.0	−4.54
11.0	−4.26	14.0	−4.63
12.0	−4.46	15.0	−4.61

Table 5. Kinematic parameters of populations in the model.

Population	$(\sigma_U, \sigma_V, \sigma_W)$ km s^{-1}	$V_{\rm as}$ km s^{-1}
Disc M dwarfs	(35, 25, 15)	15
Disc white dwarfs	(40, 30, 20)	20
Thick disc	(80, 60, 40)	40
Stellar halo	(141, 106, 94)	180
Dark halo	(156, 156, 156)	220

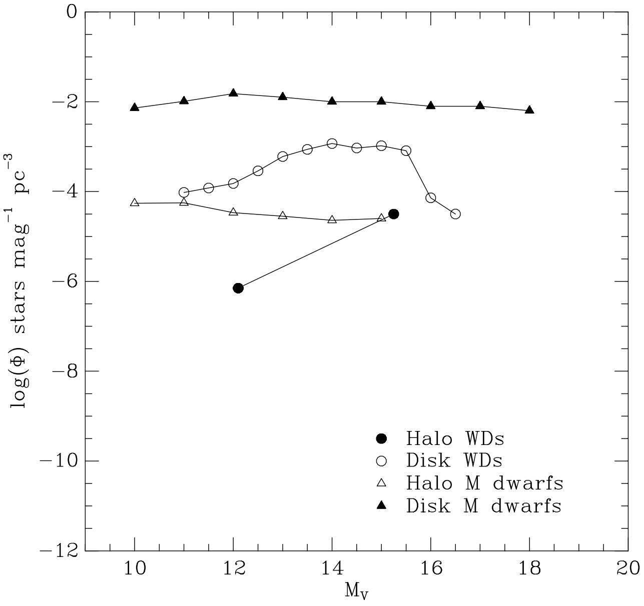

Figure 2. The luminosity functions for the various low-mass stars in the model, as shown in Tables 1–4 .

3 MODELLING THE LHS AND OHDHS SURVEYS

The model allows us to run Monte Carlo simulations of a proper motion survey. Stars are generated within a small sphere around the Sun, with a uniform density distribution in the case of the halo and thick disc populations, and with a density distribution which is falling off in z as $\mathrm{sech}^2(z/z_\mathrm{h})$ in the case of the disc (where we adopt $z_\mathrm{h} = 125$ pc, which is equivalent to an exponentially falling disc scale height of 250 pc far from the plane).

For each star, a V-band absolute magnitude is selected from the appropriate luminosity function, and its apparent magnitude computed. A $V - I$ colour is assigned to the stars as follows:

For the disc M dwarfs we use the empirically calibrated relation due to Reid & Cruz (2002, their section 4.1), which gives M_V as a function of $V - I$ (in three continuous polynomial segments) for the colour range $1.0 < V - I < 4.5$.

For the white dwarfs, $V - I$ colours are calculated similarly:

$$(V - I)_\mathrm{WD} = 0.385 M_V - 4.85.$$

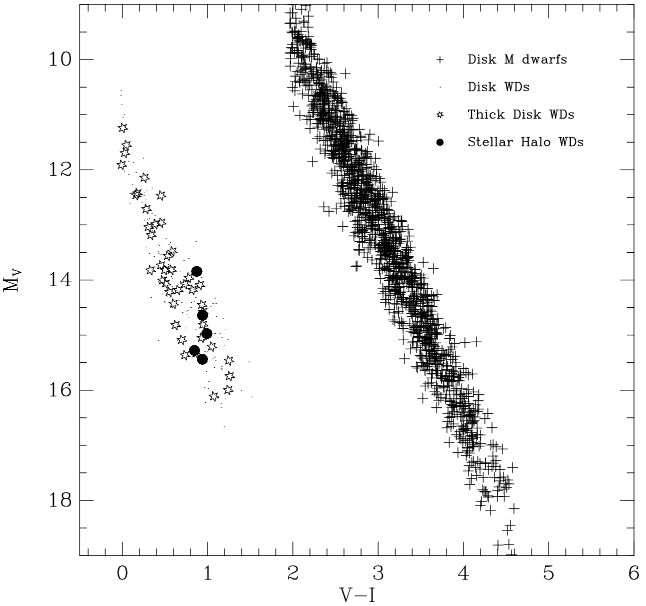

Figure 3. The main components of the model in the M_V versus $V - I$ colour–magnitude diagram. A small random number is added after assigning the colour to avoid stars settling strictly on a line. The main-sequence stars and white dwarfs are clearly separated in this plane.

This relation comes from fitting white dwarfs in the sample of Bergeron, Leggett & Ruiz (2001). We have also derived transformation equations for white dwarfs from $V - I$ to other colours from the same sample:

$$B - V = 1.05(V - I) - 0.13,$$

$$R - I = 0.473(V - I) + 0.01.$$

Note that a small Gaussian random number with standard deviation $\sigma = 0.05$ is added to the $V - I$ colour to avoid clutter in the figures.

An absolute magnitude M_V versus colour $V - I$ diagram from a typical simulation of the LHS catalogue is shown in Fig. 3. Main-sequence disc stars dominate the sequence on the right side. The left sequence consists of white dwarfs of the disc, the thick disc and the stellar halo.

3.1 Simulation of the OHDHS survey

The OHDHS survey covers 4165 deg^2, centred on the South Galactic Pole, to a limiting magnitude of $R_{59\mathrm{F}} = 19.7$ in a proper motion μ window of $0.33 < \mu < 3.0$ arcsec yr^{-1}. In order to simulate the OHDHS sample, we generate colour–magnitude diagrams of nearby stars using the model described in the previous section. We then transform the M_V and $V - I$ values to the bands used in the OHDHS survey. For *white dwarfs*, we use the following transformations to the (photographic) $R_{59\mathrm{F}}$ and the (photographic) B_J bands (i.e. for the III-aJ emulsion) used in the OHDHS survey:

$$R - R_{59\mathrm{F}} = 0.006 + 0.059(R - I) - 0.112(R - I)^2 - 0.0238(R - I)^3$$

$$B - B_\mathrm{J} = 0.28(B - V) \quad \text{for} \quad -0.1 \leqslant B - V \leqslant 1.6$$

which come from Bessell (1986) and Blair & Gilmore (1982).

For the M dwarfs, we have derived a transformation from $R - I$ to $B_\mathrm{J} - R_{59\mathrm{F}}$ based on figure 10 of Hambly, Irwin & MacGillivray

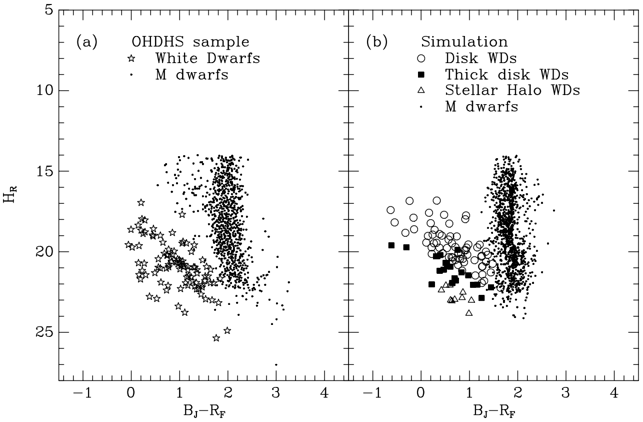

Figure 4. Reduced proper motion versus colour plots for the OHDHS and simulated samples: (a) the data from OHDHS, with white dwarfs marked by stars and M dwarfs by dots; (b) a typical simulation of the OHDHS survey using our model. The main features of the data are well reproduced by the simulations; most of the white dwarfs detected are plausibly from the disc, thick disc and stellar halo. Two of the OHDHS white dwarfs (at high RPM) are not easily accounted for by the model, and are very interesting as dark matter candidates.

(2001), who describe in detail the Super COSMOS sky survey, upon which the OHDHS survey is based.

Fig. 4 shows the results of a simulation in the reduced proper motion (RPM) $H_{\rm R}$ versus colour $B_{\rm J} - R$ plane (hereafter, $H_{\rm R}$ and the R-band refer to the $R_{\rm 59F}$ band, used by OHDHS). Fig. 4(a) shows the simulation, and Fig. 4(b) shows the actual OHDHS data: circles denote disc stars, squares thick disc stars and triangles stellar halo stars. There is close agreement between the simulated sample and the actual data. First, the disc white dwarfs form a wide sequence from $(B_{\rm J} - R, H_{\rm R}) = (0.0, 17.0)$ to $(B_{\rm J} - R, H_{\rm R}) = (1.5, 22.0)$. Most white dwarfs appear to be members of the disc. Below this sequence, most of the thick disc and stellar halo white dwarfs appear, because they have generally greater space velocities than the disc stars, and thus higher RPMs.

The M dwarfs lie in an almost vertical line at $B_{\rm J} - {\rm R} \approx 2.0$ in both panels. The total number of M dwarfs in the simulation is similar to the observations, as a result of adjusting the kinematic parameters of the disc to achieve this consistency. The number of disc M dwarfs turns out to be quite sensitive to the disc kinematics, and we achieved this good fit by using the kinematic parameters for the disc shown in Table 5. The kinematic parameters adopted are, however, quite consistent with the observed kinematics of M dwarfs; see Upgren et al. (1997) and also Section 2.1.

To a limiting magnitude of $R = 19.7$, OHDHS identify a total of 97 white dwarfs, of which 82 have direct spectroscopic confirmation, and 15 are assumed with reasonable confidence to be white dwarfs based on their position in the RPM versus colour diagram.

We have computed the expected numbers of various white dwarf types using the model. The expected numbers are: for the disc 60 ± 8 white dwarfs, for the thick disc 21 ± 5 white dwarfs and for the stellar halo, 10 ± 3 white dwarfs, for a total of 91 white dwarfs.

The adopted kinematical parameters have a small effect on the predicted numbers of white dwarfs. For example, adopting the disc, thick disc and halo kinematics used by Reylé et al. (2001) (i.e. for the disc, $\sigma = (42.1, 27.2, 17.2)$ km s^{-1} and $V_{\rm as} = 16.6$ km s^{-1}; for the thick disc, $\sigma = (67, 51, 42)$ km s^{-1} and $V_{\rm as} = 53$ km s^{-1}; and for the halo, $\sigma = (131, 106, 85)$ km s^{-1} and $V_{\rm as} = 229$ km s^{-1}; compare with Table 5), we obtain 54 disc white dwarfs, 18 thick disc white dwarfs and 11 halo white dwarfs – that is, the numbers are very similar.

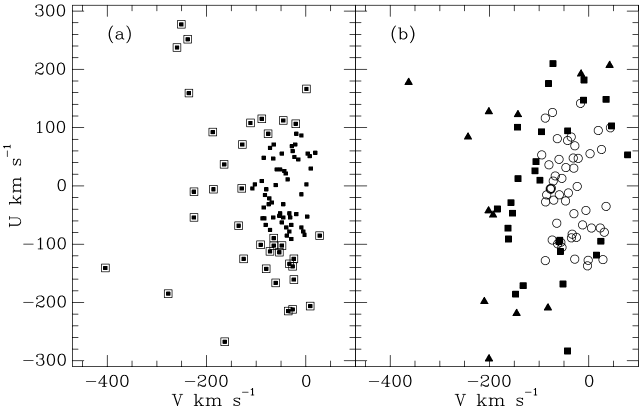

Figure 5. Kinematics of the white dwarfs: (a) V versus U velocities for the white dwarfs in the OHDHS sample; (b) results from a typical simulation using disc, thick disc and stellar halo white dwarfs, but no dark halo white dwarfs. The same symbols are used as in Fig. 4(b). The main features of the observations appear to be well reproduced by the classical stellar populations alone.

The total number of white dwarfs in the model and the OHDHS sample are in good agreement. We now check the relative numbers of white dwarfs of each population type. The simulations indicate that a neat dividing line between disc and other types of white dwarfs can be drawn from $(B_{\rm J} - R, H_{\rm R}) = (-0.5, 17.0)$ to $(B_{\rm J} - R, H_{\rm R}) = (2.0, 26.0)$. Counting white dwarfs below this line in the simulations yields 25 ± 4 stars, compared to 21 white dwarfs in the OHDHS sample.

OHDHS argue that many or all of these higher RPM white dwarfs are part of a new dark halo population, comprising some 2 per cent of the local dark matter halo density. We argue instead that these white dwarfs can just as well be interpreted as coming from a mixture of the thick disc and stellar halo. Further evidence for this assertion comes from the kinematics of the white dwarfs.

We show in Fig. 5 the space velocities of the white dwarfs in the V versus U plane, i.e. projected on to the Galactic plane. A typical simulation is shown in Fig. 5(a) and the OHDHS sample stars in Fig. 5(b). In the simulation, disc stars are denoted by diamonds, thick disc stars by crosses and halo stars by circles. The similarity between the diagrams is striking. In particular, the thick disc and stellar halo white dwarfs in the simulation lie mostly outside the 2-σ circles used by OHDHS to isolate the dark halo stars (squares in squares). (The 2-σ circle is where stars with velocities twice that of the disc velocity dispersion lie, relative to the mean motion of the old disc at $(V, U) = (-35, 0)$ km s^{-1}.) In a typical simulation, we count 41 ± 6 white dwarfs outside the 2-σ circle, while OHDHS find 37 such stars. The distribution of these simulated stars in the (V, U) plane is also found to be very similar to the observations.

We show in Fig. 6 the V versus U velocities for a sample of local dwarf stars for which [Fe/H] is available (Fuchs & Jahreiß 2001, private communication). The availability of abundances means that the stars can be classified by their population type directly, rather than compared statistically to the models (as is the case for the white dwarfs). There are 282 stars in total, of which 245 are in the metallicity range $-1.6 <$ [Fe/H] < -0.5, and are here termed ‘thick disc’ stars, while 37 have [Fe/H] < -1.6 and are here termed ‘halo’ stars. What is striking about this figure is how similarly the (V, U) distribution of the stars is to the OHDHS sample [Fig. 5(a)]. Thick

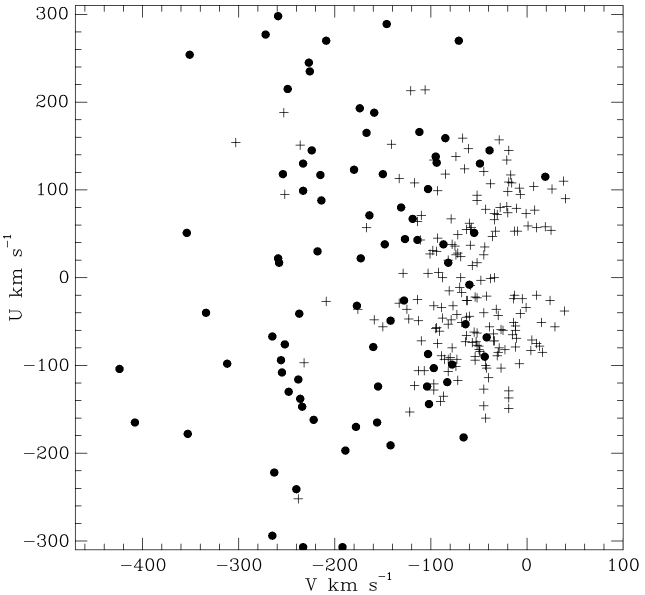

Figure 6. Kinematics of a sample of nearby dwarfs (Fuchs & Jahreiß 2002, private communication). Crosses indicate stars in the range $-1.6 <$ [Fe/H] < -0.5 (broadly, 'thick disc' stars) while circles are stars with [Fe/H] < -1.6 (broadly, 'halo' stars). The distribution of velocities for the two metallicity types is very similar to that of the white dwarfs of the OHDHS sample [Fig. 5(a)].

disc stars dominate the region around $(V, U) = (-35, 0)$ km s^{-1}, while the halo stars fill a much broader region centred roughly at $(V, U) = (-200, 0)$ km s^{-1}.

3.2 Simulation of the LHS catalogue

The LHS catalogue covers about 28 000 deg^2, mostly of the Northern sky, to an apparent magnitude limit of $R = 18.6$ and with a proper motion window of $0.5 < \mu < 2.5$ arcsec yr^{-1}. We simulate the LHS catalogue by covering the fraction of the sky ($\delta > -33°$ and $|b| > 10°$, i.e. 65 per cent of the sky) which is estimated to be complete to better than 90 per cent by Dawson (1986).

Fig. 7 shows the RPM $H_{\rm R}$ versus colour for the simulated LHS sample, where the Luyten R-band magnitude ($R_{\rm L}$) is related to the V magnitude via (see Flynn et al. 2001, appendix B)

$$R_{\rm L} = V - 0.17 - 0.228(B - V)$$

and we adopt Johnson B for the Luyten blue magnitude, $B_{\rm L}$.

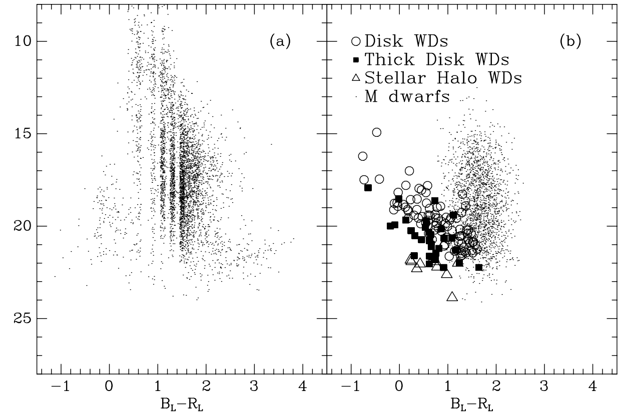

Figure 7. Reduced proper motion versus colour for the LHS sample: (a) data from the LHS catalogue; (b) a typical simulation. The white dwarf part of the LHS data is broadly reproduced by the simulation.

For the M dwarfs, we have obtained a transformation from M_V to Luyten's photographic $B_{\rm L} - R_{\rm L}$ colour by matching up stars in the LHS catalogue with parallaxes in the Catalogue of Nearby Stars (CNS3). We derived the following third-order polynomial

$$B_{\rm L} - R_{\rm L} = -0.70066 + 0.41268M_V - 0.02382M_V^2 + 0.00046M_V^3.$$

Fig. 7 shows good agreement between the observed and modelled white dwarfs, and only fair agreement with the M dwarfs. This is likely due to the fact that we do not have an independent estimate of the error in the Luyten photographic colours as a function of apparent magnitude. We adopted an error of 0.3 mag in the M dwarf colours in the LHS catalogue; judging by the figure, this is likely to be an underestimate. Because we are primarily interested in the white dwarfs in the LHS catalogue, this has no impact on the conclusions of this paper.

Although the LHS and OHDHS surveys probe similar volumes of space, it is much easier to compare our simulations with OHDHS. This is because the OHDHS sources have been spectroscopically classified into white dwarfs and red dwarfs (such work is underway with the LHS catalogue and should be available in the near future) and furthermore the colour transformations are better understood than in the LHS catalogue. Hence, we regard the comparison of our model with OHDHS in the previous section as superior to any comparison with the LHS catalogue. Nevertheless, the broad features of the LHS observations are well reproduced by the simulation, and we regard this as a qualitative consistency check on the model.

3.3 Dark halo white dwarfs?

We now introduce dark halo white dwarfs into the simulations. We begin by adopting a luminosity function in which all the dark halo white dwarfs are as faint as the faintest white dwarf found in the OHDHS sample, i.e. at absolute magnitude $M_R = 15.9$ and at $B_{\rm J} - R_{\rm F} \approx 2$. This choice *minimizes* the number of dark halo white dwarfs generated in the simulations, while not being inconsistent with the luminosities of the white dwarfs actually found in the OHDHS survey. Still, it appears to produce too many simulated dark halo sources. Following OHDHS, we adopt a white dwarf mass of 0.6 M$_\odot$ and local density of 2 per cent of the dark halo, i.e. $0.02 \times 0.008 = 1.6 \times 10^{-4}$ M$_\odot$ pc^{-3}. Using our colour equations, these white dwarfs are estimated to have an absolute V-band magnitude of $M_V \approx 16.7$. In Fig. 8 we show where these dark halo white dwarfs lie in the RPM versus colour plane. Despite being conservative and minimizing the number of 'dark' white dwarfs, there are plenty of these white dwarfs at a RPM of $H_{\rm R} \approx 25$, where just a few stars are found in the observed samples.

Judging from the simulations, a good discriminator between white dwarfs of the disc, thick disc and stellar halo and those of the dark halo is to divide them at $H_{\rm R} = 24$. In the OHDHS sample, two white dwarfs are found with RPM $H_{\rm R} > 24$, while none were found in the LHS catalogue. We plot in Fig. 9 the number of high RPM white dwarfs ($H_{\rm R} > 24$) expected in the LHS and OHDHS surveys as a function of their fraction of the dark halo. Assuming that no dark halo white dwarf candidates were found in the LHS catalogue, and two (the two absolutely faintest stars) were found in OHDHS, we conclude that approximately 0.2 per cent of the dark matter density could be in white dwarfs (i.e. a total of two white dwarfs were found corresponding to a dark matter fraction of ≈0.2 per cent in Fig. 9). A dark matter fraction of 2 per cent, as suggested by OHDHS, would

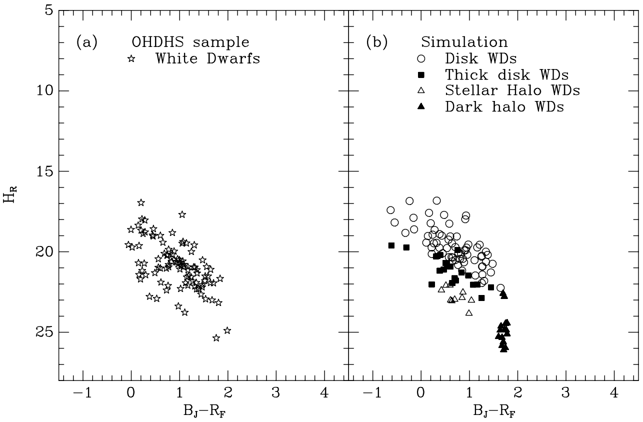

Figure 8. Reduced proper motion versus colour plots for the OHDHS and simulated samples: (a) data from OHDHS, with white dwarfs marked by stars; (b) a typical simulation of the OHDHS survey using our model, now including white dwarfs from the dark halo (the figure is otherwise the same as Fig. 4). Two per cent of the dark halo mass has been placed in white dwarfs of 0.6 $\mathrm{M}_{\odot}$ at an absolute magnitude of $M_R = 15.9$, and these are shown in the simulated survey by filled triangles. Most of the white dwarfs in OHDHS are plausibly from the disc, thick disc and stellar halo, but two high RPM white dwarfs in OHDHS do lie in the region where dark halo white dwarfs with an absolute magnitude of $M_R = 15.9$ are expected to lie. However, as shown in Fig. 9, the simulations produce a factor of a few more such stars than actually seen in the combined LHS and OHDHS surveys.

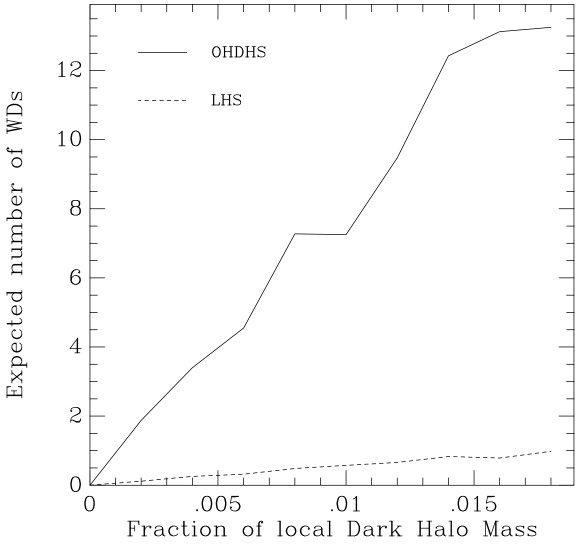

Figure 9. Expected number of high RPM ($H_{\mathrm{R}} > 24$) white dwarfs in the two surveys analysed, as a function of the fraction of the local dark matter density in such objects (for a white dwarf mass of $M_{\mathrm{WD}} = 0.6\ \mathrm{M}_{\odot}$. The white dwarfs in the simulation have $M_R = 15.9$ and $M_V \approx 16.7$, which means that they are more easily detected in the OHDHS survey than in the LHS catalogue, even if both surveys probe similar volumes. The actual number of objects found in both surveys with this high a RPM is two, which corresponds to a local density of ≈0.2 per cent of the dark halo. The dark halo density adopted is 0.008 $\mathrm{M}_{\odot}\ \mathrm{pc}^{-3}$.

yield about 12 high RPM white dwarfs in the OHDHS sample and about one in the LHS sample, for a total of 13, compared to two white dwarfs actually found. Judging from both surveys, we conclude that OHDHS's estimated fraction of 2 per cent of the dark halo density in white dwarfs is an overestimate, and should be a few factors smaller. If a significant fraction (>0.2 per cent) of the dark halo is in white dwarfs, then they should be fainter than absolute magnitude $M_R \approx 16$ in order to avoid being detected in large numbers in the OHDHS sample.

4 CONCLUSIONS

We have built a model of the kinematics and luminosities of low-mass stars in the Solar neighbourhood, which we use to simulate the results of various proper motion surveys. We discuss in particular the search for very faint white dwarfs in the LHS proper motion survey and the recent survey of OHDHS, which are the largest surveys of this type. The surveys sample similar volumes of space. We argue that the contribution of 'normal' white dwarfs of the thick disc and stellar halo is sufficient to explain the high velocity white dwarfs found by OHDHS, and that they are not necessarily part of a new, massive population from the dark halo. This work confirms results from a similar study by Reylé et al. (2001).

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